The Distributed Model Intercomparison Project: Phase 2

Science Plan

Updated July 13, 2006

Mike Smith, Victor Koren, Seann Reed, Ziya Zhang,
Dong Jun Seo, Fekadu Moreda, Zhengtao Cui,

Hydrology Laboratory
Office of Hydrologic Development
NOAA National Weather Service

Executive Summary

The Hydrology Laboratory (HL) of the NOAA National Weather Service (NOAA/NWS) proposes the second phase of the Distributed Model Intercomparison Project (DMIP). The NOAA/NWS realizes the need for a continued series of science experiments to guide its research into advanced hydrologic models for river and water resources forecasting. This need is accentuated by NOAA/NWS' recent progression into a broader spectrum of water resources forecasting to complement its more traditional river and flash flood forecasting mission. To this end, the NOAA/NWS welcomes the input and contributions from the hydrologic research community in order to better fulfill its mandate to provide the Nation with valuable products and services.

Twelve groups participated in DMIP 1, resulting in a wealth of knowledge for the scientific community and valuable guidance for the NOAA/NWS research program. DMIP 2 is designed around two themes: 1) continued investigation of science questions pertinent to the DMIP 1 test sites, and 2) distributed and lumped model tests in hydrologically complex basins in the mountainous Western US.

DMIP 2 will be supported by exciting, cross-cutting linkages to the Oklahoma Mesonet, the Hydrometeorological Testbed program of NOAA Environmental Technnology Laboratory, and the Sierra-Nevada Hydrologic Observatory proposal to the Consortium of Universities for the Advancement of Hydrologic Science, Incorporated (CUAHSI). As such, DMIP 2 will contribute to the goals of these partner institutions in a way that will garner greater results than if these programs were executed in an isolated manner.

NOAA 'Weather and Water Mission Goals' are directly addressed through DMIP 2 by conducting experiments to guide the development, application, and transition of advanced science and technology to operations and new services and products. DMIP 2 also contributes to the NOAA 'Cross-Cutting Priority' of ensuring sound, state-of-the-science research as a vigorous, forward-looking effort that invites contributions from academia, other federal agencies, and international institutions.

We expect that DMIP 2 will provide multiple opportunities to develop data requirements for modeling and forecasting in hydrologically complex areas. These requirements fall in the general categories of needed spatial and temporal resolution and quality. From these, new sensor platforms could be designed or appropriate densities of existing gages could be specified to meet specific project goals. From the river forecasting viewpoint, we think these data needs are particularly acute in the mountainous west. In addition, DMIP 2 will serve as a multi-institutional evaluation of the Oklahoma Mesonet sensors and data. Such an evaluation may be able to promote an expansion of these sensors to larger geographic domains. Or, DMIP 2 my point out a need for other soil moisture sensors to meet the needs of NOAA/NWS water resources forecasting mission.

Table of Contents

1.0 Introduction

1.1 Background

The Hydrology Laboratory (HL) of the NOAA National Weather Service (NOAA/NWS) proposes the second phase of the Distributed Model Intercomparison Project (DMIP). The first phase of DMIP (hereafter called DMIP 1) proved to be a landmark venue for the comparison of lumped and distributed models in the southern Great Plains (Smith et al., 2004a; Reed et al., 2004a). Twelve groups participated in DMIP 1, including representatives from China, Denmark, Canada, New Zealand, and universities and institutions in the US. Models ranged from conceptual representations of the soil column applied to various computational elements, to more comprehensive physically-formulated models based on highly detailed triangulated representations of the terrain. DMIP 1 attracted the attention of many in the hydrologic research community, resulting in the publication of a DMIP Special Issue of the Journal of Hydrology in October, 2004. In addition, DMIP 1 provided valuable guidance to the NWS HL research program for improved hydrologic models for river and water resources forecasting.

The first phase of DMIP formally concluded in August, 2002 with a meeting of all participants at NWS headquarters in Silver Spring, Maryland. The purpose of this meeting was to present and discuss the formal analyses of participants' results. At this meeting, the participants eagerly discussed the need for a second phase of DMIP. Ideas from this meeting were compiled and are presented herein along with other science questions.

1.2 Need for DMIP 2

While DMIP 1 served as a successful comparison of lumped and distributed models, it also highlighted significant problems, knowledge gaps, and topics that need to be investigated. First, DMIP 1 was limited by a relatively short data period containing only a few significant rainfall-runoff events in the verification period from which statistics could be computed and inferences made. Thus, the need remains for further DMIP 1-like testing in order to properly evaluate the hypotheses related to lumped and distributed modeling. At this time, almost five years of additional data are available to support such additional comparisons. Also, DMIP 1 was somewhat hampered by the quality of the radar estimates of observed precipitation. The quality of these data has been oft-studied (e.g., Stellman et al., 2001; Young et al., 2000; Johnson et al., 1999; Wang et al., 2000; Smith et al., 1999) and includes problems such as underestimation and non-stationarity resulting from changes in the processing algorithms. The effects of data errors propagating through distributed models also need to be further explored. The DMIP 1 participants discussed this need at the 2002 concluding DMIP 1 workshop.

Moreover, additional model comparisons must be performed in more hydrologically complex regions. Most notably, experiments are needed in the western US where the hydrology of most of the areas is dominated by complexities such as snow accumulation and melt, orographic precipitation, steep and other complex terrain features, and data sparcity. The need for advanced models in mountainous regions is coupled with the foundational requirements for more data in these areas. Experts at NWS River Forecast Centers (RFCs) point to the need for explicit and intense instrumentation programs to determine the required sensor network density to improve forecast operations (Rob Hartman, California-Nevada RFC, personal communication). Advanced models cannot be implemented for RFC forecast operations without commensurate analyses of the data requirements in mountainous regimes. Some argue that the greatest knowledge gaps are in mountain hydrology, leading to the proposed Sierra Nevada Hydrologic Observatory (SNHO) as a hydrologic test area for the initiative established by the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI).

Another unresolved question from DMIP 1 is: 'Can distributed models reproduce processes at basin interior locations?' Included here is the computation of spatial patterns of observed soil moisture. DMIP 1 attempted to address this question through blind simulations of nested and basin interior observed discharges at a limited number of sites. Investigations into this question have typically been hampered by a lack of soil moisture observations organized in a high spatial resolution. While much work has been done to estimate soil moisture from satellites, these methods are currently limited to observing only the top few centimeters of the soil surface. The test basins in DMIP 1 are mostly contained in Oklahoma, offering an opportunity for the soil moisture observations from the Oklahoma Mesonet to be used. Despite the limitations of the Oklahoma Mesonet, (e.g., one sensor per county) it is prudent to perform experiments to understand the real value of the currently available data and work towards developing requirements for future sensor deployment.

Yet another major need highlighted by DMIP 1 experiments is the testing of models in a 'pseudo-forecast environment' with forecast-quality forcing data. Such tests are a logical complement to the process simulation experiments in DMIP 1. The well-documented model intercomparsion experiment of the WMO (WMO, 1992) highlighted the testing of models in a forecasting environment. One of the conclusions of this workshop was that good simulation (process) models are necessary for longer lead-time forecasts. In DMIP 1, we tested process models in simulation mode and thus satisfied this conclusion from the WMO experiment. Now, we propose that DMIP 2 include a forecast test component as a natural complement to the process experiments in DMIP 1.

Finally, as with DMIP 1, the NOAA/NWS realizes the need for an accelerated venue of science experiments to guide its research into advanced hydrologic models for river and water resources forecasting. This need is accentuated by NOAA/NWS' recent progression into a broader spectrum of water resources forecasting to complement its more traditional river and flash flood forecasting mission (NWS, 2004b). Moreover, the NOAA/NWS heeds the recommendations of the National Research Council (NRC) that point to hydrologic forecasting as one of the ten 'grand challenges' in environmental sciences in the next generation. (NRC, 2000). To this end, the NOAA/NWS welcomes the input and contributions from the hydrologic research community in order to better fulfill its mandate to provide the Nation with meaningful products.

1.3 Relation to NOAA/NWS Goals

DMIP 2 is specifically designed to meet NOAA/NWS goals identified in the NOAA 2005-2010 Strategic Plan (NOAA, 2004) and the NWS Strategic Plan (NWS, 2004a). NOAA 'Weather and Water Mission Goals' are directly addressed through DMIP 2 by conducting experiments to guide the development, application, and transition of advanced science and technology to operations and new services and products. DMIP 2 also contributes to the NOAA 'Cross-Cutting Priority' of ensuring sound, state-of-the-science research as a vigorous, forward-looking project that invites contributions from academia, other federal agencies, and international institutions.

Moreover, elements of DMIP 2 support the recommendations of the NWS Integrated Water Science Plan (IWSP, 2004). One of the primary IWSP objectives is to 'provide new water resources products and services' by implementing a new comprehensive suite of high-resolution digital water resources analysis and forecast products. DMIP 2 contributes to this via a experiment designed to evaluate spatially-varied soil moisture simulations. Georgakakos and Carpenter (2004) proved the value of such distributed soil moisture estimates for irrigation scheduling. DMIP 2 will augment their work with agricultural benefits by providing multiple computations and evaluations of soil moisture fields.

1.4 Relation to NLDAS

The North American Land Data Assimilation System (NLDAS) (Mitchell et al., 2004) was designed to provide enhanced soil moisture (and temperature) initial conditions for numerical weather prediction models. Four land surface models (LSMs) were run in NLDAS over a three-year analysis period: NOAH model from the National Center for Environmental Prediction (NCEP); the Mosaic model from Goddard Space Flight Center (GSFC) of NASA, the Variable Infiltration Capacity (VIC), and the NWS Sacramento Soil Moisture Accounting Model (SAC-SMA). The models were run in retrospective, uncoupled mode, on a $1/8^{th}$ degree grid over the continental US (CONUS). NLDAS models used a common linear channel routing scheme and meteorological forcings. Interestingly, three of these models (SAC-SMA, VIC, and NOAH) also participated in DMIP 1.

NLDAS provided valuable insight into model performance for predicting land surface states and fluxes. While there is some level of overlap between the NLDAS and DMIP experiments, there are major science questions and issues that are central to DMIP apart from NLDAS. Amongst these is the difference in project goals: the DMIP experiments are designed to guide the NWS science direction for models and techniques for improved water resources, river, and flash flood forecasting, at current modeling scales as well as at increasingly finer spatial and temporal scales. One of the dominant foci of the DMIP experiments is the generation and evaluation of hydrographs. The focus of NLDAS was to evaluate the models' ability to generate enhanced initial conditions for weather models with an emphasis on fluxes. Another major differentiation is the model scale. Many of the DMIP 1 models were run at finer scales to assess the ability to predict small scale events at basin interior points. In contrast, NLDAS models were run on a rather coarse $1/8^{th}$ degree scale.

2.0 Science Questions

We present the following science questions to be addressed in DMIP 2. Some of these are repeated from DMIP 1 in order to evaluate them given longer archives of higher quality data than were available in DMIP 1. We frame the science questions for the interest of the broad scientific community and in most cases provide a corollary for the NOAA/NWS.

I. Can distributed hydrologic models provide increased simulation accuracy compared to lumped models? If so, under what conditions? Are improvements constrained by forcing data quality? This question was one of the dominant questions in DMIP 1. Reed et al. (2004a) showed that only one of the DMIP basins showed improvements from deterministic distributed modeling. Furthermore, work by Carpenter and Georgakakos (2004a) indicates that even when considering operational parametric and radar-rainfall uncertainty, flow ensembles from lumped and distributed models are statistically distinguishable in the same basin where the deterministic model showed improvement. The specific question for the NOAA/NWS mission is: under what circumstances should NOAA/NWS use distributed hydrologic models rather than lumped models to provide hydrologic services?

II. What simulation improvements can be realized through the use of a more recent period of radar precipitation data than was used in DMIP 1? One of the issues faced in DMIP 1 was the time-varying biases of the NEXRAD precipitation data (Reed et al., 2004a) which affected the simulations in the model calibration and verification periods. For DMIP 2, we propose to avoid the problematic 1993-1996 period of radar data. Simulations and analyses will be based on the period starting in 1996. For the NOAA/NWS, the question is whether this later (and less bias-prone) period of data can lead to improved calibrations and simulations.

III. What is the performance of (distributed) models if they are calibrated with observed precipitation data but use forecasts of precipitation? Georgakakos and Smith (1990) argued for such an experiment as follow-on work to the 1980's WMO model comparisons. (In those tests, observed real-time mean areal precipitation values were used.) They stated that:

> 'It is imperative however that a follow-up workshop be planned during which forecasts of rainfall are utilized instead of actual future rainfall observations. It is the rainfall input component of the input uncertainty that contributes the most to prediction uncertainty ………..'

While much work has been done to evaluate the improvements realized by distributed models in *simulation* mode, the NOAA/NWS also needs to investigate the potential gains when used for forecasting. For example, the following questions are relevant: is there a forecast lead time at which the distributed and lumped model forecasts converge? How far out into the future can distributed models provide better forecasts than currently used lumped models? Reed et al. (2004a) stated that because forecast precipitation data have a lower resolution and are much more uncertain than their observed counterparts, the benefits of distributed models may diminish for longer lead times.

IV. Can distributed models reasonably predict processes such as runoff generation and soil moisture re-distribution at interior locations? At what scale can we validate soil moisture models given current models and sensor networks? The soil moisture observations derived through the Oklahoma Mesonet provide a good opportunity to address the latter question over a large spatial domain. Koren et al. (2005) presents a comparison of computed and observed soil moisture using the Mesonet data. Fortin (1998) provided a good example of such experiments with the Sacramento model. Schaake et al. (2004) inter-compare CONUS-scale computed soil moisture values from four models and with available observations. They found better agreement between observed and simulated ranges of water storage variability than between observed and simulated amounts of total water storage. For the NOAA/NWS, the corollary question is: can distributed models provide meaningful, spatially-varied estimates of soil moisture to meet the US needs for an enlarging suite of water resources forecast products?

V. In what ways do routing schemes contribute to the simulation success of distributed models? In other words, can the differences in the rainfall-runoff transformation process be better understood by running computed runoff volumes from a variety of distributed models through a common routing scheme? Such experiments are necessary complements to validating distributed models with interior-point flow and soil moisture observations in that we are attempting to generate 'the right results for the right reasons.' Mitchell et al. (2004) present one large scale example of such a test. Such experiments also help the NOAA/NWS focus its research program.

VI. What is the nature of spatial variability of rainfall and basin physiograpic features, and the effects of their variability on runoff generation processes? What physical characteristics (basin shape, feature variability) and/or rainfall variability warrant the use of distributed hydrologic models for improved basin outlet simulations? The corollary question for the NOAA/NWS is: at what river forecast points can we expect distributed models to effectively capture essential spatial variability so as to provide better simulations and forecasts?

While this question was not explicitly investigated via DMIP 1 modeling instructions, it was nonetheless a good opportunity to explore these questions. Using the DMIP 1 data sets, Smith et al. (2004) attempted to derive quantitative indicators to determine the benefit of distributed models in an *a priori* sense. Distinct differences in precipitation spatial variability and basin behavior were identified. Yet, no quantifiable indexes could be derived. At present, five more years of observed precipitation and streamflow data are available to continue the types of analyses performed by Smith et al. (2004) and others. This question was not part of the experiments explicitly called for by DMIP 1. However, it and others were investigated at the initiative of the DMIP 1 participants.

VII. What is the potential for distributed models set up for basin outlet simulations to generate meaningful hydrographs at interior locations for flash flood forecasting? Inherent in this question is the hypothesis that better outlet simulations are the result of accurate hydrologic simulations at points upstream of the gaged outlet. This question is repeated from the DMIP 1 experiments. Reed et al. (2004a) identified reasonable performance for small ungaged areas. In DMIP 2, we will make available longer data periods as well as a few more gaged locations for such tests.

For the NOAA/NWS, we restate this question as: can distributed runoff and flow predictions for small, ungauged locations be used to improve upon the existing NOAA/NWS flash flood forecasting procedure (i.e. Flash Flood Guidance)? Analysis tools that are now being developed as part of the statistical-distributed modeling investigation using HL-RMS (Reed et al. 2004b) can also be used to analyze participant uncalibrated simulations. Streamflow gauge data for 6 basins smaller than 157 km2 are available for DMIP 2 (5 of these were not available for DMIP 1).

