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Skill evaluation of water supply forecasts in western Sierra Nevada and Colorado River basins

Author

Harrison, Brent

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SKILL EVALUATION OF WATER SUPPLY FORECASTS IN WESTERN SIERRA NEVADA AND COLORADO RIVER BASINS

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in

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by

Brent David Harrison

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Committee in charge:

Professor Roger Bales

Professor Hans Bjornsson

Professor Elliott Campbell

Professor Yihsu Chen

The Dissertation of Brent David Harrison is approved, and it is acceptable
in quality and form for publication on microfilm and electronically:

Roger Bales

Hans Bjornsson

Yihsu Chen

Elliott Campbell Chair

University of California, Merced

2014

DEDICATION

I would like to thank my wife Donna and my sons David and Jonathan for their support and patience during my study and research for the PhD degree.

I wish to dedicate the information in this dissertation to the water resources community in the state of California and the western United States.

ABSTRACT

Skill evaluation of water supply forecasts
in western Sierra Nevada and Colorado River basins
by
Brent David Harrison
Doctor of Philosophy in Environmental Systems
University of California, Merced, 2014

Runoff records from thirteen major river basins on the western slope of the Sierra Nevada in California were compared to runoff forecasts for those watersheds to determine the skill of those runoff forecasts. The forecasts, some dating back to the 1930's, were made at the beginning of the months of February, March, April and May. An array of summary, correlation and categorical skill measures were computed for each forecast and associated observation. The same array of skill measures were computed for 28 basins tributary to the Colorado River, again with some forecasts dating back to the 1930's. The skill measures were reviewed for each region and compared to watershed characteristics to develop explanations for the trends and results. Finally the Sierra Nevada results were directly compared with the watersheds in the Colorado River basin, thereby developing explanations for the trends, similarities and differences obtained.

A strong relationship between increasing watershed elevation and increased forecast skill was shown by the western Sierra forecasts but was not found in the Colorado locations. This result can be explained by snow dominance of the Sierra Nevada runoff. The snow dominance was shown to increase to the south as the elevation of the watersheds increased. The summary measures included a skill score based on Mean Absolute Error which showed clearly the increase in skill during the forecast season, with both the skill scores starting at 0.3 for both regions. This increase in skill over the forecast season is attributed to the increasing knowledge of climatology during the forecast season. The skill of the western Sierra forecasts ends the season somewhat higher at 0.8 compared to 0.6 for the Colorado Basin. The monthly increase in NS score was higher at 0.19 for the western Sierra watersheds when compared to watersheds elsewhere in the western United States, which ranged from 0.08 to 0.12 per month. These results can be explained by the snow magnitude and dominance of runoff in the Sierra Nevada. The under forecasting of

high runoff years was illustrated in both the low False Alarm Rate and the under forecast Bias for high flow runoff years.

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CURRICULUM VITAE

BRENT D. HARRISON

ACADEMIC PREPARATION

Ph.D. (Environmental Systems), University of California, Merced
Master of Engineering (Civil Engineering), University of Idaho
    Golden Key International Honour Society
M.B.A. (Master of Business Administration), California State University, Chico
    Beta Gamma Sigma Business Honor Society
B.S. (with Honors, Engineering), University of California, Davis
    Tau Beta Pi Engineering Honor Society

PROFESSIONAL LICENSES

Registered Civil Engineer (Calif.) No. 34768
Licensed Land Surveyor (Calif.) No. 5291

PROFESSIONAL APPOINTMENTS

Teaching Assistant, School of Engineering, University of California, Merced
Graduate Student Researcher, University of California, Merced
Civil Engineer, Turlock Irrigation District

ENGINEERING PUBLICATIONS (senior author)

“Mitigating the Effects of Urbanization on Irrigation District Rights of Way and Facilities,” USCID Conference, Scottsdale, Arizona, 2008.

“Water User Management and Financing of Irrigation Facilities Through Use of Improvement Districts,” USCID Conference, San Diego, California, 2005.

“Modernization of Water Measurement Systems in the Turlock Irrigation District,” USCID and ASCE Irrigation Conference, San Luis Obispo, California, 2002.

“Managing Urban Growth, An Irrigation District’s Perspective,” ASCE Irrigation and Drainage Conference, Park City, Utah, 1993.

CV Continued
Brent Harrison

RESEARCH PUBLICATIONS

Brent Harrison and Roger Bales. Percent Bias Assessment of Water Supply Outlooks in the Colorado River Basin, paper presented at 2014 Western Snow Conference, Durango, Colorado, 15 April, 2014.

Brent Harrison and Roger Bales. Watershed Characteristics and Skill Level of Runoff Forecasts on the Western Slope of the Sierra Nevada – Implications for a Changing Climate, poster presented at 2013 World Environmental & Water Resources Congress, Cincinnati, Ohio, 29-23 May, 2013.

B D Harrison and R C Bales. Skill Analysis for Runoff Forecasts on the Western Slope of the Sierra Nevada, poster presented at AGU fall meeting, San Francisco, Calif., 3-7 December 2012.

Roger Bales, Robert Rice, Xiande Meng, Brent Harrison. Climate change, shifts in snowmelt, and adaptation in the Eastern Sierra Nevada based on MODIS fractional snow-covered area data, poster presented at 2011 World Environmental & Water Resources Congress, Palm Springs, Calif., 23-26 May, 2011.

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CHAPTER 1

Introduction

1. Runoff forecasts

The runoff water from the Sierra Nevada is used for agricultural, municipal, industrial, recreational and environmental purposes. Agencies responsible for the water rely on runoff forecasts prepared during the snow accumulation and ablation period to estimate water supplies for the remainder of the water year. In California, runoff forecasts have been prepared on watersheds in California since the 1930's and are issued from February to May of each year. Snow water content is measured in snow courses consisting of 7 to 10 sample points. Runoff forecasts are based on historical relationships defined by regressions between April through July runoff and snow water content of the applicable snow course, precipitation to date and preceding month's runoff. The forecasts are issued in two parts, the runoff in the April through July period, which is generally considered snowmelt, and runoff for the water year, October through September. Runoff for remaining months in the winter period is estimated using relationships with runoff to date of the forecasts and precipitation accumulations. Runoff amounts for August and September are correlated with April through July runoff for forecasting purposes. Forecasts for one river basin are checked with the forecasts for adjoining basins for quality control purposes (CDEC 2014). These forecasts are used by water project operators and customers in determining the amount of water available and to adjust their operations to optimize the uses of the available water. The forecasts are also used by environmental and regulatory agencies for fishery and ecosystem purposes. Some agencies use the state issued forecasts as foundation information for their internal customized forecasts.

Snowmelt runoff from the Colorado River basin provides water to a significant area of the southwestern United States. Water managers use seasonal water-supply outlooks that forecast runoff as the basis for operating decisions throughout the year. These water supply outlooks have been prepared on some Colorado River watersheds since the 1950’s. In much of the basin, the outlooks are issued from January to May and forecast runoff in the April through July period.

2. Skill measures

Evaluations of the skill of these various forecasts have been made since the late 1950’s on various subsets of the forecasts in the western United States. These reviews have used a variety of skill measures and some have examined the relationship of watershed characteristics to skill in forecasting runoff.

Summary measures of forecast skill quantify the error in runoff forecasts by developing a numeric magnitude of the difference between the forecast and the observation. The absolute value of the error can be accumulated and a mean taken for the Mean Absolute Error. A skill score (SS) that will normalize the computed mean error using the mean difference of the observation about its mean can be developed. These skill scores offer the advantage of being unit-less and are independent of the runoff measurement units. The correlation measure used is the Nash-Sutcliffe score (NS) which is unit-less.

Categorical skill measures address the skill of the forecast in predicting the magnitude category of the runoff. For example, if the forecast was for flows assigned to the low flow partition, did the low flow actually occur? The yearly runoff over the historical record was ranked and three types of flow regimes, the lower 30% of the flows, the mid 40% of flows, and highest 30% of flows were established. We calculated the forecast skill in predicting flow in each of the three categories. The categorical measures used were the probability of detection, the false alarm rate, the bias, the threat score and the hit rate.

3. Source of data

Thirteen forecast points are located in the western Sierra Nevada. We used a calculated April through July runoff total, the Full Natural Flow (FNF). The state of California Department of Water Resources (DWR) tabulates the FNF on river basins that have runoff forecasts in Bulletin 120, Water Conditions in California, and makes those data available over the internet (CDEC). This bulletin is published in February, March, April and May of each year and contains the snow-survey data and runoff forecasts analyzed in this study. Watershed areas and elevations were obtained along with annual precipitation by river basin

Forecast and observation data for twenty-eight locations that currently forecast April to July runoff were obtained from the Colorado Basin River Forecast Center (CBRFC).

4. Purpose

The work includes assessment of the skill of seasonal water supply forecasts using summary, correlation and categorical measures. The skill measures for the western Sierra Nevada are compared with the measures for the Colorado River basin and measures from a previous study of forecasts in the western United States. Information on the individual watersheds is obtained to identify specific topographic, climatic and hydrological features that influence forecast skill. Recommendations on methods to improve forecast skill are made.

5. Organization of studies

The discussions of runoff forecast skill measures from the western Sierra Nevada and the Colorado River basin are arranged by chapter in this publication.

Chapter 1 (this chapter) presents an introduction to runoff forecasting and measuring skill along with a discussion of the data sources and analysis procedures for computing forecast skill.

Chapter 2 presents the analysis of the forecast skill for thirteen sites in the western Sierra Nevada. Included in the work is a complete panel of computed measures including summary, correlation and categorical measures combined with a percent bias assessment. It includes analysis of the effect of watershed elevation on forecast skill. The correlation of forecast skill and accumulated precipitation is reviewed along with the computation of watershed yield and its relationship to forecast skill.

Chapter 3 presents the analysis of the skill measures for twenty-eight sites in the Colorado River basin, including summary measures, correlation measures and categorical measures.

Chapter 4 presents the percent bias assessment of the sites within the Colorado River basin, along with the elevation analysis and computation of watershed yield.

Chapter 5 presents the comparison of watershed characteristics and the forecast skill analyses for the forecast sites within the western Sierra Nevada and the Colorado River basin.

Chapter 6 presents conclusions for the work performed in the studies, along with possible impacts on forecast skill due to changing climate. Suggestions for improvements in the forecasting process to raise skill level are offered.

There are five appendices containing supplementary information.

Appendix A contains a graphical comparison between April-July runoff magnitude and April 1 percent bias for the 13 locations in the western Sierra Nevada.

Appendix B contains tabulations of skill measures consisting of summary, correlation and categorical measures for the 13 forecast locations in the western Sierra Nevada.

Appendix C contains graphics of hydrological characteristics of the 13 forecast locations in the western Sierra Nevada, including runoff time series, time series of ratio of April-July runoff to water year runoff, and a representation of the distribution of water year runoff.

Appendix D contains a graphical comparison between April-July runoff magnitude and April 1percent bias for the 28 locations in the Colorado River basin.

Appendix E contains tabulations of skill measures consisting of summary, correlation and categorical measures for the 28 forecast locations in the Colorado River basin.

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CHAPTER 2

Skill Assessment of Water Supply Forecasts for Western Sierra Nevada Watersheds

Brent Harrison [1,*], Roger Bales [2,†]

[1] Sierra Nevada Research Institute, University of California Merced, 5200 N. Lake Rd., Merced CA 95343, bharrison3@ucmerced.edu

[2] Sierra Nevada Research Institute, University of California Merced, 5200 N. Lake Rd., Merced CA 95343, rbales@ucmerced.edu

† This author contributed equally to this work.

***** Author to whom correspondence should be addressed; E-Mail: bharrison3@ucmerced.edu; Tel.: +1-209-228-7674 ; Fax: +1-209-228-4158.

Abstract: The western slope of the Sierra Nevada contains 13 major river basins with the necessary long term forecast and runoff data that could be used to compute forecast skill. An analysis of precipitation by river basin indicated a trend of reduced precipitation in going from 1500mm in the Yuba in the north to 600 mm in the Kern to the south. Specific yield for the various watersheds generally ranged between 0.2 and 0.5 except for the lower elevation watersheds and the Kern in the south. The difference between precipitation and runoff, primarily evapotranspiration, was higher in the Cosumnes and Mokelumne basins. Approximately half of the Percent Bias was calculated to be in a band of +/- 15%. Analysis of skill scores for the 13 watersheds in the study area showed low scores around 0.3 in February increasing through the forecast season to 0.8 in May. Correlation skill measures such as the Nash Sutcliffe scores also exhibited increases in skill through the season from 0.45 to 0.95 in May. A linear regression between Nash Sutcliff scores and watershed elevation yielded a strong relationship with a coefficient of determination of 0.77. This relationship between increased elevation and increased forecast skill explained the increase in skill scores for the higher elevation central and southern watersheds in the study area. The strong relationship between snow and rain accumulation and forecast skill measured by the Nash Sutcliffe score exhibited correlation coefficients exceeding 0.90. April through July runoff for each year was classified as the lower 30%, the mid 40% and upper 30% and categorical skill measures were computed on the three runoff categories. Increases in forecast skill during the forecast season were visible in the low and high flow probability of detection but not visible in the mid-flow probability of detection. Both low-flow and high-flow forecasts exhibited lower false alarm rate and reduced bias as the forecast season progressed. Difficulty of making mid-flow forecasts early in the season was illustrated by high early season false alarm rate and over forecasting bias. The threat score increased uniformly from 0.4 to 0.8 for all flow categories. The hit rate for the mid 40% of runoff years exhibited a lower skill level of 0.6 for February and March compared to the hit rate for high and low flow years of nearly 0.8. Difficulty in making accurate forecasts for mid-flow runoff along with the under forecast of high runoff years and the over forecast of low runoff years are showed to be common difficulties in runoff forecasting, especially early in the forecast season.

Keywords: forecast; runoff; skill

1. Introduction

Runoff from the Sierra Nevada is used for agricultural, municipal, industrial, and environmental purposes. In order to apportion the water to its many uses, the agencies responsible rely on runoff forecasts prepared during the snow accumulation and ablation period to estimate water supplies for the remainder of the water year. These forecasts use information on snowpack, precipitation and other hydrologic conditions to make runoff projections. In California, the Cooperative Snow Survey Program, part of California Department of Water Resources (DWR), coordinates the measurements and prepares the forecasts. Local agencies sometimes use these forecasts to prepare specialized forecasts for their own use. The DWR forecasts have been prepared on watersheds in California since the 1930’s. The forecasts predict April through July runoff and by extension estimate runoff for the water year. The forecasts are issued monthly, February through May of each year.

Similar runoff forecasts are made for watersheds in other western states of the United States. The first formal evaluations of the skill of runoff forecasts in other western states were made in the late 1950’s on various portions of these forecasts. Additional work to evaluate forecast skill in the western states (excluding the western Sierra Nevada) was done again in the mid 1980’s. Shafer and Huddleston (1984) reviewed historical seasonal volume forecasts based on regression techniques and found a small improvement in forecasting skill in recent years but cautioned that large improvements in skill are not to be expected in the future by refining regression techniques. Starting in 2002, the latest work was initiated to evaluate the skill of water-supply forecasts in the western United States, again excluding the western Sierra Nevada. Franz et al. (2003) evaluated the forecasts at 14 sites in the Colorado River basin and determined that the Ensemble Streamflow Prediction (ESP) system, developed by the National Weather Service (NWS), performed better than climatology forecasts.

Pagano et al. (2004) evaluated forecasts using Nash-Sutcliffe scores and other measures on 29 unregulated rivers in the western United States. They found high skill for forecasts issued on 1 April. Forecasts made earlier in the season contained more uncertainty but were shown to still be skillful. They also found that areas with wet winters and dry springs presented higher skill improvement over the forecast season than for areas with dry winters and wet springs. In addition, they also found mixed changes in skill over time when comparing different areas of the study. Pagano and his co-authors have noted that it is desirable that the measures to evaluate forecast skill be chosen carefully so they are understandable and relevant to forecast users.