VIII. What are the advantages and disadvantages associated with distributed modeling (versus lumped) in hydrologically complex areas using existing model forcings? DMIP 1 was limited to experiments in test basins in the southern Great Plains. These basins contain few complications such as snow accumulation and melt, forcing data scarcity, and orographic precipitation patterns. Many distributed hydrologic models have been developed to account for such complexities through accounting for slope, aspect, governing albedo, etc. (e.g., Wigmosta et al., 1994). The NOAA/NWS corollary is: what can be improved over the current lumped model (Snow-17) used in the NWSRFS?

IX. Is there a dominant constraint that limits the performance of hydrologic simulation and forecasting in mountainous areas? If so, is the major constraint the quality and/or amount of forcing data, or is the constraint related to a knowledge gap in our understanding of the hydrologic processes in these areas? In other words, given the current level of new and emerging data sets to drive advanced distributed models, can improvements be realized? Or, do we still not have data of sufficient quality in mountainous areas? As a corollary to the latter question, what data requirements can be specified for the NOAA/NWS to realize simulation and forecasting improvements in mountainous areas? Simpson et al. (2004) state that the primary limiting factors in the application of snow accumulation/melt models continue to be the 1) lack of spatially resolved meteorological inputs corresponding to the model computational units, and 2) lack of spatially relevant observations of hydrologic and snowpack conditions.

A related corollary for the NOAA/NWS is: How can new observation sites that were not included in the calibration data set be incorporated into the hydrological modeling system? The NOAA HMT instrumentation effort provides the ideal forum to address this question. Presumably the hydrologic models - both distributed and lumped - will need to be calibrated from existing datasets that do not include the NOAA HMT dataset. How then, can these models best utilize these new sources of data? Answers to this question will have a wide application - specifically whenever RFC operations encounter a new sensor that did not exist during the calibration period.

X. Can improvements to rain-snow partitioning be made? Partitioning between rainfall and snow fall plays a major role in determining both the timing and amount of runoff generation in high altitude basins (Kim et al., 1998). Advanced instrumentation such as vertically pointing wind profilers and S-Band radars have been used to detect freezing levels by locating the bright-band height (BBH) (White et al., 2002). This latter study reported that a 609m (2,000ft) rise in melting level can triple the amount of runoff. For the NOAA/NWS, such information is critical. In one case, these advanced techniques located the observed freezing level at 2700 feet, which was 1300 feet lower than the forecast models suggested. This observed departure (lowering) from the forecast snow level led the Portland Weather Forecast Office to upgrade their Snow Advisory to a Winter Storm Warning.[1] The question for the NOAA/NWS is: can advanced sensors planned for implementation via the NOAA HMT in the American River lead to improved simulations and forecasts?

XI. What are the dominant scales (if any) in mountainous area hydrology? Understanding the variations of snowpacks and the timing and volume of snowmelt that generate streamflow has grown in recent periods but is complicated by difficult scale issues (Simpson et al. 2004). Mismatches exist between the spatial and temporal scales of observations and the scales over which snowpacks and runoff vary. As stated by Simpson et al. (2004):

> '*The hydrologic results of these spatially and temporally varying land surface and climate conditions are complex differences and changes in snowmelt, soil moisture and streamflow……As a consequence, understanding, observing, and predicting such variations are central goals for hydrologists and resource managers alike in snow-dominated and snowfed regions….*'

For the NOAA/NWS, the question can be restated as: is there an appropriate modeling scale in the mountainous areas that captures the essential rain/snow processes?

[1] Personal communication: David Kingsmill, NOAA/ETL, Boulder, CO.

3.0 Description of Proposed Sites

3.1 Overview

Figure 1 shows the two major geographic regions for the experiments to be conducted in DMIP Phase 2. As seen in Figure 1, the Oklahoma region and watersheds in DMIP 1 will be used. Second, we propose two neighboring basins in the Sierra Nevada mountains as good candidates for hydrologically complex areas. We present the basins here and provide more specific information in Appendices A, B, and C.

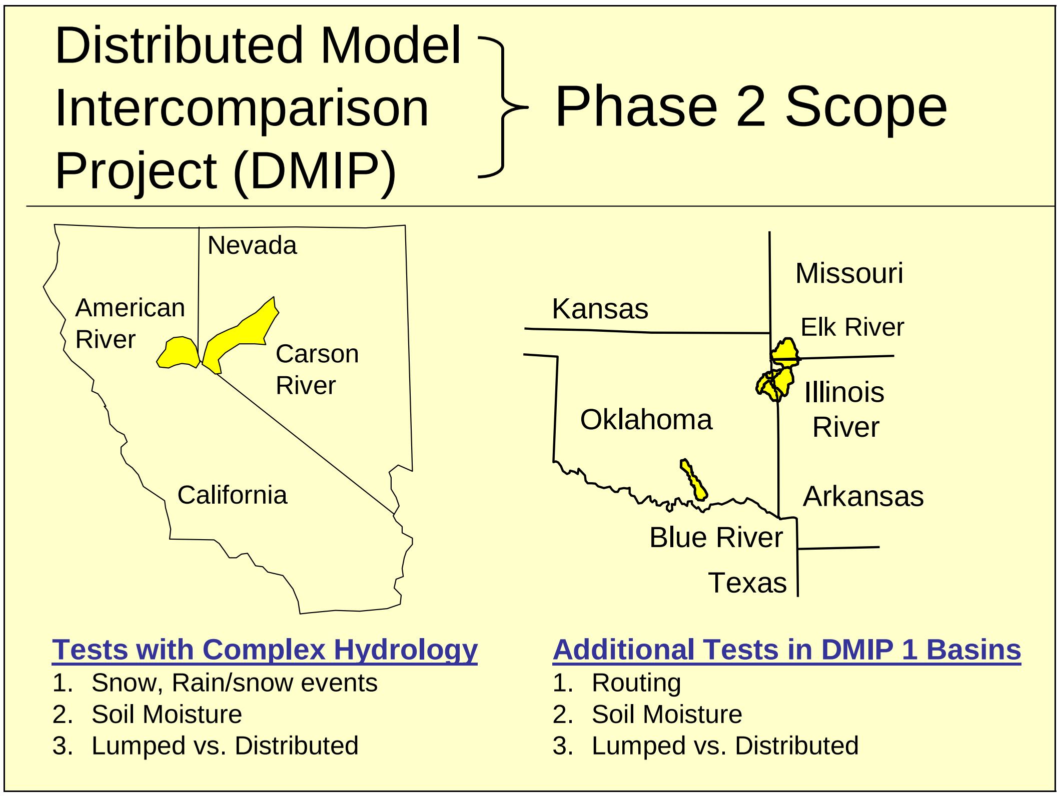


Figure 1. The geographic scope of DMIP 2 experiments.

3.2 Oklahoma Region

Here, we propose to use an area including the state of Oklahoma as shown in Figures 1, 2 and 3. As in DMIP 1, we will use the Blue River and Illinois River basinsfor specific tests regarding lumped and distributed models. For tests related to the soil moisture, we propose to model a 'synthetic basin' encompassing the entire state of Oklahoma with its Mesonet series of soil moisture observations. Smith et al. (2004) present a description of the Illinois and Blue River basins and the rationale for their selection for lumped and distributed model comparisons.

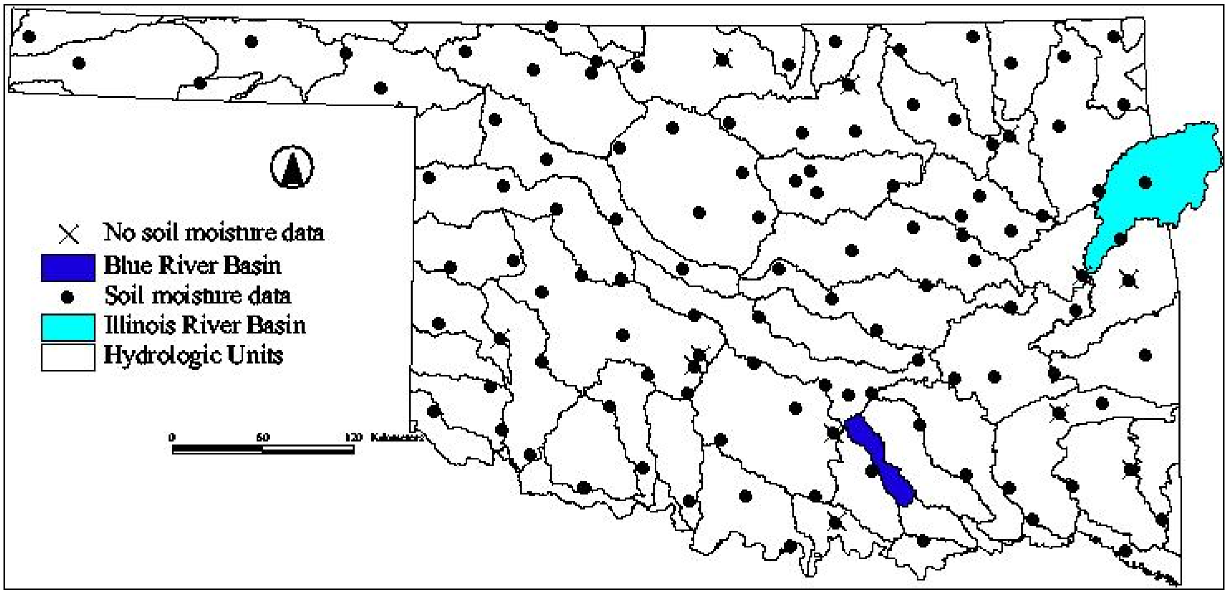


Figure 2. Location of Oklahoma Mesonet sites as they relate to the test basins in DMIP 1.

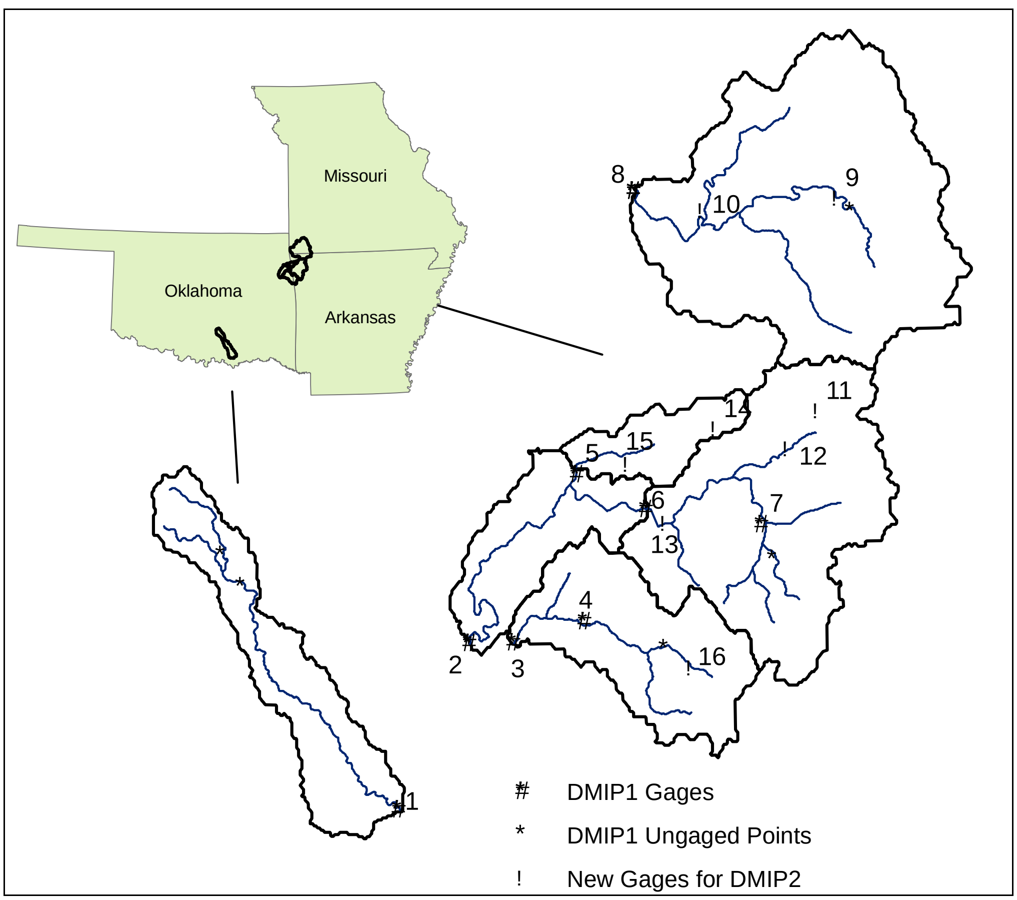


Figure 3 Location of DMIP test basins and interior computational points in the Oklahoma, Missouri, Arkansas area. Note that additional gages have been located for DMIP 2

Table 1 shows the USGS stream gages and basin drainage areas for the Oklahoma region basins. Note that we have located additional gages that were not used in DMIP 1.

Table 1. Data for USGS Stream Gages in the Oklahoma Region

No	USGS No	Name	Area(km2)
1	7332500	Blue R. nr Blue, OK	1233
2	7196500	Illinois River near Tahlequah OK	2484
3	7197000	Baron Fork at Eldon OK	795
4	7196973	Peacheater Creek at Christie OK	65
5	7196000	Flint Creek near Kansas OK	285
6	7195500	Illinois River near Watts OK	1645
7	7194800	Illinois River at Savoy AR	433
8	7189000	Elk River near Tiff City Mo	2258
9	7188653	Big Sugar Creek near Powell MO	365
10	7188885	Indian Creek near Lanagan MO	619
11	7194880	Osage Creek near Cave Springs AR	90
12	7195000	Osage Creek near Elm Springs AR	337
13	7195430	Illinois River South of Siloam Springs AR	1489
14	7195800	Flint Creek at Springtown AR	37
15	7195865	Sager Creek near West Siloam Springs OK	49
16	7196900	Baron Fork at Dutch Mills AR	105

3.3 Basins in the Sierra Nevada

3.3.1 Description

We propose to use sub-basins in the American and Carson River basins located on the border of California and Nevada as shown in Figure 4. Although these basins are geographically close, their hydrologic regimes are quite different due to their mean elevation and location on either side of the Sierran divide (Simpson et al. 2004). The Carson River basin is a high altitude basin with a snow dominated regime, while the American River drains an area that is lower in elevation with precipitation falling as rain and mixed snow and rain (Jeton et al. 1996). Figure 5 shows the area-elevation curves of each basin and shows that the East Fork Carson River is higher in elevation. Jeton et al. (1996) present a similar figure. Figures B.3 and C.6 present expanded versions of each areal elevation curves. These figures show differences in the shape of the two curves, indicating that different hydrologic responses may result.