Hartmann et al. (2006) performed an assessment of water-supply outlooks in the Colorado River Basin which established a baseline for identifying improvements in hydrologic forecasts. The following work by Morrill et al. (2007) was an assessment of the strengths and weaknesses of seasonal water-supply outlooks at fifty-four sites in the Colorado River basin using an assortment of skill measures. Morrill found that the water-supply outlooks were an improvement over climatology during the historical record for most sites. They also found that most of the forecasts were conservative, with above-average flows under predicted and below-average flows over predicted.

The aims of this research were to assess the skill of seasonal water-supply outlooks for the Sierra Nevada, and to analyze the skills as a function of basin-specific topographic, climatic and hydrologic features. We also aim to identify where improvement in the forecast skill level would help water managers and other interested stakeholders to effectively plan and schedule water releases, delivery and transfers in the region.

2. Methods and data

We assessed the skill of seasonal water-supply outlooks for the 13 main river basins draining the western Sierra Nevada using summary, correlation and categorical measures of forecast skill. All of the forecast points were at the mountain front, and in most cases are at a rim dam on the main river draining the basin (Figure 1). Records of runoff for these basins extend for multiple decades, with most extending back over 100 years. Forecast records extend back to the 1930’s in many cases.

2.1 Skill measures

We introduce summary and correlation (Table 1) and categorical measures (Tables 2 and 3) of the skill of runoff forecasts. Summary measures indicate the error in forecasts as an arithmetic difference between the forecast and the observation. The Mean Absolute Error (MAE) and Mean Square Error (MSE) have dimensions and depend on the magnitude of the runoff. For the current analysis we use a skill score (SS), which is a correlation measure, calculated by normalizing by the difference of each observation from the mean (Table 1). A zero skill score indicates no skill over using the historical average observation as the forecast, a negative value indicates that using the average would be better than using the forecast, and a skill score of 1 indicates perfect skill (no error in the forecast). The SSMSE is mathematically equivalent to the Nash-Sutcliffe score (NS).

The Percent Bias (PBias) is the direct measure of the error divided by the observation, expressed as a percent. A perfect forecast will have a PBias of zero, a positive value indicates over forecast (forecast exceeds observation) and a negative PBias indicates under forecast. As PBias is normalized by the observation, it is a dimensionless measure. PBias is an easily understood skill measure, and values from a series of annual forecasts can be readily analyzed for the influence of independent climate variables.

Categorical measures indicate the skill of the forecast in predicting the magnitude category of the runoff, in this case low, middle and high runoff categories. For example, if the forecast was for flows assigned to the low-flow category, did the low flow actually occur? Historical runoff records for each forecast point were divided into 3 runoff categories, the lower 30%, the mid 40% and highest 30% of flows. A 2 ×2 contingency table was used to count the results of forecasts versus observations in each category (Table 2) (Wilks, 2011). Five categorical measures were assessed (Table 3).

The Probability of Detection (POD) is intuitive, being the proportion of times the event or category was forecast compared to the times it occurred. The False Alarm Rate (FAR) is the proportion of forecast events in a category that failed to occur. The Bias indicates if a category is over forecast (>1) or under forecast (<1). The Threat Score (TS), also known as the Critical Success Index, normalizes correct forecasts by total forecasts plus observations for that category. Unlike the POD and FAR, the TS takes into account both missed events and false alarms. The Hit Rate (HR) credits correct forecasts and non-forecasts by dividing by the total forecasts plus observations. It thus reflects both correct detection, or classification, and lack of incorrect classification. The POD, TS and HR all range from zero (poor) to 1.0 (perfect). FAR has an opposite orientation, ranging from zero (perfect) to 1.0 (poor).

2.2. Source of data

The 13 forecast points drain watersheds ranging in size from 1010 to 9386 km^2, and range from the Feather River in the north to the Kern River in the south (Table 4). These watersheds are highly developed with water storage and diversion facilities, providing water to extensive areas of cropland and urban development in California. Owing to the many diversions occurring above each main gauging point, we used a calculated April through July runoff total, the Full Natural Flow (FNF). It is the reconstructed flow in the river if there were no diversions or storage, and is calculated on a daily basis from existing flow gages, adding any increases in reservoir storage, and adding estimates of diversions from the river basin. The California (DWR) tabulates the Full Natural Flow (FNF) on river basins that have runoff forecasts in Bulletin 120, Water Conditions in California, and makes those data available over the internet (CDEC, 2014).

Bulletin 120 is published in February, March, April and May of each year and contains the snow-survey data and runoff forecasts analyzed in this study. We used the DWR tabulations of Bulletin 120 runoff forecasts for the April-July runoff period for the years 1930 to 2012, or shorter periods if forecasts started in later years (Stephen Nemeth personal communication, 28 Oct. 2011). The starting year of forecast for each location varies considerably, especially for forecasts other than the month of April. Most February and March forecasting started by 1953. Most April and May forecasts started by 1939. All forecasts on the Cosumnes River started in 1963 and on the Tule River in 1959. The April to July runoff forecasts were analyzed in this study as April to July runoff is historically the main period of snowmelt runoff in the Sierra Nevada.

Watershed areas and elevation distributions were extracted from Calwater basin polygons, overlain on 30-m digital elevation data. Precipitation data used in the interpretation were from PRISM, which are spatial datasets incorporating a wide range of climatic observations. Monthly precipitation data for the years 1896-2013 were downloaded from PRISM and the average precipitation was calculated for each basin (PRISM, 2014).

3. Results

3.1 Watershed features

From a plot of area vs. elevation for each watershed (Figure 2) it is apparent that the southern Sierra basins have more high elevation, snow producing area with the highest elevation watershed being the Kings and the two lowest being the Cosumnes and Tule. Basin-average precipitation declines from north to south (Figure 3), with precipitation for the 3 most southern watersheds roughly half of that in the Yuba basin. There is an increase in precipitation when comparing the Yuba to the Feather River, which is opposite of the trend for the remaining 11 river basins. There is also slightly less precipitation for the Cosumnes River than would be expected by the precipitation for neighboring watersheds, which may be related to its lower relative elevation.

Full Natural Flow records go back to 1900 for many of the forecast points, and cover a range of wet and dry years (Figure 4). Quite visible in the time series is the extended drought during the 1920’s and 1930’s and the historical drought of 1976 and 1977. Also visible in the time series are the heavy runoff years prior to 1920 and the record runoff in 1983. The figure shows that runoff varies more than does precipitation over the period of record.

As runoff is related to both precipitation and topography, among other factors, it exhibits more variability across the latitudinal gradient than does precipitation (Figure 5a). There is an uneven trend of decreasing precipitation from north to south. This trend of decreasing precipitation leads directly to decreasing yield from north to south in the western Sierra Nevada. There is an uncharacteristic increase in precipitation and discharge for the Yuba River, with a decrease for the Cosumnes River. There is also an uncharacteristic decrease in discharge for both the Tule and Kern rivers. Figure 5b shows the difference between precipitation and discharge, primarily evapotranspiration, overlain on total precipitation. The Cosumnes and the Mokelumne have the highest evapotranspiration with the Tule higher than adjacent watersheds. Figure 5c summarizes the precipitation and discharge relationship by showing the specific yield, or fraction of precipitation that shows as runoff from the watershed. Low specific yield for the Cosumnes is consistent with its lower elevation, with the drop for the Tule and Kern related to the drier conditions of the two southern watersheds.

April-July runoff accounted for an average of 35% (Cosumnes) to 74% (Kings) of the annual runoff, and is correlated with median elevation (Figure 6a). Precipitation and runoff are not well correlated with elevation (not shown); however, the difference between precipitation and runoff, evapotranspiration, decreases with increasing elevation (Figure 6b).

3.2 Forecast skill – summary and correlation measures

Annual PBias values for April for one central-Sierra basin, the Tuolumne, range from about 40% to -40% (Figure 7). The high variability of April-to-July runoff is shown in the bottom panel. In the top panel, there is little evidence of a trend in PBias over the time series, either in the aggregate or partitioned into low, mid or high flows. There is evidence of over forecast of low flows, as 15 low flows are over forecast with only 8 under forecast. In contrast, 14 of the high flows are under forecast with only 5 over forecast. The mid-flow years are nearly evenly split with 15 over forecasts and 16 under forecast. PBias values for the other 12 river basins are included as supplementary information.

It is apparent that low-runoff years tend to be somewhat over forecast, with high-runoff years somewhat under forecast for all months (Figure 8). It is also apparent that forecasts for February and March have a much higher bias than those for April and May. Low-flow years are greatly over forecast early in the forecast season, which would be expected as average climatology is assumed for the remainder of the runoff season. As more information is gathered on snowpack and precipitation, the PBias decreases steadily from 40% with some decrease in width of the distribution, ending near zero for the May forecasts. For the mid-flow years, there is limited change through the forecast months, with the median staying near zero PBias. The width of the PBias distribution does decrease as information increases. High-flow years behave the opposite of low flow years. The high-flow years are under forecast early in the forecast season, as limited information is available and average climatology is assumed for the remainder of the forecast. The PBias increases from -30% to near zero by April, along with a decrease in width of the distribution that extends to May. See the supplementary information for plots of PBias for other basins, which exhibit similar patterns.

The range of PBias is similar across most of the 13 forecast points (Figure 9). Absolute values are shown as PBias is relatively symmetrical around zero for most basins. Two basins, the Cosumnes and Tule, show a wider distribution of values, with outliers larger than 50% lumped in the highest category of 50%. For most of the basins, 25% of the PBias values exceed 20-25%, with 50% exceeding 10-15%. Again, the Cosumnes and Tule have higher values.

The Skill Scores for MAE (SSMAE) and the NS coefficient show similar patterns to the PBias, improving from February to May as more information becomes available (Figure 10). The forecast skill in February is quite low, with the SSMAE centered near 0.3 but with a tight distribution as this early in the forecast season the forecasts are made using average climatology. The forecasts in March contain additional winter-storm information and thus have higher skill but a much wider distribution. The figure indicates that the runoff forecast skill increases quite steeply from the start to end of the forecast period, with the Skill Score in March around 0.4, 0.65 in April, and ending the forecasts season in May with a Skill Score of approximately 0.75. The width of the score distribution decreases from March to April and then again to May, as additional climate information is available.

The distributions of NS for the four forecast months at the 13 forecast locations exhibit a similar pattern (Figure 10b). The median February NS starts at 0.45 and steadily increases to 0.95 for the median in May. Again the width of the distribution decreases with increasing information from March to May. For the months of February, March and April, there is an increase in NS score in going from the Feather River in the north to the Kings River to the south, excepting the smaller Cosumnes basin (Figure 11). As noted above, the drops in scores for the Cosumnes and Tule are expected as these watersheds are smaller and lower elevation, with less snow.

3.3 Forecast skill – categorical measures

The Probability of Detection (POD) shows the previously discussed increase in skill during the forecast months for the low and high flow years (Figure 12a). By April the POD for low and high flow years is above 0.6 for most basins and averages about 0.8. For March the average is closer to 0.5. The mid-flow years exhibit some dispersion around a flat POD during the forecast season. This characteristic may be reflective of the assumption of average climatology for the remainder of the runoff season.

The False Alarm Rate (FAR) reinforces the difficulty of forecasting mid-flow years, as each year looks mid-flow early in the forecast season (Figure 12b). For the FAR, it is much higher early in the mid-flow years, with a steep improvement as the forecast season progresses. The FAR in the low and high-flow years shows a small decrease over the forecast season.

The Bias also illustrates the effect of information on mid-flow-year forecasts (Figure 12c). For the mid-flow years, the graph indicates over forecast early in the season (February and March) with a movement to no bias (1.0) as climate information becomes more available. Interestingly, the Bias shows under forecast of both low and high flow years early in the forecast season, with a movement to little or no Bias by April. This is also related to the assumption of average climatic conditions early in the forecast period.

The Threat Score (TS) is shown in Figure 12d. The TS values are fairly uniform across the three runoff year types, with the previously observed increase in skill from 0.5 to 0.8 as information increases during the forecast season. The steady increase in TS values over the season for the high and low categories mirrors that of the POD. However, it also improves for the mid category, reflecting the improvement in FAR from Feb-Mar to Apr-May in that category. Still, the median TS is only 0.5 for April for the mid category and 0.6 for the high and low categories.

The Hit Rate (HR) for February forecasts (Figure 12e) is high for both the low-flow and high-flow years (0.8), while lower for mid-flow years (0.6). The HR increases through the forecast season and for the April forecasts the HR is 0.85 for low and high flows, but for mid-flow years is approximately 0.75. The slightly lower scores for mid-flow years may reflect the occurrence of low or high flows for the season even if average flows occur during the early part of the forecast season. More forecasts are in the mid-flow category as low and high flow years are forecast less than they occur. The HR values are somewhat higher than those for TS, reflecting the addition of correct non-forecasts to both the numerator and denominator.

4. Discussion

The trend of increasing forecast skill by month reflects the occurrence of precipitation and snow accumulation throughout the winter and spring (Figure 13). Watershed elevation, an index of rain vs. snow, also affects the forecast skill. Monthly precipitation and snow accumulation amounts from 1971 to 2013 were obtained from the Central Sierra Snow Laboratory at Soda Springs, California (Randall Osterhuber personal communication, 25 Feb 2014). This site was chosen as an index of precipitation and snow accumulation due to its central location and long period of records. Figure 13a shows the monthly precipitation and cumulative fraction of annual precipitation at that site. Figure 13b shows the snowfall and cumulative fraction of snowfall at the site. There is a strong correlation between the accumulation of the seasonal precipitation and the increase in skill in runoff forecasts. In February the NS is 0.4, with the cumulative snow at 0.7 and cumulative precipitation at 0.6 (Figures 10 and 13). The NS and cumulative precipitation and snow increase in April to an NS of 0.80 with nearly all of the snow and 0.9 of the yearly precipitation. These measures increase again with the May forecasts. As more of the seasonal precipitation falls, is measured and incorporated into the runoff forecasts, the skill of the forecast increases. The relationship is confirmed by the NS to snow correlation coefficient of 0.92 and a NS to precipitation correlation coefficient of 0.93. For the months of February, March and April, there is an increase in NS score from the Feather River in the north to the Kings River to the south, excepting the smaller Cosumnes basin (Figure 11). This is due to higher elevations and increased snow dominance of the southern watersheds. In Figure 6a, the ratio of April through

July runoff is plotted as a function of median watershed elevation. The associated linear regression indicates a solid relationship with an R^2 of 0.70. These results reflect increasing snow dominance of the central and southern Sierra watersheds.

The uneven skill of the forecasts south of the Kings River can be attributed to the lower elevation of the watersheds, the lower levels of precipitation to the south and the north-south aspect of the Kern River watershed, in contrast to the east-west aspect of most of the other watersheds. As seen previously, the drops in scores for the Cosumnes and Tule are expected as these watersheds are smaller and lower elevation. This increase in forecast skill in the southern direction is attributable to the higher elevations of the Sierra to the south. The increase in forecast skill as elevation increases is illustrated further in Figure 14 which shows a linear regression between April NS and median basin elevation with an R^2 of 0.77. The relationship would be steeper if the 0.56 NS score for the Cosumnes were omitted from the regression.

Of the categorical measures, POD and FAR are the simplest mathematically and conceptually straightforward, though are poorly correlated (not shown). BIAS is correlated with POD for the low-flow category, suggesting that non-correct low-flow forecasts are not that important (Figure 15). However, the lack of correlation between BIAS and POD for mid flows reflects the high number of incorrect mid-flow forecasts for April. This point is reinforced by the correlation between BIAS and FAR. The lower importance of incorrect low-flow forecasts is also reflected in the similar correlation between TS and POD, as between BIAS and POD. Note that TS differs from POD by including incorrect forecasts in the denominator. The higher correlations between TS and POD for high and mid flows, versus the correlations for BIAS and POD, also reflect the addition of incorrect forecasts. But in the case of TS, the incorrect forecasts are in the denominator, resulting in lower TS versus POD values. Note that slopes of the TS and POD correlations are near 1.0 for mid and high flows. This is also reflected in the high correlation between TS and FAR for mid and high flows, versus lower correlation for low flows. Note also the relatively high FAR values for mid flows, versus lower FAR values for high flows. HR differs from TS by including correct non-forecasts in both the numerator and denominator. The HR and TS skill measures are thus very highly correlated, with R^2 values of 0.92-0.98 (not shown). Note that HR values are higher than POD values, especially for low and high flows, reflecting the importance of correct non-forecasts for those categories. Mid flows have HR values much closer to their POD values, and also a very high correlation between HR and FAR. The HR is more highly correlated to elevation in mid and high flow years (Figure 16), thus illustrating the influence of snow dominated runoff in forecasting skill.