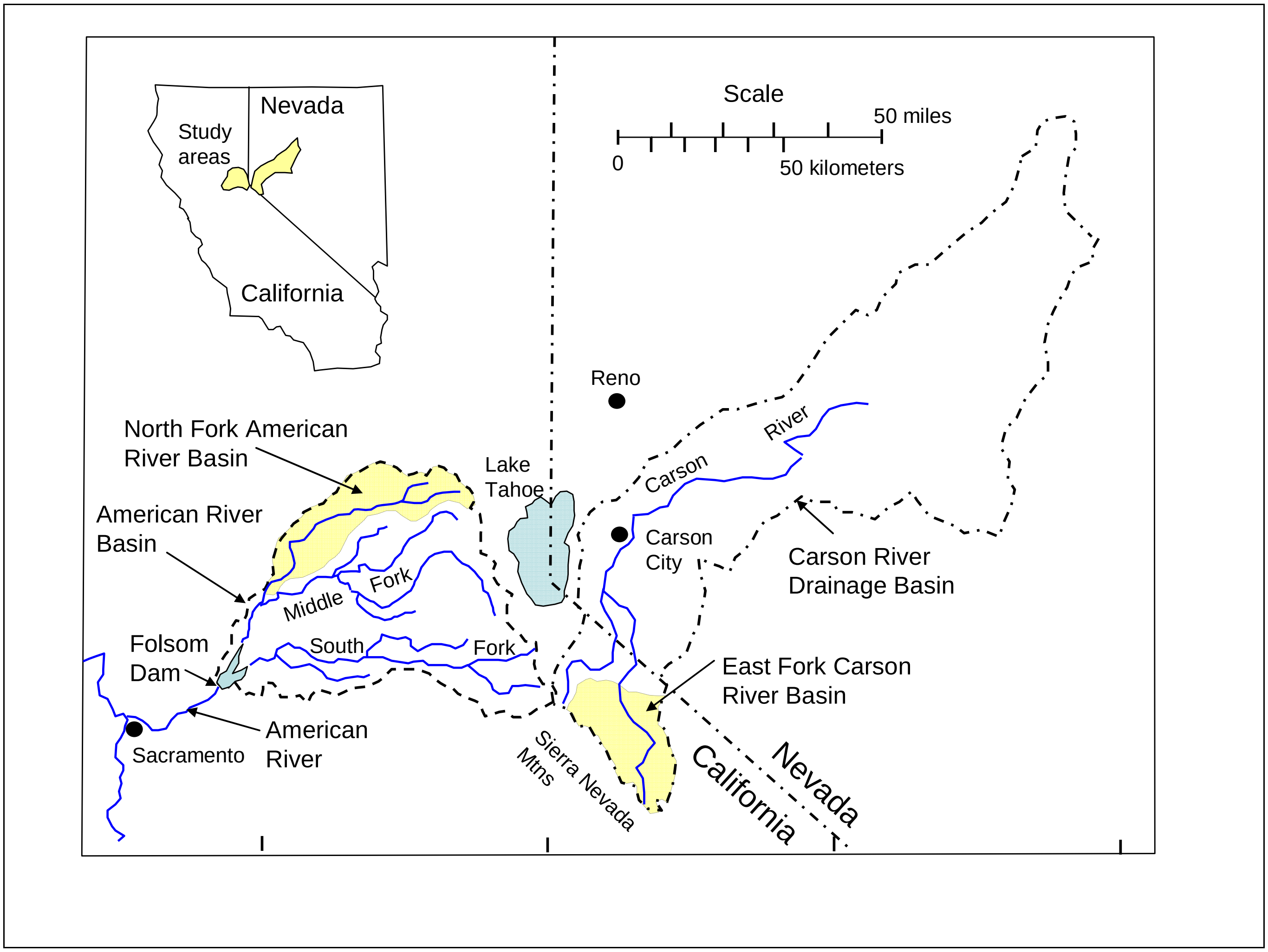


Figure 4. Location map of the American and Carson River basins (after Jeton et al., 1996)

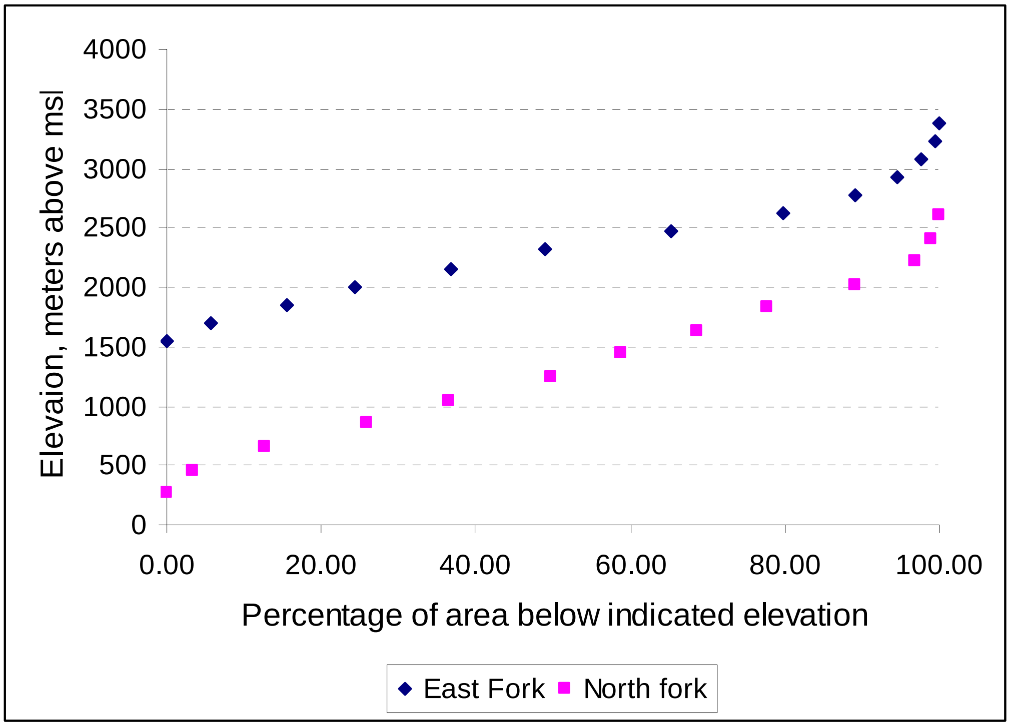


Figure 5. Area-elevation curves for the East Fork and North Fork basins.

In the American River basin, we propose the North Fork sub-basin above the North Fork dam forming Lake Clementine. Hereafter, we refer to this test site as the American basin. This basin is 886 km^2 in area and rests on the western, windward side of the Sierran divide. The USGS gage at the North Fork dam is number 11-417000. Precipitation is dominated by orographic effects, with mean annual precipitation varying from 813mm at Auburn (elev. 393m. above msl) to 1,651 mm at Blue Canyon (elev. 1,676 m. above msl) (Jeton et al., 1996). Precipitation occurs as a mixture of rain events and rain-snow events. The mean annual precipitation is 60.3 in and the annual runoff is 33.5 in (Lettenmaier and Gan, 1990). Streamflow is about two-thirds wintertime rainfall and snowmelt runoff and less than one-third springtime snowmelt runoff (Dettinger et al. 2004). The basin is highly forested and varies from pine-oak woodlands, to shrub rangeland, to ponderosa pine, and finally to sub-alpine forest as one moves up in elevation. Much of the forests are secondary-growth due to the extensive timber harvesting to support the mining industry in the late 1800's. (Jeton et al.,1996). Soils in the basin are predominately clay loams and coarse sandy loams. The geology of the basin includes metasedimentary rocks and granodiorite (Jeton et al.,1996). The American basin is designated as a Wild and Scenic River (Dettinger et al., 2004).

In the Carson River basin, we propose the East Fork sub-basin. While the American River and other west-facing Sierran basins are generally less steep than the basins on the east side of the divide, the East Fork Carson River generally flows from south to north so that its average slope is not as steep as it could be if it were to face directly east-west. As stated earlier, the East Fork of the Carson River is a high altitude basin, with a drainage area of 714 km^2 above USGS gage 10-308200 near Markleeville, CA and 922 km^2 above USGS gage 10-309000 at Gardnerville, NV. Elevations in the East Fork basin range from 1,650m. near Markleeville to about 3,400m. at the basin divide. Mean annual precipitation varies from 559mm at Woodfords (elev. 1,722) to 1,244mm near Twin Lakes (elev. 2,438m). Hereafter, we refer to this basin as the Carson basin.

Table 2 presents a summary of the characteristics of the American and Carson river basins.

Table 2. Summary of the characteristics of the Carson and American Basins.

	Carson River	American River
Area	922 km2	886 km2
Median altitude	2417 m	1 270m
Annual rainfall	560mm -1244mm	813mm -1651mm
Min and max temp	0 ^{0}C, 14	3^{0}C 18
Forcings	mostly snow	snow and rain
Aspect	leeward	windward
Soil	Shallow sandy and Clay soil	clay loams and coarse sandy loans
Geology	volcanic rock and granodiorite	metasedimentary rock and granodiorite
Vegetation	rangeland in lower altitude and conifer forests upper altitude	pine-oak woodlands, shrub rangeland, ponderosa pine forest, and subalpine forest
USGS gage	1030900 near Garderville, NV	11427000 at North Fork Dam

3.3.2. Rationale for Basin Selection.

Several factors underscore the selection of the American and Carson basins for use in DMIP 2. Numerous previous studies, largely unregulated flows, and exciting linkages to cross-cutting initiatives will provide the DMIP 2 participants with a multi-institutional venue for sound scientific investigation.

First, both basins are largely unregulated (Jeton et al., 1996; Dettinger et al., 2004), even though a few small reservoirs and diversions exist in both basins. The American is largely unaffected by upstream reservoirs and diversions (Jeton et al., 1996; Dettinger et al., 2004). Figure B.10 in Appendix B shows a schematic of the small reservoirs and diversions in this basin. None of the investigators found it necessary to remove the effects of the small reservoirs to derive a 'natural' flow (Carpenter and Georgakakos, 2001). Also, the Corps of Engineers studied reservoir effects in California basins and concluded that the North Fork dam would not have significant effect on streamflow hydrographs. (personal communication, Brett Whitin, USACE).

Second, these basins are geographically close, yet they present an opportunity to study different hydrologic regimes. Moreover, their proximity allows for more expedient data processing by DMIP 2 organizers and participants.

Third, the selection of the American River for hydrologic analysis dovetails with the planned deployment of the Hydrometeorological Testbed (HMT) of NOAA's Environmental Technology Laboratory (ETL) in the same basin for meteorologic analyses and development. Previously, NOAA deployed the HMT in the Russian River, a flood prone basin also draining to the Sacramento/San Francisco area. The Russian River HMT proved to be a successful venture, providing a wealth of data and a sound footing for subsequent HMTs. The American River HMT will allow advanced techniques to address the problem of data scarcity in the mountainous west. DMIP 2 and the NOAA HMT would afford a multi-institutional evaluation of hydro-meteorological observations gathered via advanced techniques.

Fourth, these basins have been studied by numerous researchers, providing substantial modeling experience and insight into their hydrologic behavior. Moreover, we hope that these studies will encourage participation in DMIP 2 by reducing project spin-up costs. Leavesley et al., (2003) used the Carson basins for experiments on *a priori* parameter estimation. Lettenmaier and Gan (1990) subjected these basins to global warming scenarios to determine the resultant hydrologic sensitivity. Jeton and Smith (1993) used these basins for GIS-based parameter derivation for distributed model application. Using these distributed models, Jeton et al. (1996) later modeled the potential effects of climate change on the streamflow. Carpenter and Georgakakos (2001) used the American River basin to investigate the effects of climate scenarios on flood control, hydro-electric power generation, and low flow augmentation. They were able to calibrate the North Fork basin and other sub-basins of the American River to a satisfactory degree. They did notice a slight over-simulation bias for the North Fork. Lundquist and Cayan (2002) used the American river and others throughout the West to study the seasonal and spatial patterns of diurnal streamflow patterns. They found that the American River has a rain-dominated power spectrum without a distinct diurnal cycle from January to April, and a snowmelt-dominated diurnal peak from April to July. Cayan and Riddle (1993) examined the influence of temperature and precipitation on streamflow for a number of basins including the American River across a range of elevations in California. Kim et al. (1998) performed a numerical study of precipitation and streamflow for the winter of 1994 and 1995. Simpson et al. (2004) examined issues of scale and improved estimates of solar insolation for forecasting snowmelt and streamflow in the American and Carson basins.

Several authors used these basins in the Sierra-Nevada mountains to study the dynamics of the precipitation generation process in mountainous areas. Reynolds and Dennis (1986) reported on cloud seeding efforts to modify winter precipitation over the Sierra Nevada. Pandey et al. (1999) studied the influences of upper air characteristics along the California coast on wintertime precipitation. Shortly thereafter, Pandey et al. (2000) used a hybrid physical-statistical scheme to resolve fine-scale precipitation patterns in the same region. Hay and Clark (2003) used statistically and dynamically downscaled weather model output to force hydrologic simulation models in the Carson River Basin. Tsintikidis et al. (2002) used the American river to examine the estimation of hourly precipitation and related uncertainties given the existing operational real-time network of gauges. Wang and Georgakakos (2004) used the MM5 model to simulate 62 winter storms in the American River basin. They investigated the dependence of model precipitation on boundary and initial conditions and physical system parameterizations. Dettinger et al. (2004) investigated the degree of orographic enhancement in winter storms.

Finally, the American River basin is part of the Sierra-Nevada Hydrologic Observatory (SNHO) proposal to the Hydrologic Observatory initiative of the Consortium for the Advancement of Hydrologic Science, Inc. (CUAHSI, see http://www.cuahsi.org/ and http://www.cuahsi.org/HO/Prospectuses/prospectus_SNHO_080204.pdf). One of the primary aims of CUAHSI is to establish and maintain a set of long-term hydrologic observatories (HO) at which research can be conducted on pressing hydrologic problems by utilizing data generated by CUAHSI as well as by other entities in the environs of the observatories. Observatories will be selected on the basis of their regional representation and their viability as laboratories to study particular subsets of hydrologic problems from the master list, and data networks will be designed and implemented to study these problems. However, basic networks at each of the observatories will be implemented to assure that cross-laboratory syntheses can be conducted.

These hydrologic observatories (HOs) are conceived to be large-scale field facilities that will provide the coherent, multi-disciplinary characterization of the landscape necessary to advance a number of environmental sciences, including hydrology, biogeochemistry, ecology, geomorphology and limnology. The hydrologic cycle provides the organizing principle for the design of these observatories.

4.0 Overview of Proposed Experiments

To address the science questions presented in Section 2.0, we propose the following experiments. These are organized by geographic region, although there is some overlap.

4.1 Oklahoma Region

4.1.1 Simulation experiments: lumped and distributed models.
These will essentially follow the DMIP 1 Project Design and Modeling Instructions (see http://www.nws.noaa.gov/oh/hrl/dmip/default.html). Calibrated and un-calibrated simulations from participants' distributed models will be tested against observed streamflow and corresponding lumped-model simulations. As in DMIP 1, such simulations help the NOAA/NWS evaluate the effort and benefits of model calibration.

4.1.1.a Data: We will make available data forcing data from 1996 (or earlier) to the present, and will define appropriate calibration and verification periods. We propose to use the archived operational NOAA/NWS radar data. We propose to add additional interior simulation points at USGS gage locations that were not used in DMIP 1. Estimates of potential evaporation will be provided as was done in DMIP 1. Data from the Oklahoma Mesonet may be used to derive PE.

4.1.1.b Standard of Comparison: As in DMIP 1, we propose to compare distributed model simulations (calibrated and uncalibrated) to 1) corresponding simulations from a lumped model and 2) observed hourly streamflow from the USGS.

4.1.1.c Evaluation metrics: We propose to use essentially the same criteria specified in Smith et al. (2004) that were used in DMIP 1. We will make available our statistical analysis program to participants.

4.1.1.d HL will ask for two simulations: uncalibrated and calibrated. Note: If the DMIP 2 participant also generated DMIP 1 simulations, then an additional simulation will be requested.

Here, we will ask the participant to run the DMIP 2 radar data through their models calibrated with the DMIP 1 radar forcing. This test will provide a meaningful analysis of the dependence of model parameters on precipitation forcing.

4.1.2 Forecast experiments

Here, we propose a 'pseudo' forecast experiment not unlike that undertaken by the WMO (1992). Participants will use their calibrated (with NEXRAD re-analysis data) distributed models. Forecast-quality data from numerical weather models will be made available.

4.1.2.a Data: we propose to use Eta model-derived forecast fields from NCEP. These are not reanalysis fields. Observed forcing will be used to run models up to the current time. An alternative would be to use archives of precipitation forecasts archived in the National Precipitation Verification Unit. See: http://www.hpc.ncep.noaa.gov/npvu/

4.1.2.b Standard of Comparison: Calibrated lumped model forecasts, observed data. Evaluation Metrics: we propose standard forecast metrics to be evaluated at various lead times (Kitanidis and Bras, 1980).

4.1.2.c Data Assimilation: The models in the WMO real-time comparison (WMO, 1992) all used assimilation techniques. Here, we propose that no data assimilation be used. Data assimilation for distributed models still needs considerable development before use in an experiment like DMIP 2.

4.1.2.d Basins: We propose that only one or two basins be used for the forecast experiments. A limited period containing a select set of events is proposed. We will specify the forecast lead time to be used.