This analysis suggests that use of POD, FAR and BIAS together can be a good diagnostic for the Sierra Nevada overall. However, examining individual basins, these measures individually show only moderate correlations with elevation (not shown). HR shows a stronger correlation, reflecting the combined effects of correct and incorrect forecasts, plus non-forecasts. This correlation with elevation also suggests that better measurements of winter precipitation and snowpack, which are generally better in the higher-elevation basins with more snow than rain, contributes to improved forecasts.

Increasing average temperatures in the Sierra, as the Earth's climate warms, will mean that all basins will receive a greater fraction of precipitation as rain rather than as snow. Using an approximate temperature lapse rate of 2^oC per 300 m elevation, a 2^oC increase could result is a drop in the NS score by about 0.1 (Figure 14). That is, statistical forecasts that are based on indices of snow accumulation would not be expected to yield as much skill in forecasts if the snow is no longer accumulating. Similarly, the skill of categorical forecasts, also strongly elevation dependent, can be expected to decrease as temperature increases and higher elevations tomorrow become more like lower elevations are today.

5. Conclusions

The summary and correlation skill measures such as SSMAE and NS can appraise forecast skill over a period of years. In contrast, PBias will generate a time series for each location that can be reviewed for changes in skill over time. Currently, there is no indication of a long term trend in forecast skill in the PBias record. The categorical skill measures appraise forecast skill for three different flow scenarios and clearly show tendency to under forecast high flows.

Various changing climate scenarios present the possibility of an increase of 2° or 4°C in temperature. This will result in the loss of snow cover along with a rise in elevation of the snow line. Both results will decrease forecast skill. As a result, users of water supply forecasts may consider use of forecasting tools and data that are based on principles of mass balance and on the spatially distributed data needed to drive the models. Although current modeling tools are sufficiently flexible to incorporate immediate and larger future changes in climate that are outside the current stationarity assumption, data for those models are largely lacking.

One other effect of changing climate is projected to be an increase in the amount of total precipitation falling as rain, emphasizing the potential of distributed, representative rainfall, as well as snowfall measurements to enhance forecasts. This shift to rain will decrease the skill level of forecasts in the northern Sierra Nevada and lower-elevation basins more than the higher-elevation southern basins.

Future increases in skill level, could be enabled by incorporating snow cover data estimated by remote sensing blended with representative ground measurements into the forecasting process. Increased forecast skill earlier in the water year, if new measurements can facilitate that, can provide significant economic benefits to water users, and introduce flexibility and resiliency into water-management decisions.

Acknowledgments

The authors wish to thank the staff of the California Cooperative Snow Survey Program and the staff of the Central California Snow Laboratory for assembling the data used in this study. UC Merced’s support of the first author’s graduate studies is gratefully acknowledged.

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Table 1. Summary and correlation measures of forecast skill

Skill measure	**Equation**[a]
Mean Absolute Error (MAE)	$\text{MAE}=\frac{\sum\lvert f_i-o_i\rvert}{n}$
Mean Square Error (MSE)	$\text{MSE}=\frac{\sum(f_i-o_i)^2}{n}$
MAE skill score	SS_{MAE} = 1-MAE/MAE$_{\text{cl}}$, where MAE$_{\text{cl}}$= $\frac{\sum\lvert\bar{o}-o_i\rvert}{n}$
MSE skill score[b]	SS_{MAE} = 1-MSE/MSE$_{\text{cl}}$ where MSE$_{\text{cl}}$ = $\frac{\sum(\bar{o}-o_i)^2}{n}$
Percent Bias (PBias)	$\text{PBias}=\left(\frac{f_i-o_i}{o_i}\right)100\%$

[a] Variables: o_i is the observation, $\bar{o}$ is the mean of the observations, f_i is the forecast, $\overline{f}$ is the mean of the forecasts
n is the number of observations

[b] Equivalent to Nash-Sutcliffe (NS) score

Table 2. Variables for 2 x 2 contingency table

	Observed	**Not observed**
Forecast	a	b
Not forecast	c	d

Table 3. Categorical measures

Measure	**Explanation**	**Equation**	**Range**
Probability of Detection (POD)	Correct forecasts divided by observations	a/(a+c)	0-1 (perfect)
False Alarm Rate (FAR)	Incorrect forecasts divided by forecasts	b/(a+b)	1-0 (perfect)
Bias	Correct and non-correct forecasts divided by observations	(a+b)/(a+c)	>1 over; and <1 under forecast
Threat Score or Critical Success Index (TS)	Correct forecasts divided by the forecasts plus non-forecast observations	a/(a+b+c)	0-1 (perfect)
Hit Rate (HR)	Correct forecasts and correct non-forecasts, divided by total forecasts and observations	(a+d)/(a+b+c+d)	0-1 (perfect)

Table 4. Forecast points and river basins

No.	**Location**	**Lat.**	**Long.**	**Runoff records**	**Forecast records**	**Area, km^2**
1	Feather River at Oroville	39.522	121.547	1906-2012	1938-2012	9386
2	Yuba River near Smartsville plus Deer Creek	39.235	121.273	1901-2012	1937-2012	3085
3	American River inflow to Folsom Lake	38.683	121.183	1901-2012	1932-2012	4921
4	Cosumnes River at Michigan Bar	38.5	121.044	1908-2012	1963-2012	1373
5	Mokelumne River at Mokelumne Hill (Pardee)	38.313	120.719	1901-2012	1936-2012	1489
6	Stanislaus River at Goodwin Dam	37.852	120.637	1901-2012	1932-2012	2422
7	Tuolumne River at La Grange Dam	37.666	120.441	1901-2012	1932-2012	3963
8	Merced River at Merced Falls	37.522	120.331	1901-2012	1932-2012	2642
9	San Joaquin River at Friant Dam	36.984	119.723	1901-2012	1932-2012	4248
10	Kings River at Pine Flat Dam	36.831	119.335	1901-2012	1932-2012	3989
11	Kaweah River below Terminus Reservoir	36.412	119.003	1901-2012	1932-2012	1458
12	Tule River below Lake Success	36.061	118.922	1931-2012	1953-2012	1010
13	Kern River inflow to Lake Isabella	35.556	118.484	1930-2012	1932-2012	5387

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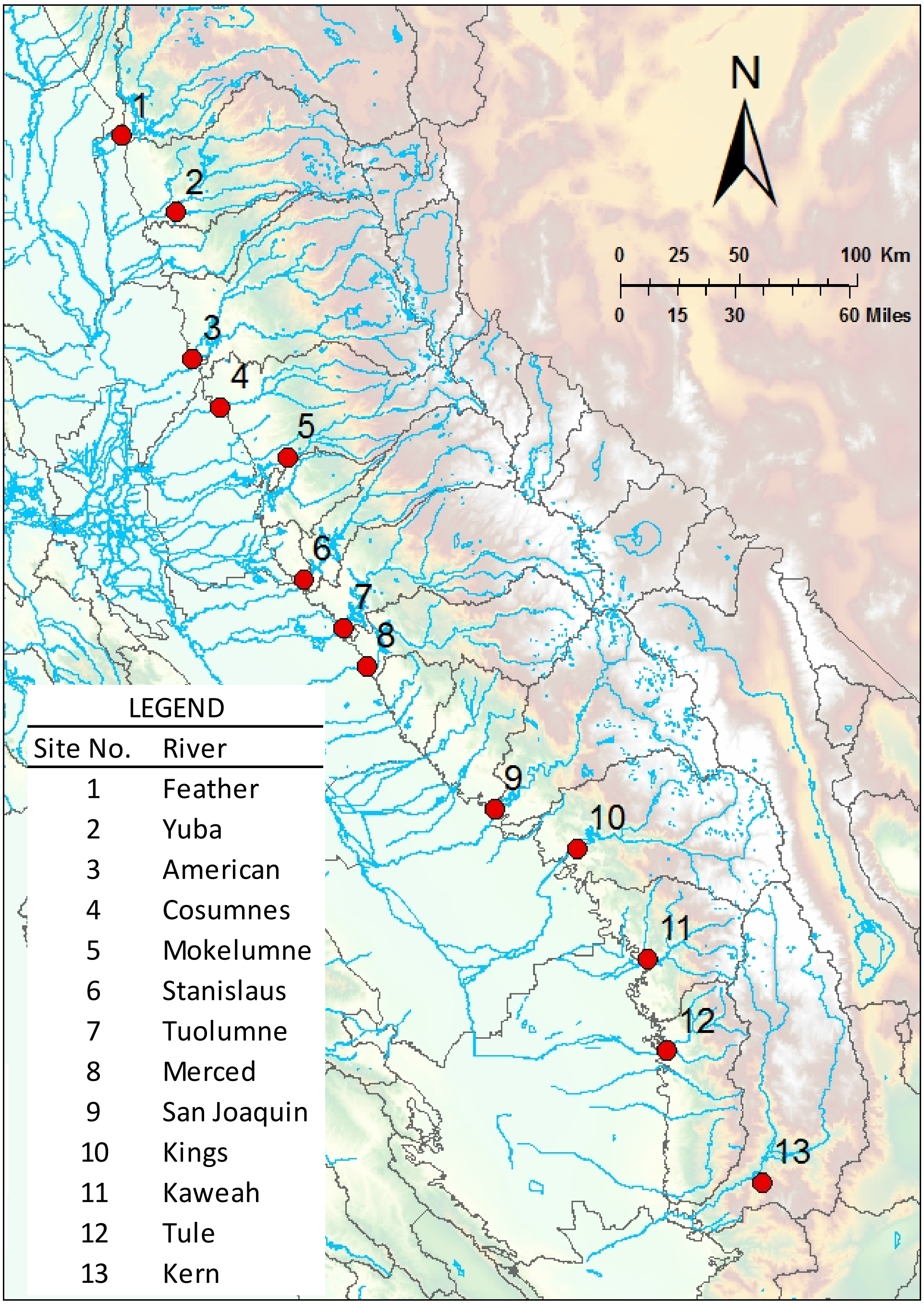


Figure 1. Map of western Sierra Nevada forecast locations

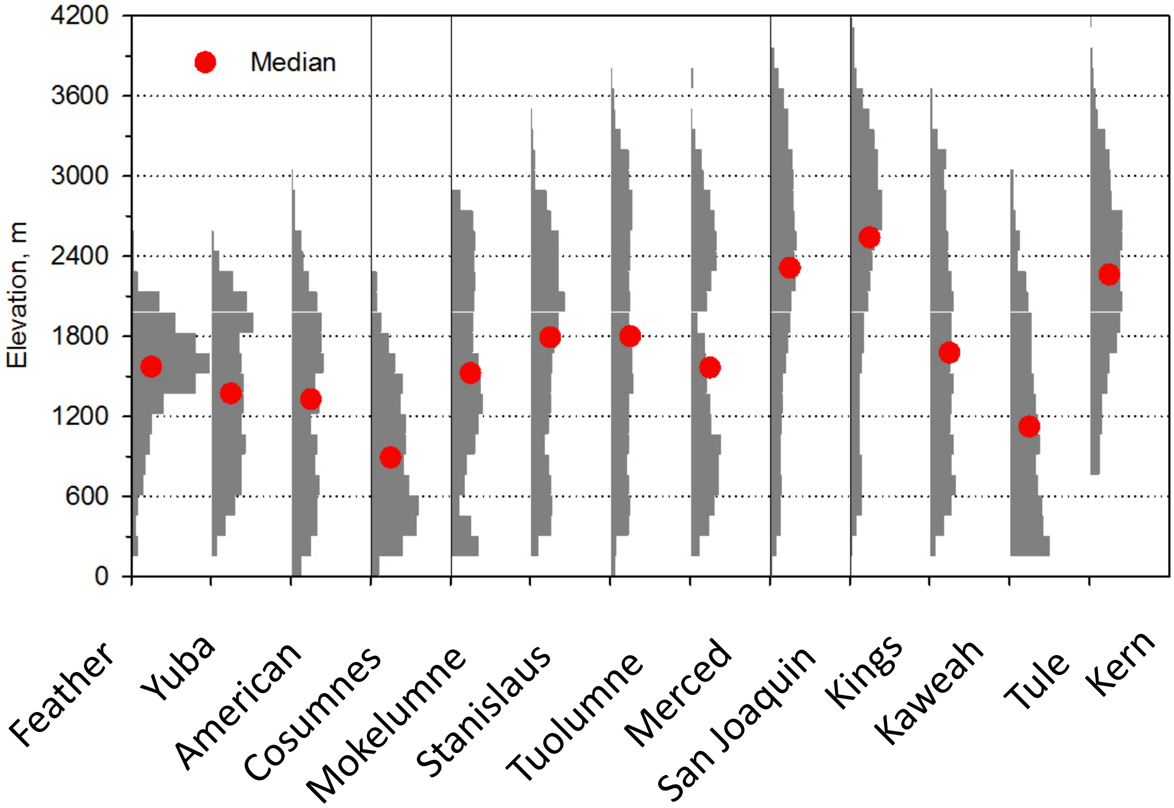


Figure 2. Western Sierra Nevada watershed elevation histogram with median elevation shown