4.1.3 Comparisons of Computed and Observed Runoff Volumes and Water Balance Components

We propose that participants set up their model to run over an area encompassing the Oklahoma Mesonet shown in Figure 1. Models can be set up at any resolution, but must convert the soil moisture estimates to the 4km2 HRAP scale. We propose to compare computed and observed soil moisture contents at the 0-25mm and 25-75mm depth ranges.

Models will not perform routing; only water balance computations. No model calibration will be performed. We propose to evaluate state variables: soil moisture and runoff volumes. In DMIP 2, we wish to build on the NLDAS experience. In that experiment, Schaake et al. (2004) intercompared NLDAS model-generated soil moisture fields with each other and with available observations. The NLDAS soil moisture estimates were generated on a 1/8th degree grid, which is too coarse for the current and expected NWS water resources forecast products. Observed soil moisture data were taken from the Illinois State Water Survey. These data were collected twice per month. We propose to use data from the Oklahoma Mesonet which has a finer temporal resolution.

4.1.3.a Data: More recent NEXRAD radar data and other tested forcings will be made available.

4.1.3.b Standard of Comparison: Mesonet soil moisture observations

4.1.3.c Evaluation Metrics: For soil moisture, we propose that a subset of the following measures could be used to evaluate the goodness of fit of computed vs observed values of soil moisture over a region. We will also use these for noting intermodel differences:

1. Visual Agreement (Perica and Foufoula-Georgiou, 1996)
2. Compare time series of computed soil moisture at various depths to corresponding observations. These time series comparisons will be performed at the locations of the OK. Mesonet soil moisture sites.
3. Pattern correlation (Huang et al. 1996)
4. Frequency Scaling Ratio (Guetter et al. 1996)
5. 2-d wavelet transforms (Briggs and Levine, 1997)
6. 'Figure of Merit'. (Perica and Foufoula-Georgiou, 1996). This is a dimensionless index defined as the area of the intersection of the observed and predicted areas, divided by the union of these two areas. Theoretical range is 0.0 (no agreement) to 1.0 (perfect agreement).
7. Hausdorf Norm (Marron and Tsybakov, 1995). Qualitatively, this is a metric for the 'visual notion' of distance between curves or shapes. Tcherednichenko et al. (2004) used this metric to compute agreement of computed spatially variable distributed model outputs. The problem with this metric is that it is very computationally expensive (Luis Bastidas, personal communication, 2004).
8. A test of the frequency at which a model soil moisture deficit exceeds a threshold (e.g., Georgakakos and Carpenter, 2004).
9. Methods used by Schaake et al. (2004). Intermodel differences were described through the dimensionality of the correlation matrix. Comparisons of modeled to observed soil moisture were not made between point soil moisture measurements and area average model estimates at the corresponding grid points. Instead, a composite average of observed total column soil water content was compared to an average of the total water content at the corresponding grid points.

4.1.4 Common Channel Routing Scheme

In this series of experiments, we propose that we rout participants' runoff time series through a common channel routing scheme. This will help discern differences amongst the participants' rainfall-runoff mechanisms. We propose that participants generate runoff volumes (aggregated to one hour time step) at the HRAP scale. Here, participants provide the runoff that they use in their models before hillslope and channel routing. The participants will be free to use whatever basin discretization is appropriate for their models, but then must average the runoff volumes to the 4km2 HRAP scale. We will ingest the runoff volumes and route them through the HL distributed model using kinematic hillslope and channel routing. We will then compute goodness-of-fit statistics. We propose to run such simulations for a 2-3 year period on the Blue and Tahlequah River basins.

4.1.4.a Data: We propose to use the more recent NEXRAD precipitation data as the primary forcing.

4.1.4.b Standard of comparison: USGS hourly discharge data at selected points.

4.1.4.c Evaluation Metrics: We propose to use essentially the same criteria specified in Smith et al. (2004) that were used in DMIP 1.

4.2 Sierra Nevada Basins

In the American and Carson sites, we propose a general multi-model inter-comparison of lumped and distributed models similar to DMIP 1. Models will be parameterized and set up to generate calibrated and uncalibrated simulations of streamflow, snow cover, and soil moisture, depending on the basin.

4.2.1 Data:

4.2.1.1 Precipitation. We propose to first make available several precipitation forcings at an hourly time step. Several preliminary options are available and are listed below. In all cases, we will evaluate the forcings to have the proper long term areal mean precipitation. The primary format/spatial resolution will be the nominal 4km HRAP grid used in DMIP-1. Other resolutions may be made available.

4.2.1.1.a MPE derived rain-gage only field.

4.2.1.1.b MPE derived rain gage – satellite merged product. Note that analyses by Kondragunta et al. (2005) show that in the Sierras, use of satellite-sensed precipitation does not provide significant improvement over a gauge-only field due to the high density gauge network.

4.2.1.1.c MM5 output. There are potentially two alternatives here. The first is to use MM5 results from George Leavesly; the second is through PhD work by Art Henkel (NWS Sacramento) at the University of California at Davis under Lavent Kavvas and John Schaake. These data sources are proposed for FY06.

4.2.1.1.d Gridded precipitation estimates derived using the procedure of Shuzheng Cong and John Schaake in HL.

4.2.1.1.e Operational data produced via the 'Mountain Mapper' application.

4.2.1.1.f Gridded precipitation amounts from the National Mosaic QPE (NMQ) being developed at the National Severe Storms Lab (NSSL).

4.2.1.1.g Following this and in participation with the NOAA Environmental Technology Lab Hydromet Testbed in the American River, we will make available revised precipitation estimates derived from the X-band polarimetric radars and other advanced sensors described in Appendix D. These data will be used to evaluate the simulation improvements possible via advanced observation sensors.

4.2.1.2 Temperature: We propose to use one or more data sets of temperature. As with precipitation, we will ensure that temperature data corresponds to the proper long term areal mean. The primary format/spatial resolution will be the nominal 4km HRAP grid used in DMIP 1. Other resolutions may be made available. We propose to provide these data at an hourly time step. We have not yet finalized the method for generating the gridded temperatures. Operational data from the “Mountain Mapper” application may be used.

4.2.1.3 Snow: snow data collected by the State of California are available at http://cdec.water.ca.gov/snow/ (also precipitation and temperature similar to SNOTEL sites).

4.2.1.4 Soil Moisture: We will make available soil moisture measurements in the North Fork as part of the NOAA HMT.

4.2.1.5 PE: We will provide an estimate of PE for both basins. One possibility would be to provide an estimate of PE versus elevation for each basin.

4.2.2 Standard of Comparison: We propose to use 1) USGS observed (hourly and daily) discharges and 2) simulations from a lumped or semi-lumped modeling approach that is the same as run by the River Forecast Center. In the American basin, we will also perform comparisons of computed and observed soil moisture as well as snow depth, snow water equivalent, and areal extent of snow as these data become available via the NOAA/ ETL Hydromet Testbed (HMT) in the cold seasons of 2005-6, 2006-7, and 2007-8. All models will be run at the same time step. We propose to investigate the data requirements for mountainous areas via model simulations with and without the HMT advanced data.

4.2.3 Metrics: We propose to use essentially the same criteria specified in Smith et al. (2004) that were used in DMIP 1 for discharge comparisons. Computed spatial fields of soil moisture and snow characteristics will be evaluated using the proposed criteria discussed earlier.

5.0 Proposed schedule

Table 3 presents the propose schedule for the major DMIP 2 activities. We have the opportunity to re-run the simulations in the American basin with enhance data anticipated from the ETL Hydromet Test Bed data collection activities in that basin. We plan to have a summary workshop in the October 2007 time frame to discuss the results from both the Oklahoma and Sierra Nevada regions. After that, the participants can run more tests using the HMT data from the 2007-2008 cool season.

Table 3. Major DMIP 2 milestones and proposed completion dates

		Oct 2005	Jan 06	April 06	July 06	Oct 06	Jan 07	April 07	July 07	Oct 07	Jan 08	April 08
Project Start		→										
Data for OK region Available Oct 1												
Generate simulations: Oklahoma region												
Soil moisture Tests Oklahoma region												
Forecast tests Oklahoma region												
Unified routing Ok.												
Analyze results												
HL summary workshop												
Basic Data available for western basins (DEM, etc)												
Basic forcing data available For Western areas.												
Generate basic simulations												
’06-’07 HMT collected, QC’d, made available												
Generate updated simulations												
HL Summary Workshop												
’07-’08 HMT data collected, QC’d, made available												
Generate updated simulations												
Additional analyses by participants: papers, etc.												

6.0 Expected Results

We envision that DMIP 2 will provide a wealth of results that can help fill the identified knowledge gaps.

First, based on updated and revised radar precipitation data sets, we expect to confirm the primary results of DMIP 1 (Reed et al., 2004a) regarding lumped and distributed models in hydrologically simple terrain. NEXRAD radar precipitation from a later and less bias-prone period will lead to reduced uncertainty and thus more appropriate conclusions. The longer archive of data will also contain more rainfall-runoff events, a problem that plagued the short verification period in DMIP 1.

Large-scale comparison of simulated and observed soil moisture will undoubtedly add to our understanding of distributed modeling to correctly model interior processes. Such testing is also necessary to generate results that are spatially coherent and consistent. Furthermore, such large scale tests will provide much experience as the NOAA/NWS moves forward with CONUS runs to generate soil moisture and other water resources forecasts.

DMIP 2 should serve as a natural complement to the growing number of other model comparison projects such as the well-known efforts by WMO (e.g., WMO, 1992). In particular, the forecast component of DMIP 2 should underscore the issues surrounding operational river and flash flood forecasting. As occurred in DMIP 1, DMIP 2 will provide a positive opportunity for developers to evaluate their models in yet another arena, potentially uncovering needed algorithmic and/or science corrections or enhancements.

We also expect that DMIP 2 will provide multiple opportunities to develop data requirements for modeling and forecasting in hydrologically complex areas. These requirements fall in the general categories of needed spatial and temporal resolution and quality. From these, new sensor platforms could be designed or appropriate densities of existing gages could be specified to meet specific project goals. From the river forecasting viewpoint, we think these data needs are particularly acute in the mountainous west. In addition, DMIP 2 will serve as a multi-institutional evaluation of the Oklahoma Mesonet sensors and data. Such an evaluation may be able to promote an expansion of these sensors to larger geographic domains. Or, DMIP 2 may point out a need for other soil moisture sensors to meet the needs of NOAA/NWS water resources forecasting mission.

Moreover, we envision that DMIP 2 will contribute to meeting the goals of partner agencies and initiatives such as the NOAA HMT and the Sierra-Nevada HO of CUAHSI. We foresee that such combined, cross-cutting efforts will provide results not possible to achieve if the same programs were executed in an isolated manner. For example, we will work closely with NOAA/ETL personnel to plan the siting of soil moisture and other sensors in the American River HMT. Such cross-cutting collaboration will facilitate an end-to-end evaluation of the new data in a multi-institutional framework.

As with DMIP 1, we hope that scientists will take advantage of the DMIP 2 project to investigate ideas not explicitly identified. For example, several DMIP 1 participants investigated uncertainty issues related to model structure (Butts et al., 2004), parametric and radar-rainfall uncertainty (Carpenter and Georgakakos, 2004b), and quantifying uncertainty via multimodal ensembles (Georgakakos et al., 2004).

We expect DMIP2 to positively impact forecasting operations at the relevant RFCs through successful technology transfer. Many aspects of the forecasting enterprise could be improved through DMIP2. Potentially, candidate models could be transferred to the RFCs and run in parallel with their existing models. Research into the questions posed by this plan could be applied to either existing RFC tools and data sources or to new tools and data sources developed for DMIP2. We expect both RFCs involved in this study to be included in the research findings. We also expect to work with the RFCs to develop methods to best apply the lessons learned from this plan.

References

Briggs, W.M., and Levine, R.A., 1997. Wavelets and field forecast verification. Monthly Weather Review, Vol. 125, June, 1329-1341.

Butts, M.B., Payne, J.T., Kristensen, M., Madsen, H., 2004. An evaluation of the impact of model structure on hydrological modeling uncertainty for streamflow simulation. Journal of Hydrology, Vol. 298, Nos. 1-4, 242-266.

Carpenter, T.M., and Georgakakos, K.P., 2004a. Intercomparison of lumped versus distributed hydrologic model ensemble simulations. Journal of Hydrology, submitted.

Carpenter, T.M., and Georgakakos, K.P., 2004b. Impacts of parametric and radar rainfall uncertainty on the ensemble streamflow simulation of a distributed hydrologic model. Journal of Hydrology, 298, No. 1-4, 202-221.

Carpenter, T.M., and Georgakakos, K.P., 2001. Assessment of Folsom lake response to historical and potential future climate scenarios: 1.Forecasting, Journal of Hydrology, Vol. 249, 148-175.

Cayan, D.R., and Riddle, L.G., 1993. The influence of precipitation and temperature on seasonal streamflow in California. Water Resources Research, Vol. 29, No. 4, 1127-1140, April.

Kondragunta, C., Kitzmiller, C., Seo, D.-J., and Shrestha, K., 2005. Objective Integration of Satellite, Rain Gauge, and Radar Precipitation Estimates in the Multi-sensor Precipitation Estimator Algorithm. AMS 19th Conference on Hydrology, San Diego, Ca. Paper 2.8 in session: Current and Future Precipitation Measurements from Space.

Deliberty , T.L., and Legates, D.R., 2003. Interannual and seasonal variability of modeled soil moisture in Oklahoma. International Journal of Climatology, Vol. 23, 1057-1086.

Dettinger, M.D., Cayan, D.R., Meyer, M.K., and Jeton, A.E., 2004. Simulated hydrologic responses to climate variations and change in the Merced, Carson, and American River basins, Sierra Nevada, California, 1900-1999. Climate Change, Vol. 62, 283-317.

Dettinger, M.D., Redmond, K., and Cayan, D., 2004. Winter orographic precipitation ratios in the Sierra Nevada – large scale atmospheric circulation and hydrologic consequences. Journal of Hydrometeorology, Vol. 5, 1102-1116.

Fortin, S. M., 1998. A Qualitative Assessment of the Soil Moisture Parameterization of the Sacramento Soil Accounting Model During the Fall of 1997 and Spring of 1998. A Non-Thesis Research Paper submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of Master of Science in Meteorology, University of Oklahoma, Tulsa.

Georgakakos, K.P., 1986. A generalized stochastic hydrometerological model for flood and flash –flood forecasting 2. case studies. Water Resources Research, Vol. 22, No. 11. 2096-2106.

Georgakakos, K.P., and Carpenter, T.M., 2004. Potential value of operationally available and spatially distributed ensemble soil water estimates for agriculture. Journal of Hydrology, in review.

Georgakakos and Carpenter, 2003. A methodology for assessing the utility of distributed model forecast applications in an operational environment. IAHS Publ. No. 282, 114-120.

Georgakakos, K.P. and Smith, G.F., 1990. On improved hydrologic forecasting – results from a WMP real-time forecasting experiment. Journal of Hydrology, 114, 17-45.

Georgakakos, K.P., Seo, D.-J., Gupta, H., Schaake, J., and Butts, M.B., 2004. Towards the characterization of streamflow simulation uncertainty through multimodel ensembles. Journal of Hydrology 298, Nos. 1-4, 222-241.

Guetter, A.K., Georgakakos, K.P., and Tsonis, A.A., 1996. Hydrologic Applications of satellite data: 2. Flow simulation and soil water estimates. Journal of Geophysical Research, Vol. 101, No. D21, 26527-26,538, November 27.

Hay, L.E., and Clark, M.P., 2003. Use of statistically and dynamically downscaled atmospheric model output for hydrologic simulations in three mountainous basins in the western United States. Journal of Hydrology, Vol. 282, 56-75.

Harmel, R.D., 1997. Analysis of bank erosion on the Illinois River in Northeast Oklahoma. Submitted to the Faculty of the Graduate College of the Oklahoma State University in partial fulfillment of the requirements for the degree of Doctor of Philosophy. UMI Number 9824424 (UMI Dissertation Services).

Huang, J., van den Dool, H., and Georgakakos, K.P., 1996. Analysis of Model-calculated soil moisture over the United States (1931-1993) and applications to long-rang temperature forecasts. Journal of Climate, Vol. 9, 14350-14362.

Jeton, A.E., and Smith, J.L., 1993. Development of watershed models for two Sierra Nevada basins using a geographic information system. Water Resources Bulletin. Vol. 29, No. 6 923-932.

Jeton, A.E., Dettinger, M.D., and Smith, J.L., 1996. Potential effects of climate change on streamflow, Eastern and Western slopes of the Sierra Nevada, California and Nevada. U.S. Geological Survey Water Resources Investigations Report 95-4260, 44 pp.

Johnson, D., Smith, M., Koren, V., and Finnerty, B., 1999. Comparing mean areal precipitation estimates from NEXRAD and rain gauge networks. Journal of Hydrologic Engineering, Vol. 4, No. 2, April, 117-124.

Kim, J. , Miller, N.L., Guetter, A.K., and Georgakakos, K.P., 1998. River flow response to precipitation and snow budget in California during the 1994/1995 winter. Journal of Climate, Vol. 11, 2376-2386.

Kitanidis, P.K., and Bras, R.L., 1980. Real-time forecasting with a conceptual hydrologic model 2. applications and results. Water Resources Research, Vol. 16, No. 6, 1034-1044.

Kondragunta, C., Kitzmiller, D., Seo, D.J., and Shrestha, K., Objective Integration of Satellite, Rain Gauge, and Radar Precipitation Estimates in the Multi-sensor Precipitation Estimator Algorithm. Poster presented at the 19th Conference on Hydrology, 2005 AMS conference in San Diego, Ca., January 10-14, 2005.

Koren, V., Reed, S., Moreda, F., Smith, M., Zhang, Z., Cui, Z., 2005. Evaluation of a grid-based distributed hydrological model over a large area: model uncertainties at different scales. Accepted for oral presentation during the VIIth IAHS Scientific Assembly, to be held in Foz do Iguaçu – Brazil from April 03 to 09, 2005.

Koren, V., S. Reed, Z. Zhang, D. Seo, F. Moreda, Kuzmin V., 2003. Use of spatially variable data in river flood prediction. AGU-EGS-EUG Assembly, April 9-14, 2003, Nice, France.

Leavesley, G.H., Hay, L.E., Viger, R.J., and Marskstrom S.L., 2003. Use of a priori parameter-estimation methods to constrain calibration of distributed-parameter models. Calibration of Watershed Models. Water Science and Application 6, AGU Press, Duan et al., editors. 255-266.

Lettenmaier, D.P. and Gan, T.Y., 1990. Hydrologic sensitivities of the Sacramento-San Joaquin River basin, California, to global warming. Water Resources Research, Vol. 26, No. 1, 69-86.
Lundquist, J.D., and Cayan, D.R., 2002. Seasonal and spatial patterns in diurnal cycles in streamflow in the western United States. Journal of Hydrometeorology, Vol. 3, October, 591-603.
Marron, J.S. and Tsybakov, A.B., 1995. Visual Error Criteria for Qualitative Smoothing. Journal of the American Statistical Association, Vol. 90, No. 430, Theory and Methods, June, 499-507.
Mitchell, K.E., Lohmann,D., Houser, P.R., Wood, E.F, Schaake, J.C., and co-authors, 2004. The multi-institution North American Land Data Assimilation System (NLDAS): Utilizing multiple GCIP products and partners in a continental distribute hydrological modeling system. Journal of Geophysical Research, Vol. 109, D07S90, doi:10.1029/2003JD003823.
National Research Council (NRC), 2000. Grand Challenges in Environmental Sciences. Committee on Grand Challenges in Environmental Sciences, Oversight Commission onfor the Committee on Grand Challenges in Environmental Sciences, National Academy Press, Washington, D.C., 96pp.
NOAA, 2004. New Priorities for the 21st Century-NOAA's Strategic Plan. Available from http://www.spo.noaa.gov/pdfs/NOAA%20Strategic%20Plan.pdf
NWS, 2004a. National Weather Service Strategic Plan for 2005-2010. Available from http://www.weather.gov/sp/NWS_draft_strategic_plan_10-15-04.pdf
NWS, 2004b. The NWS Integrated Water Science Plan (IWSP), Report of the IWSP team.
Pandey, G.R., Cayan,D.R., Dettinger, M.D., and Georgakakos, K.P., 2000. A hybrid orographic plus statistical model for downscaling daily precipitation in Northern California. Journal of Hydrometeorology, Vol. 1, December, 491-506.
Pandey, G.R., Cayan, D.R., and Georgakakos, K.P. 1999. Precipitation structure in the Sierra Nevada of California during winter. Journal of Geophysical Research, Vol. 104, No. D10, 12,019-12,030.
Perica, S., and Foufoula-Georgiou, E., 1996. Model for multiscale disaggregation of spatial rainfall based on coupling meteorological and scaling descriptions. Journal of Geophysical Research, Vol. 10, No. D21, 26,347-26,361.
Reed, S., Koren, V., Smith, M., Zhang, Z., Moreda, F., Seo, D.-J., and DMIP Participants, 2004. Overall distributed model Intercomparison project results, Journal of Hydrology, Vol. 298, Nos. 1-4, 27-60.
Reed, S., Schaake, J., Koren, V., Seo, D.J., Smith, M. 2004b, A statistical-distributed modeling approach for flash flood prediction. Proceedings of the 18th Conference on Hydrology, American Meteorology Society, Seattle, WA, 6.2.
Reynolds, D.W., and Dennis, A.S., 1986. A review of the Sierra Cooperative Pilot Project. Bulletin of the American Meteorological Society. Vol 67, No. 5, 513-523.
Schaake, J.C., Duan, Q., Koren, V., Mitchell, K.E., Houser, P.R., Wood, E.F., Robock A., Lettenmaier, D.P., Lohmann, D., Cosgrove, B., Sheffield, J., Luo, L., Wiggins, R.W., Pinker, D.T., and Tarpley, J.D., 2004. An Intercomparison of soil moisture fields in the North American Land Data Assimilation System (NLDAS). Journal of Geophysical Research, Vol., 109. D01S90, doi:10.1029/2002JD003309.

Simpson, J.J., Dettinger, M.D., Gehrke, F., McIntire, T.J., and Huffurd, G.L., 2004. Hydrologic scales, cloud variability, remote sensing, and models: Implications for forecasting snowmelt and streamflow. Weather and Forecasting, Vol. 19, April, 251-276.

Smith, M.B., Seo, D. -J., Koren, V. I., Reed, S., Zhang, Z., Duan, Q.-Y., Moreda, F., and Cong, S., 2004. The distributed model intercomparison project (DMIP): motivation and experiment design. Journal of Hydrology, Vol. 298, Nos. 1-4, 4-26.

Smith, M.B., Koren, V. I., Zhang, Z., Reed, S.M., Pan, J.-J., and Moreda, F., 2004. Runoff response to spatial variability in precipitation: an analysis of observed data. Journal of Hydrology, 298, Nos. 1-4, 267-286.

Smith, M.B., Koren, V., Finnerty, B., Johnson, D., 1999. Distributed Modeling: Phase 1 Results, NOAA Technical Report NWS 44, February, 250pp.

Stellman, K.M., Fuelberg, H.E., Garza, R., and Mullusky, M., 2001. An examination of radar and rain gauge-derived mean areal precipitation over Georgia watersheds. Journal of Hydrometeorology, Vol. 16, February, 133-144.

Tcherednichenko, I., Bastidas, L.A., and Lansey, K., 2004. Model Performance Evaluation of distributed hydrological modeling for semi-arid regions, Proceedings of the 2004 World Water and Environmental Resources Congress June 27.July 1, 2004, Salt Lake City, UT. Sponsored by Environmental and Water Resources Institute (EWRI) of the American Society of Civil Engineers).

Tsintikidis, D., Georgakakos, K.P., Sperfslage, J.A., Smith, D.E., and T.M. Carpenter, 2002: "Precipitation Uncertainty and Raingauge Network Design within the Folsom Lake Watershed," ASCE Journal of Hydrologic Engineering, 7(2), 175-184.

Wang, J., and K.P. Georgakakos, 2003: “Validation and Sensitivities of Dynamic Precipitation Simulation of Winter Events over the Folsom Lake Watershed: 1964-1999,” Monthly Weather Review, (submitted).

Wang, D., Smith, M.B., Zhang, Z., Reed, S., and Koren, V.I., 2000. Statistical comparison of mean areal precipitation estimates from WSR-88D, operational, and historical gage networks. 15th Annual Conference on Hydrology, 80th Meeting of the AMS, Long Beach, CA., January 10-14, J2.17

White, A.B., Gottas, D.J., Strem, E.T., Ralph, F.M., and Nieman, P.J., 2002. An automatied brightband height detection algorithm for use with Doppler radar spectral moments. Journal of Atmospheric and Oceanic Technology, Vol. 19, May, 687-697.

Wigmosta, M.S., Vail, L.W., and Lettenmaier, D.P., 1994. A distributed hydrology-vegetation model for complex terrain. Water Resources Research, Vol. 30, No. 6, 1665-1679.

World Meteorological Organization, 1992. Simulated real-time intercomparison of hydrological models, Operational Hydrology Report No. 38, WMO-No. 779, Secretariate of the World Meteorological Organization, Geneva, Switzerland.

Young, C.B., Bradley, A.A., Krajewski, W.F., Kruger, A., 2000. Evaluating NEXRAD multi-sensor precipitation estimates for operational hydrologic forecasting. Journal of Hydrometeorology, Vol. 1, June, 241-254.

Appendix A.
Additional Descriptive Information for the Oklahoma region

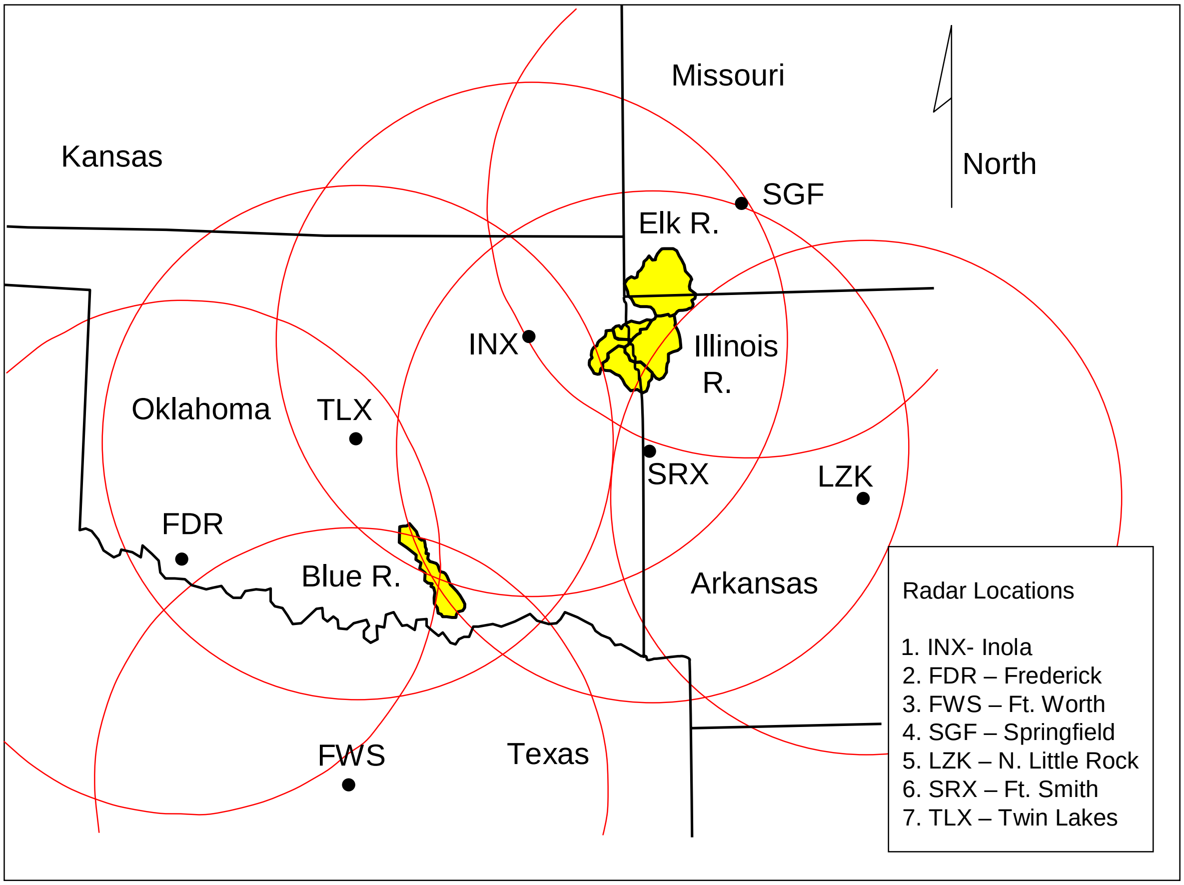


Figure A.1 Location of NEXRAD radars and extent of coverage. The red circles indicate the extent of coverage of each radar. The yellow areas are the river basins from the DMIP 1 experiment.

Appendix B.

Additional Description of the American Basin

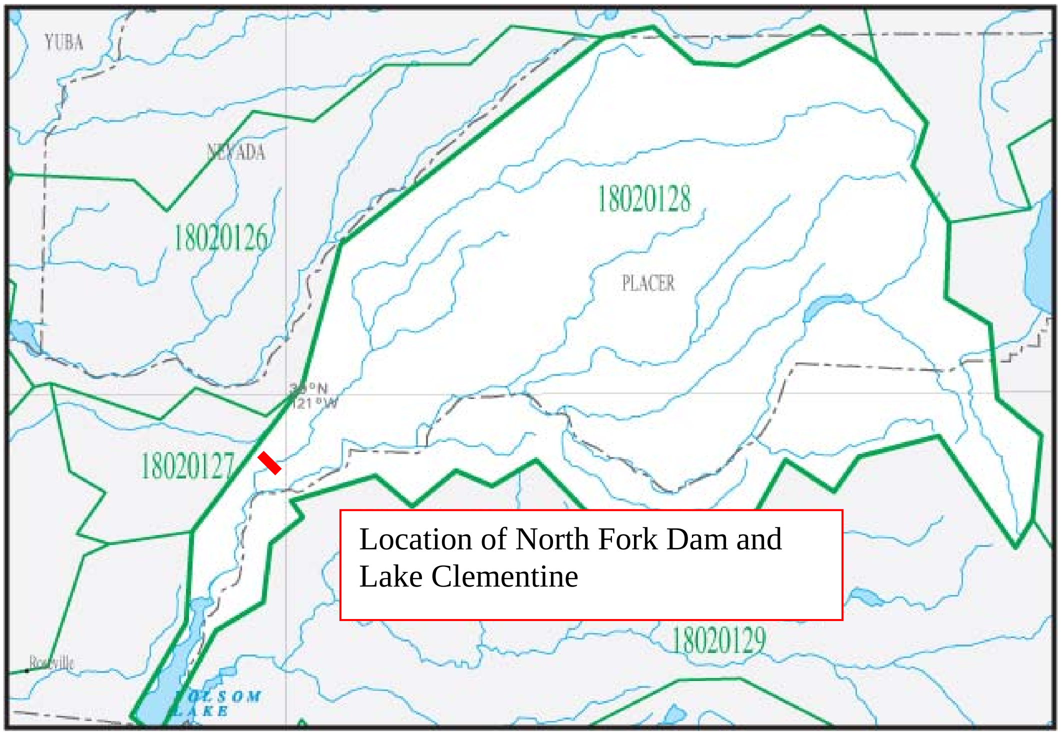


Figure B.1 USGS basin number for the American River and location of the North Fork Dam