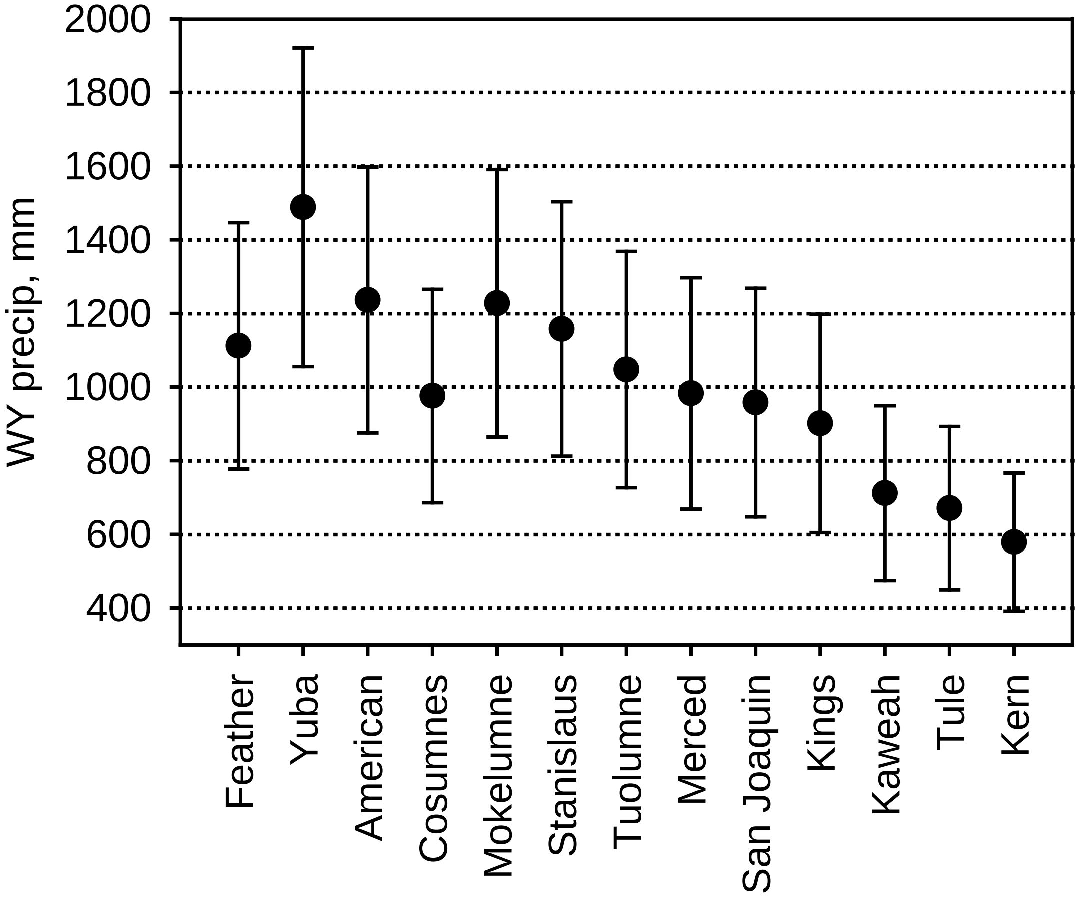
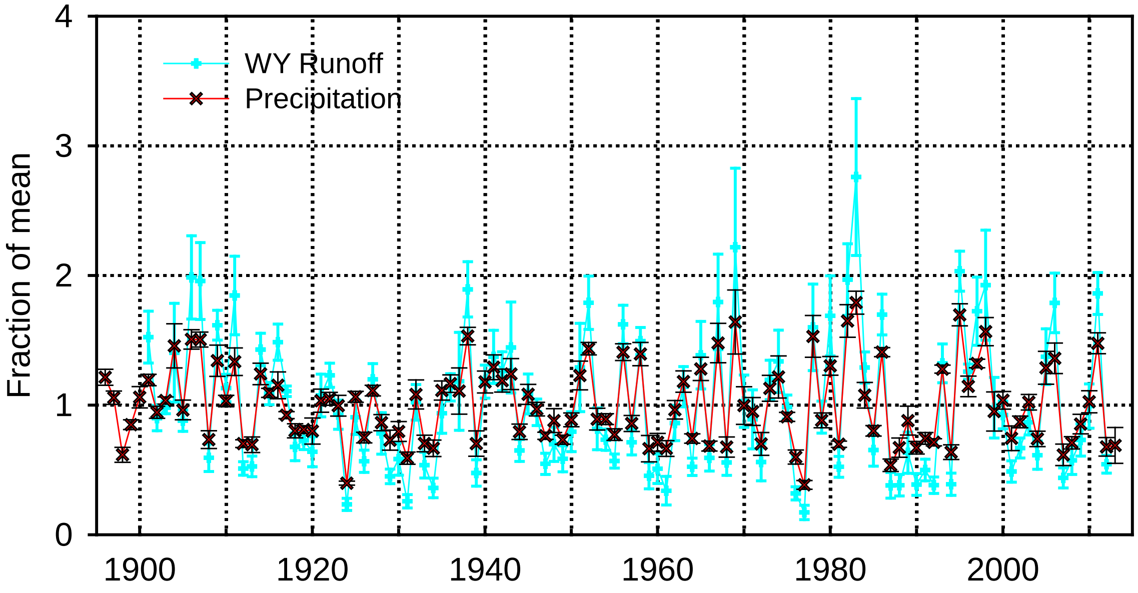


Figure 3. Mean precipitation from 1896 – 2013 for 13 western Sierra basins +/- one standard deviation (PRISM data)



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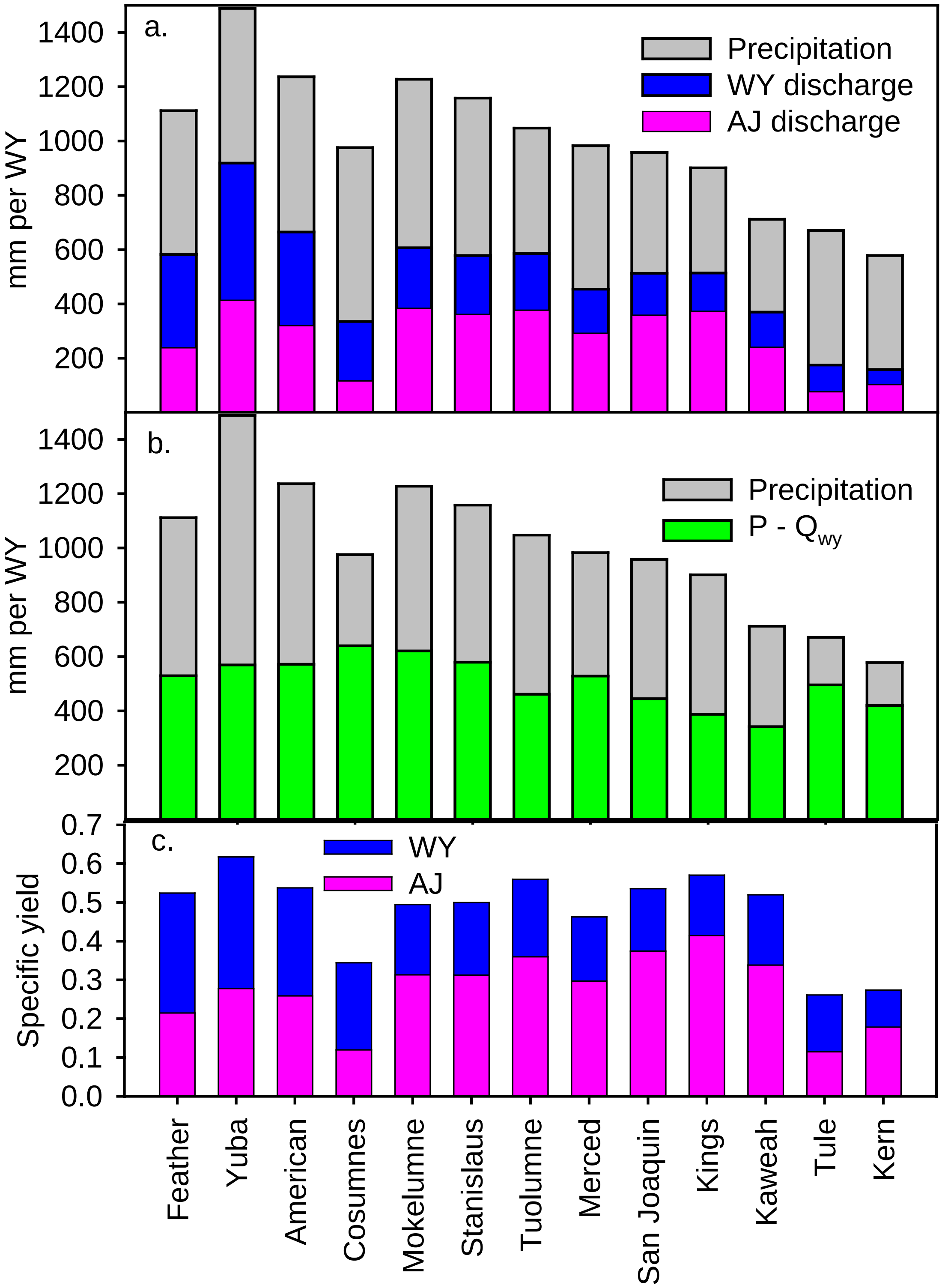
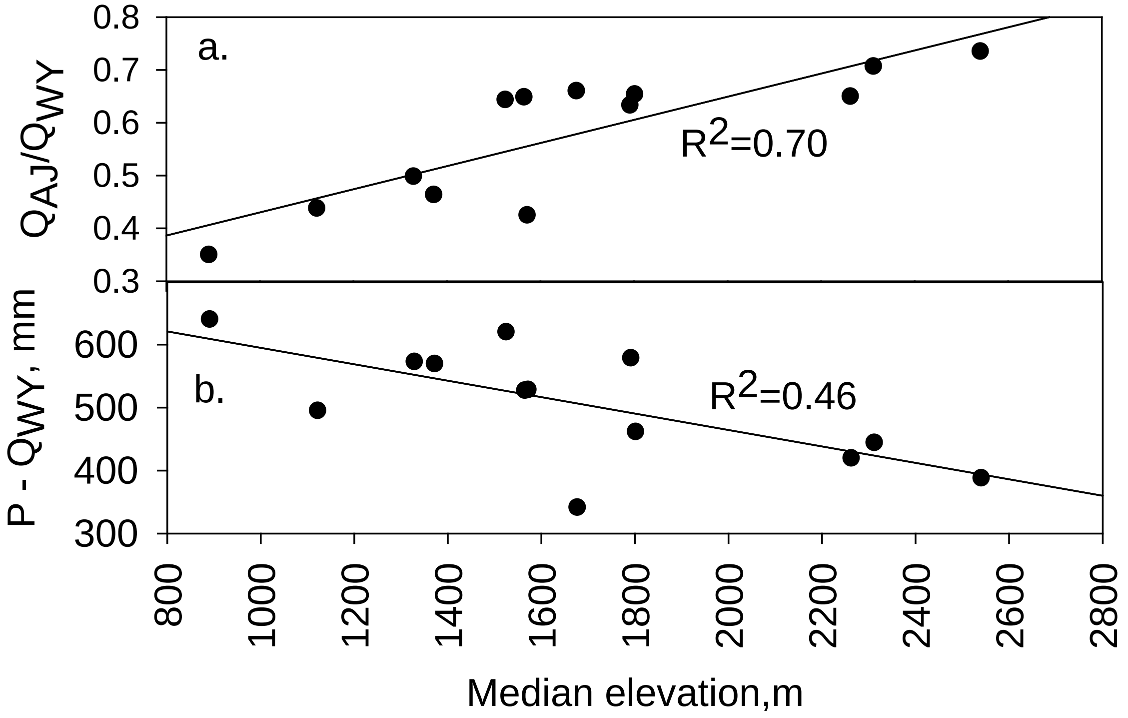