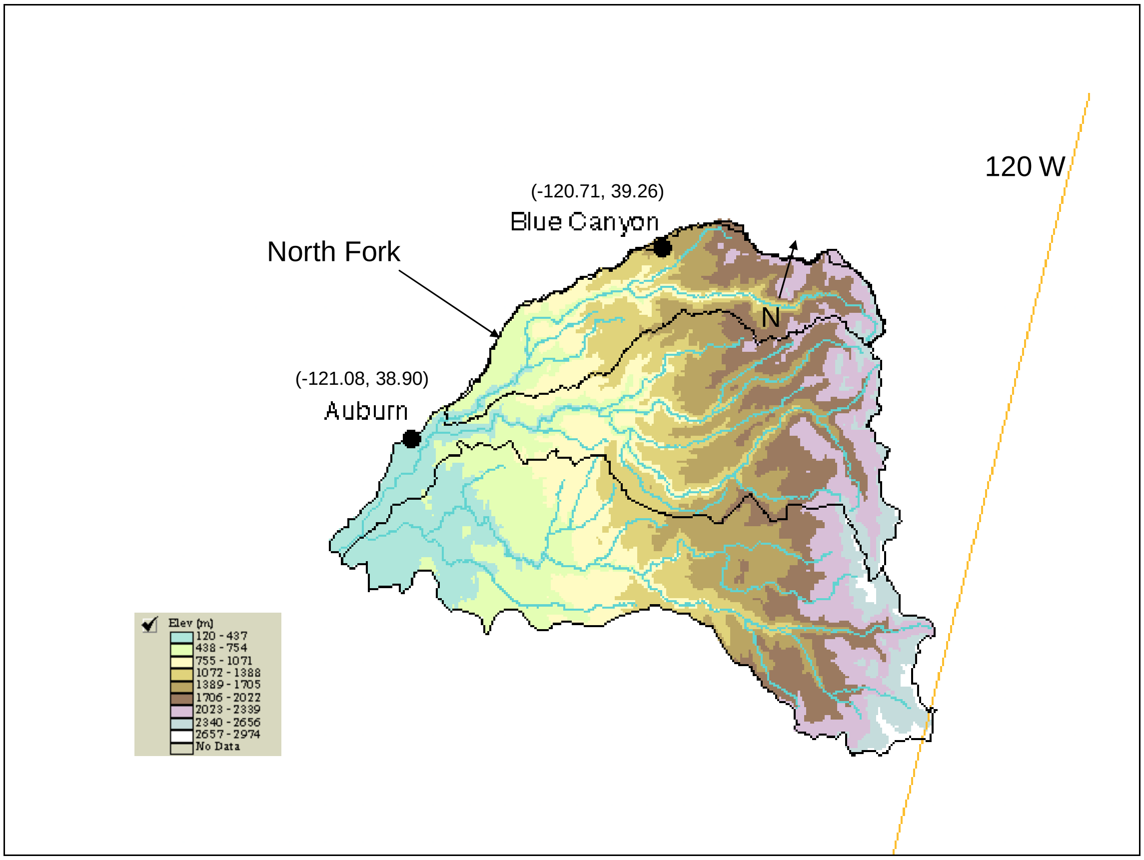


Figure B.2 Elevation variability in the American River Basin

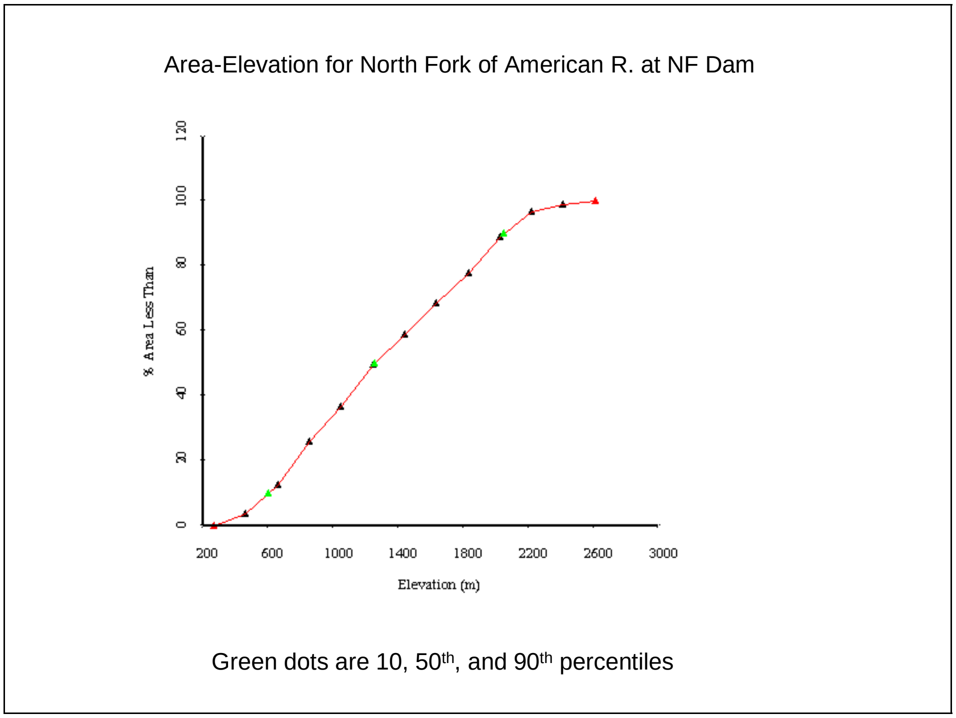


Figure B.3 Area Elevation Curve for the North Fork basin

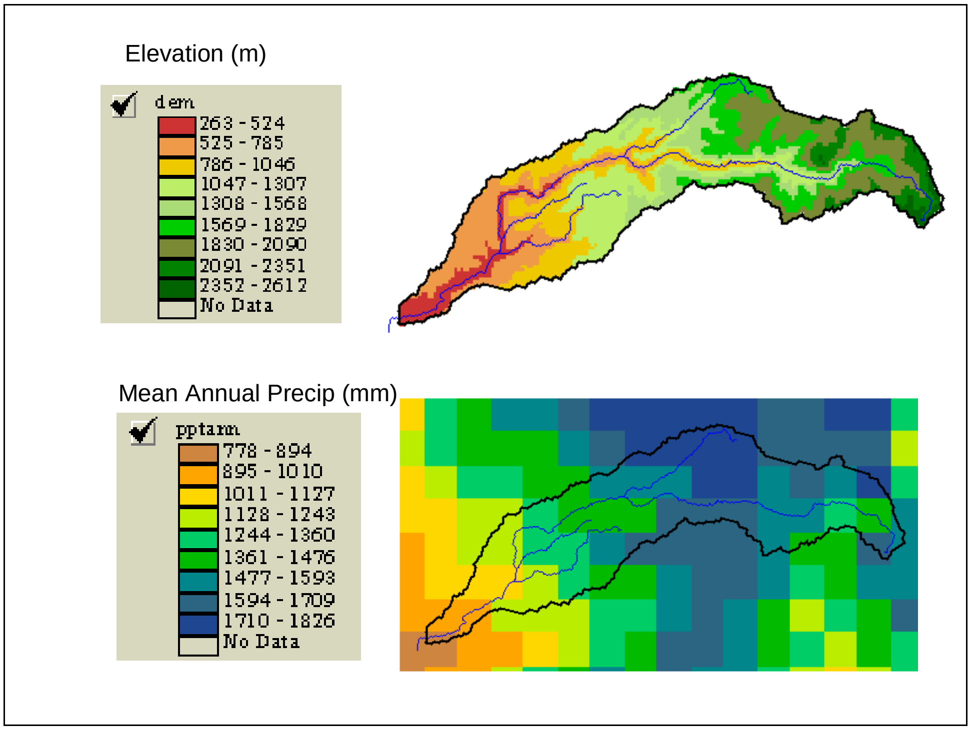


Figure B.4 Distribution of elevation and long-term mean precipitation in the North Fork basin

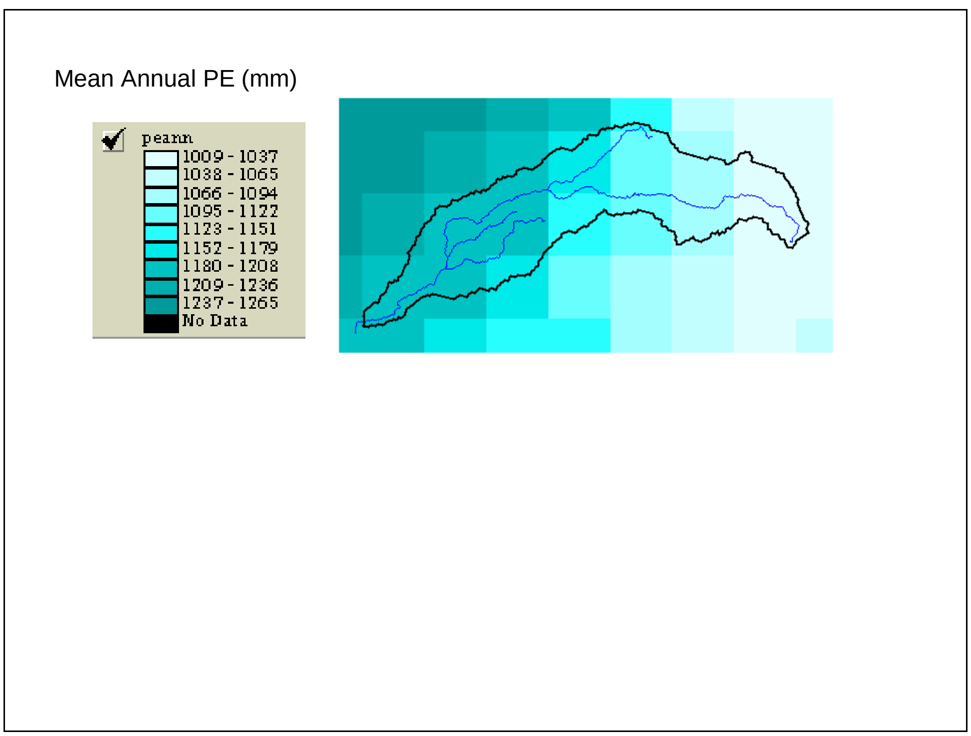


Figure B.5 Distribution of Long Term PE in the North Fork basin

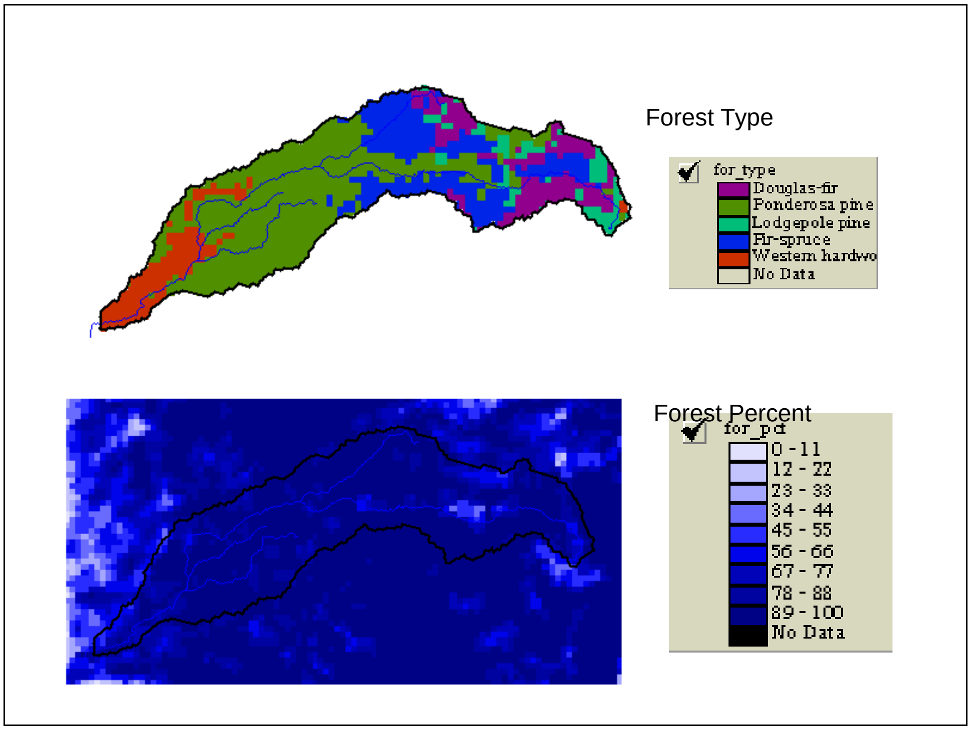


Figure B.6 Forest type and percent coverage in the North Fork basin

Description of North Fork Dam and Lake Clementine

The North Fork dam seen in Figures B.7 and B.8 is a concrete arch dam with an ogee weir overflow spillway. The dam was built as a debris retention dam and is partially full. The USGS gage is 50 feet upstream of the crest of the dam and is a water-stage recorder. The North Fork dam was built in 1939 by the Corps of Engineers. It rises 155 feet above the foundation and its crest is at elevation 718. It forms Lake Clementine, a 12,800 acre-foot lake. Lake Clementine has a surface area of 280 acres and is approximately 3.5 miles long, having a very narrow shape with steep canyon walls as shown in Figures B.8 and B.9.

The California Comprehensive Study modeled the regulation effects of many headwater reservoirs in the Central Valley of California including five in the American River Basin (Hell Hole, French Meadows, Loon Lake, Union Valley, and Ice House). Reservoirs selected for explicit modeling had to satisfy one of two criteria:

1) They have existing flood damage reduction functions, or

2) They maintain an active storage greater than 10,000 acre-feet and regulate a significant natural drainage area.

North Fork Dam original capacity is 14,700 acre-feet and its drainage area is 342 square miles. Its drainage area is fairly substantial (approximately 18% of the drainage upstream of Folsom Dam), however, the capacity today is much less than the original due to the fact that its primary purpose is debris control. Because of its reduced capacity, it was assumed by the Comprehensive Study that the North Fork Dam had little effect on hydrograph attenuation. Based on this, we believe that we can assume the North Fork dam will not negatively affect the comparisons outlined in DMIP 2.

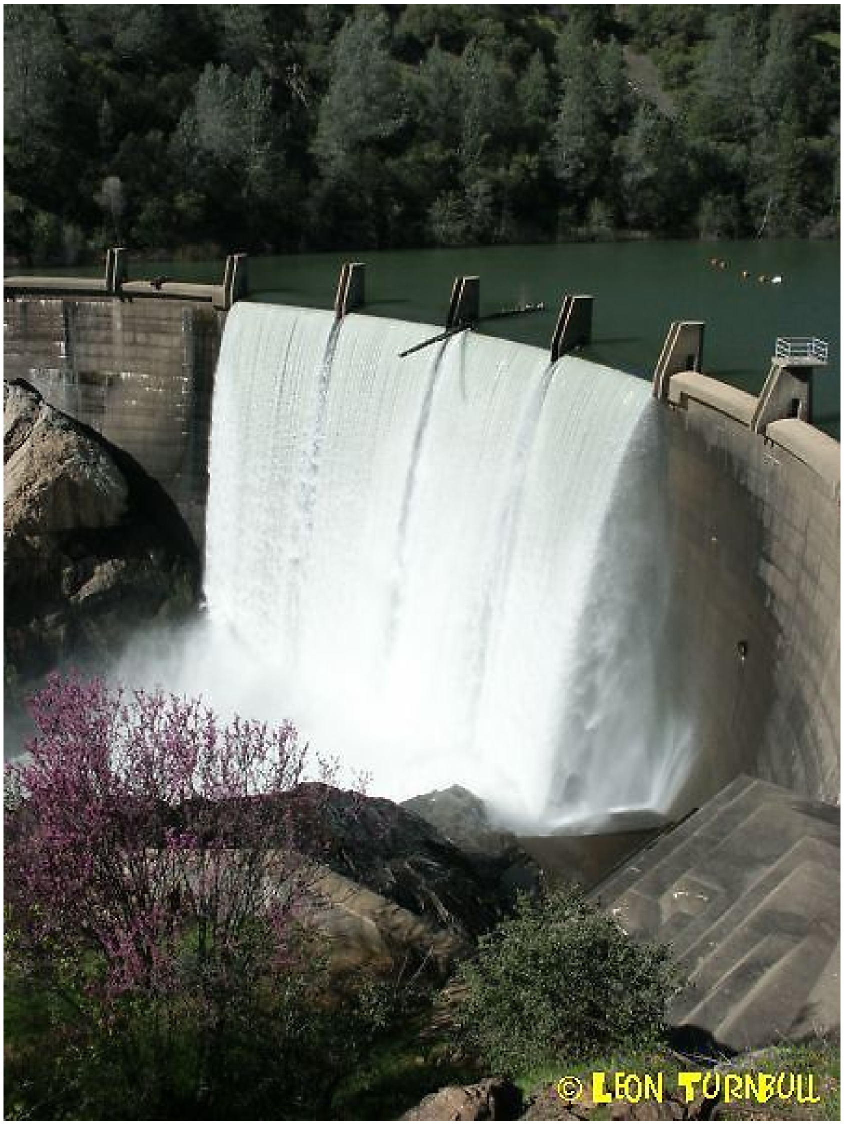


Figure B.7. Ogee weir at North Fork Debris Dam forming Lake Clementine. USGS gage 11427000 is on the bank of the lake approximately 50 feet upstream of the dam. Apparently, there are no low-flow outlets. (Photo used with permission from Leon Turnbull, see also www.waterfallswest.com)

Figure B.8 View of lower end of Lake Clementine and the North Fork dam.

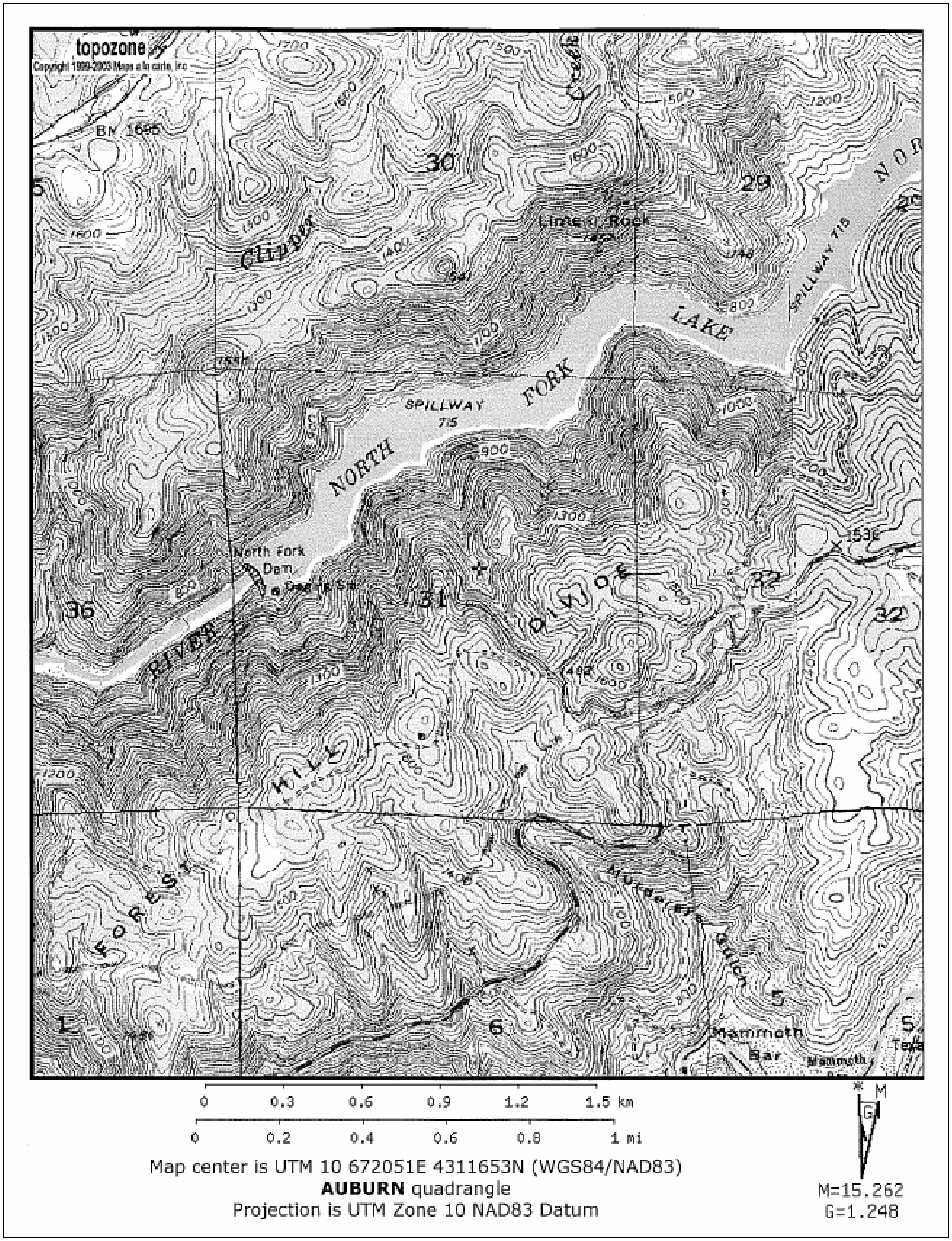


Figure B.9 Contour map of the region around Lake Clementine in the North Fork basin

Several small impoundments and diversions exist in the North Fork basin as shown in Figure B.10. A short description of each is provided (Source: USGS California Water Resources Data, 1994, Volume 4)

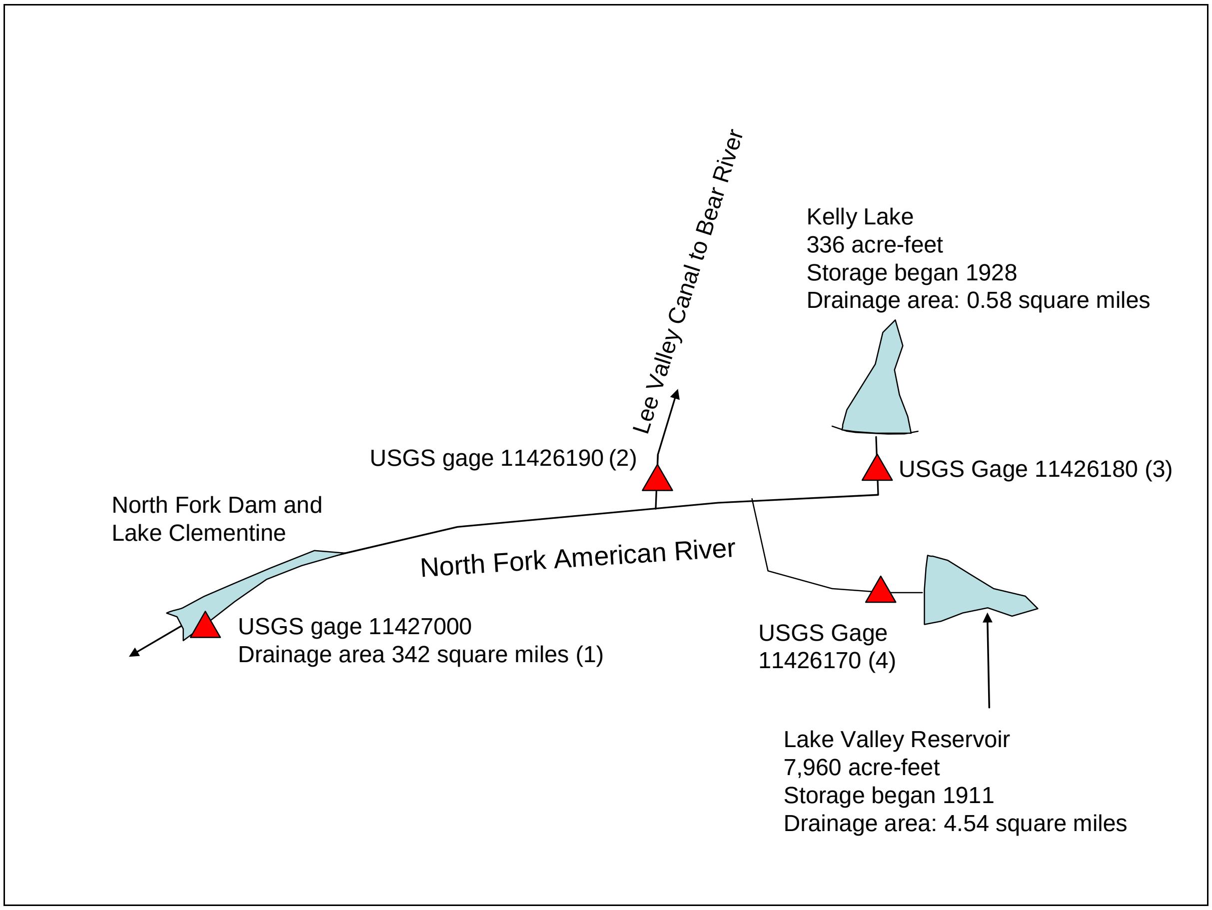


Figure B.10 Schematic of the small reservoirs and diversion in the North Fork American River basin

1. **USGS Gage 1142700** North Fork American River. Drainage area 342 square miles. Remarks: No estimated daily discharge. Records good. Minor regulation by Lake Clementine, usable capacity, 12,800 acre-ft, formed by North Fork Dam. Storage in Big Reservoir and Lake Valley Reservoir (station 11426170), combined capacity, 10,300 acre-ft upstream from station. Lake Valley Canal (station 11426190) diverts from North Fork of North Fork American River into Bear River Basin for power development in power plants of Pacific Gas and Electric Co. Combined storage and diversion have small effect on natural flow. See schematic diagrams of Bear and Lower Sacramento River basins. (page 320, USGS Ca. No. 4 1994)
2. **USGS Gage 114126190** Lake Valley Canal. Remarks: No estimated daily discharge. Canal diverts from right bank of the North Fork of the North Fork American River, 2.0

miles downstream from Lake Valley Reservoir (station 11426170) to the Drum Canal in the Bear River Basin.

3. **USGS Gage 11426180.** Kelly Lake near Cisco, Ca. Drainage area: 0.58 square miles. Remarks: Reservoir is formed on natural lake by rock-fill dam completed in 1928. Usable capacity, 336 acre-feet between gage heights 0.0 ft invert of outlet, and 17.1 feet, top of flashboards. Water is used for Power development downstream. Records, including extremes, represent useable contents at 2400 hours. See schematic of Bear River Basin.
4. **USGS Gage 11426170**. Lake Valley Reservoir. Drainage area: 4.54 square miles. Remarks: Lake is formed by an earthfill dam; storage began in 1911. Usable capacity, 7,960 acre-ft. between gage heights 6.2 feet (natural rim of lake) and 57.5 feet (top of flashboards). Released water is diverted downstream to Lake Valley Canal (station 11426190) and then to several power plants. Records, including extremes, represent usable contents at 2400 hours.

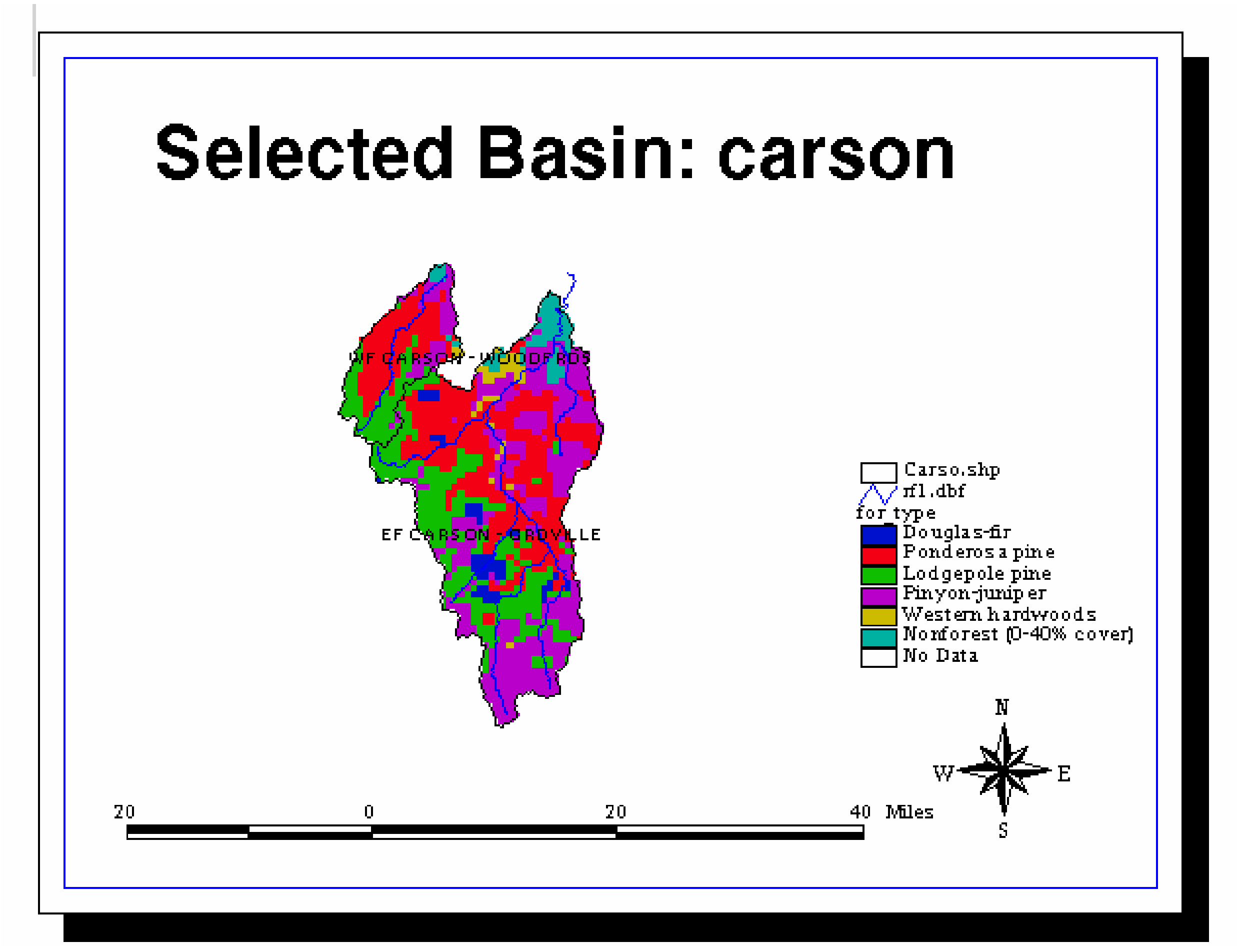


Figure C.1 Spatial variability of forest type in the Carson River Basin

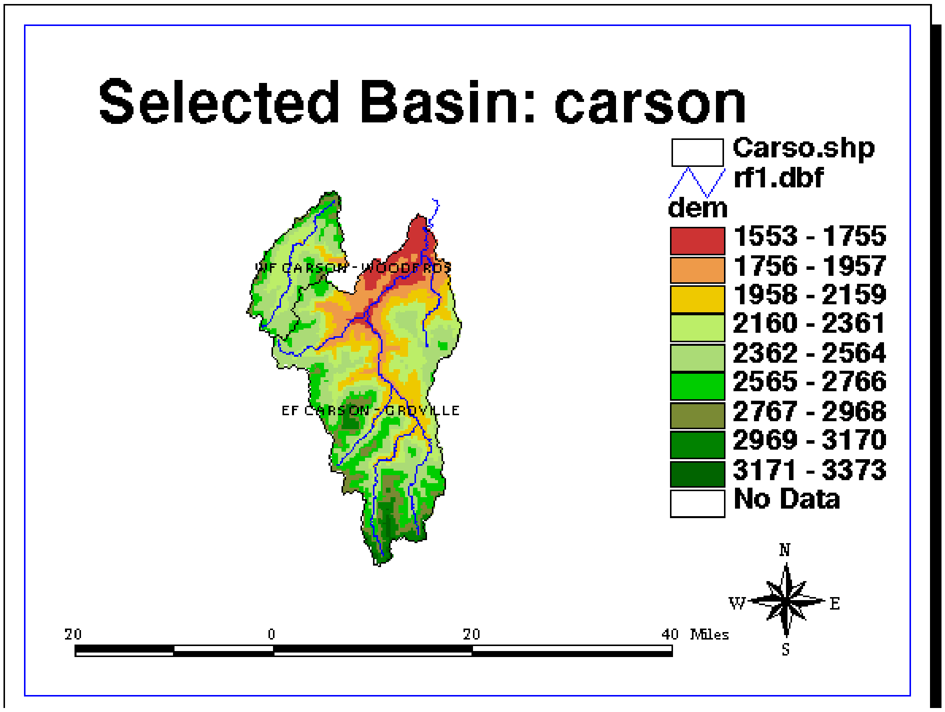


Figure C.2 Elevation distribution in the Carson River basin

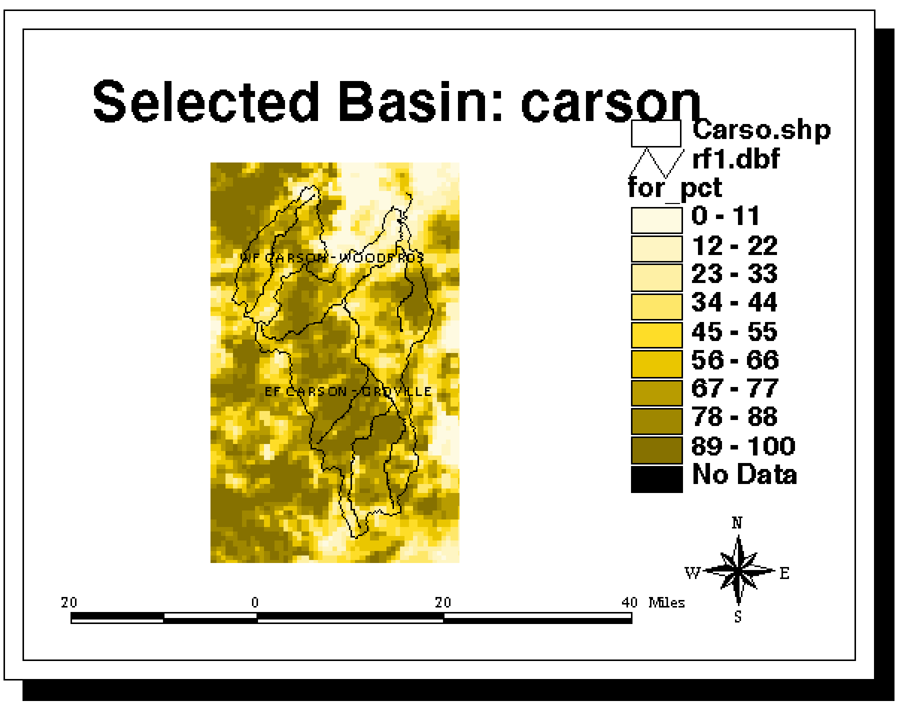


Figure C.4 Percent of forest cover in the Carson River Basin

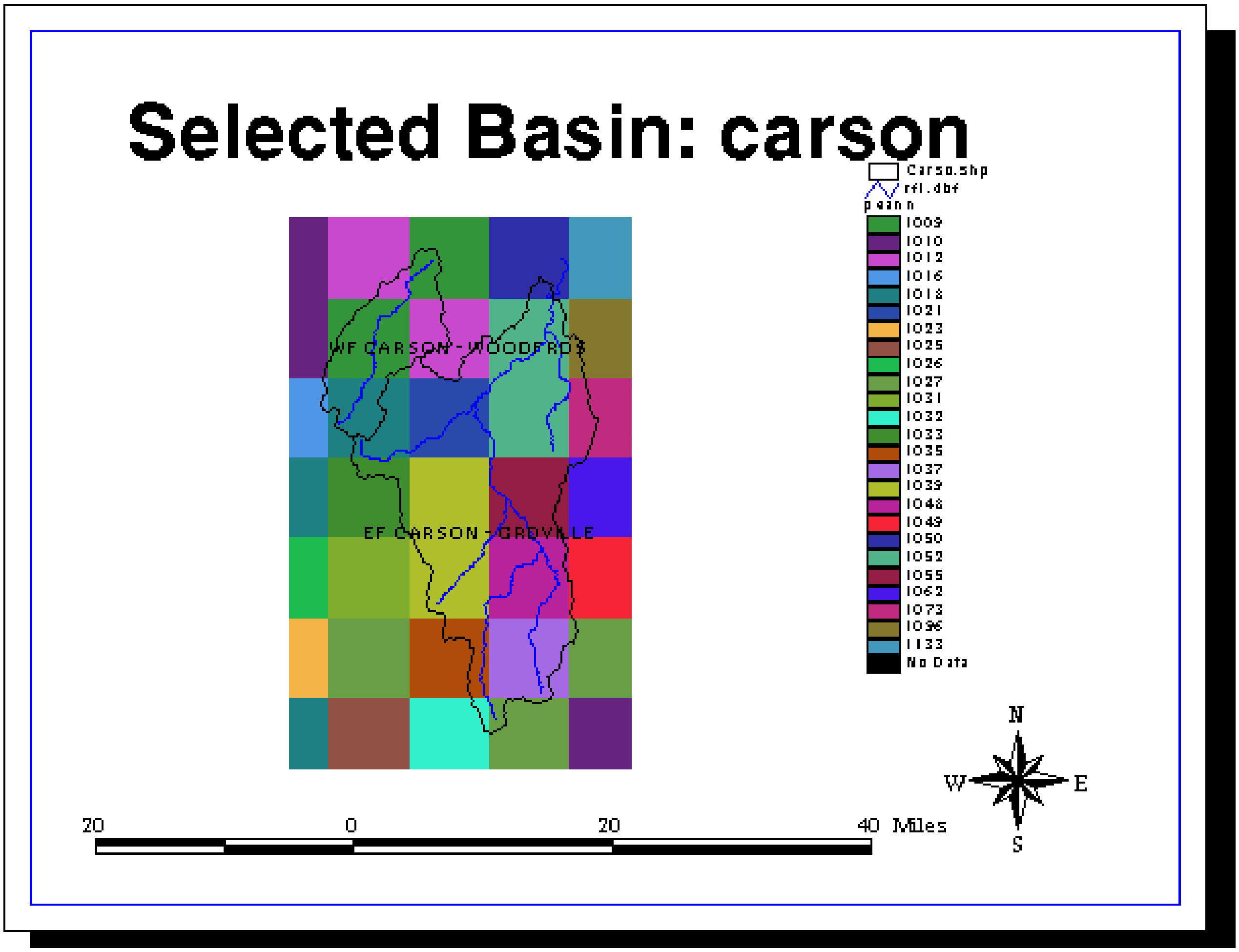


Figure C.5 Spatial variability of annual potential evaporation

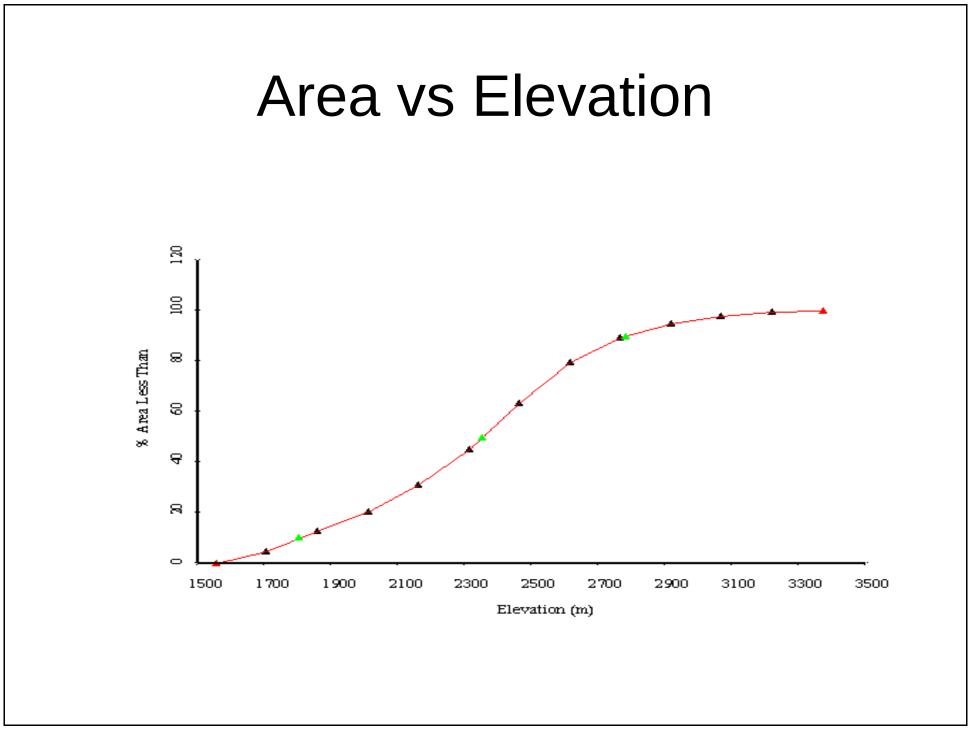


Figure C.6 Area-elevation curve for the Carson River basin

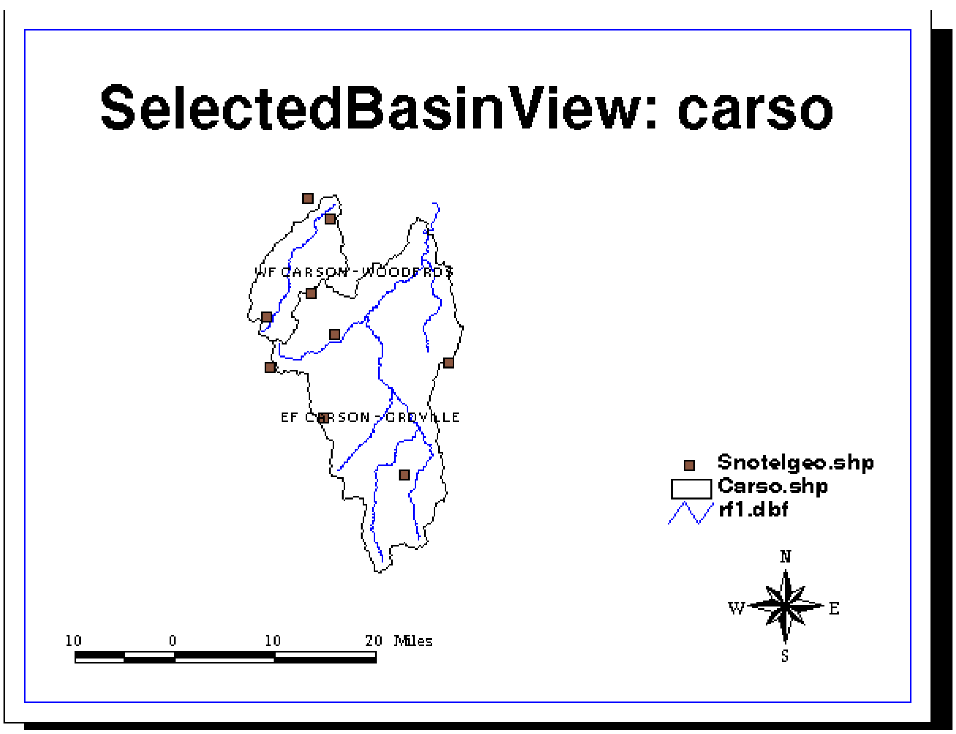


Figure C.7 Location of NRCS SNOTEL sites: Carson River basin

Appendix D

The NOAA/OAR/ETL Hydrometeorological Testbed (HMT) Program

Overview

A national Hydrometeorological Testbed (HMT) program is being developed by NOAA for the purpose of advancing water resources data assimilation. The general strategy of this effort is to conduct research and development to deploy advanced systems for observed information to support critical decision making and fresh/salt water forecasting. More specifically, high resolution atmospheric and hydrometeorologic observations (precipitation, soil moisture, snowpack, winds, temperature, and moisture) will be collected and analyzed for several key water resource applications such as distributed hydrologic model validation, quantitative precipitation forecast (QPF) and estimation (QPE) validation, and improved understanding of key physical processes such as atmospheric rivers, orographic effects, air mass transformation, soil moisture variability and streamflow response to precipitation. In turn, these analyses will be integrated into water management decision support systems for purposes of flood mitigation, hydropower energy generation, water resources control, and fisheries management.

The HMT program will ultimately be implemented incrementally in different regions of the U.S. where distinct hydrometeorological forecasting issues are unresolved. In broad terms, hurricanes are a major focus in the eastern part of the country, warm-season mesoscale convective systems are a major focus in the central part of the country and cool-season extratropical cyclone systems are a major focus in the western part of the country. These focci have driven the first realizations of HMT and will provide the basis for migration of HMT to meet national priorities in water management. The first realizations was established in the western United States during the 2002-03 and 2003-04 cool seasons through pilot studies on the flood-prone Russian River of northern California.[2] These studies have laid the groundwork for improving cool season QPF in an area where researchers and forecasters have worked closely with key forecast users. The enhanced predictability of major precipitation events created by the orographic forcing in the western U.S. during the cool season makes this area and season the most tractable to demonstrate improved user decision making. Lessons learned during these pilot studies are being applied in the planning of the first major HMT effort (HMT-WEST), a more comprehensive study centered on the American River basin of the western Sierra Nevada during cool seasons 2005-06 through 2007-08. The American River basin was selected because of its huge impact on water management within the state of California, mitigating risks of floods that can produce billions of dollars in damage and serious loss of life, and optimizing the production of hydro-electric power.

Instrumentation

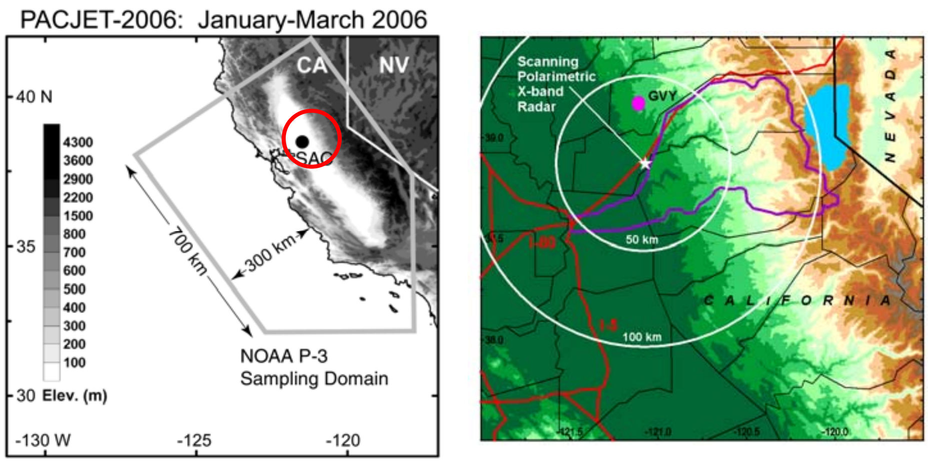
The suite of ground-based observing systems to be deployed by NOAA in the American River basin will be patterned after those used in the pilot studies. These include a scanning X-band polarimetric Doppler radar, 915 MHz wind profilers, vertically pointing S-band Doppler radars, GPS integrated water vapor sensors, GPS rawinsondes, soil moisture sensors, surface meteorology stations (e.g., temperature, moisture, wind), all-weather precipitation gauges, and liquid and frozen hydrometeor disdrometers. Airborne observing systems for soil moisture and snowpack mapping (onshore) and precipitation and water vapor mapping (offshore) will also be

[2] See http://www.etl.noaa.gov/programs/2004/hmt/ .

deployed by NOAA occasionally during HMT-WEST. These systems include GPS dropsondes, imaging radiometers for soil moisture and snowpack mapping, Doppler radars for precipitation mapping and wind field derivation, and microphysical probes for determining hydrometeor size, shape and mass characteristics. Some of the above instrumentation has been developed under the support of the NASA Terrestrial Hydrology Program for the AMSR-E calibration and validation effort, and will be reused to support HMT. Statistics from the verification will be used to improve the specification of the WRF-NMM error covariance matrix.

For soil moisture, measurements will start in November 2004 with observations at 2 depths using the Campbell Scientific 616L probe at Blue Canyon in the North Fork. The burial depths will depend on the soil conditions found at the site. Probes are typically inserted horizontally at depths from 5 to 15 cm, and deeper (root zone) if located inside of a canopy.

Looking Ahead – HMT in the American River Watershed



Request for a NOAA P-3 research aircraft and the RV Ron Brown were submitted to OAR on 31 Dec 2003.

NOAA/ETL's X-band radar and other sensors used in 2004 will be deployed in and around the American River Watershed from Dec 2005 – March 2006.

Figure D-1. Planned NOAA Hydromet Test Bed for the American River