Figure 5 a. precipitation with WY and AJ discharge for 13 western Sierra locations; b. precipitation with precipitation – WY runoff; c. specific yield for WY and AJ for 13 western Sierra watersheds.



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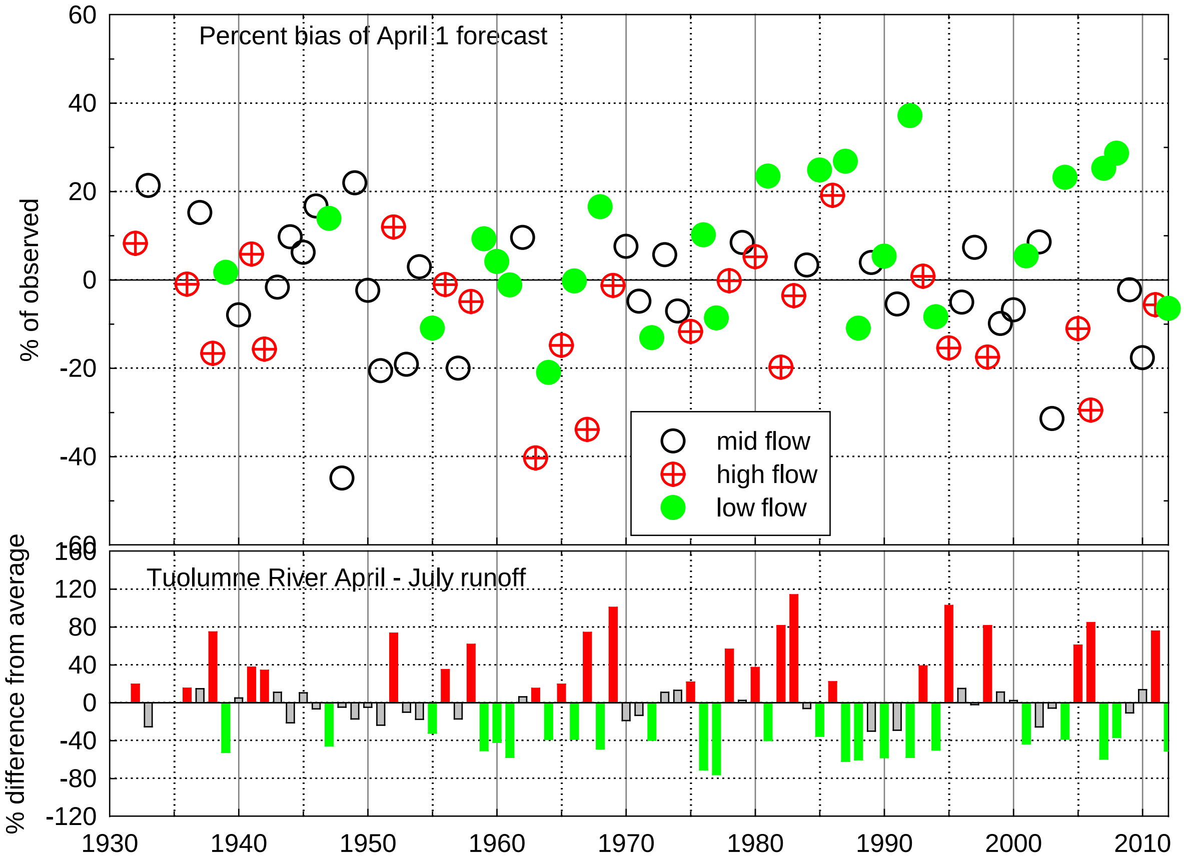

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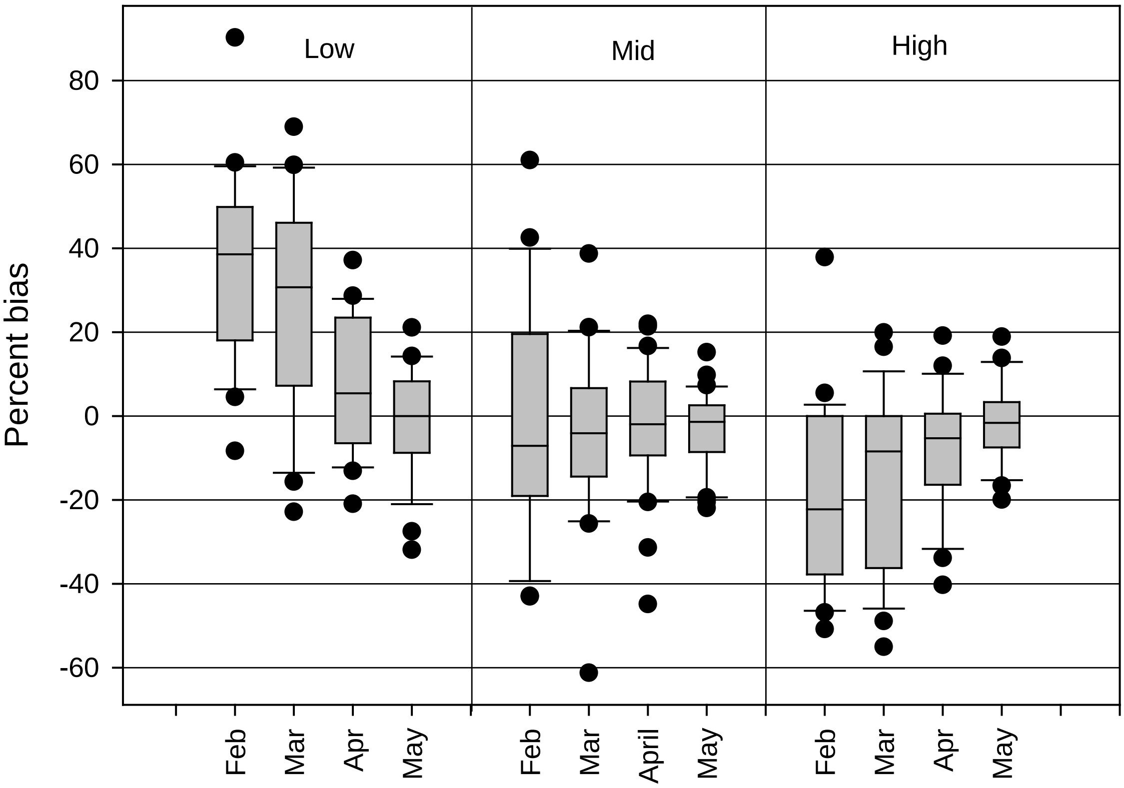
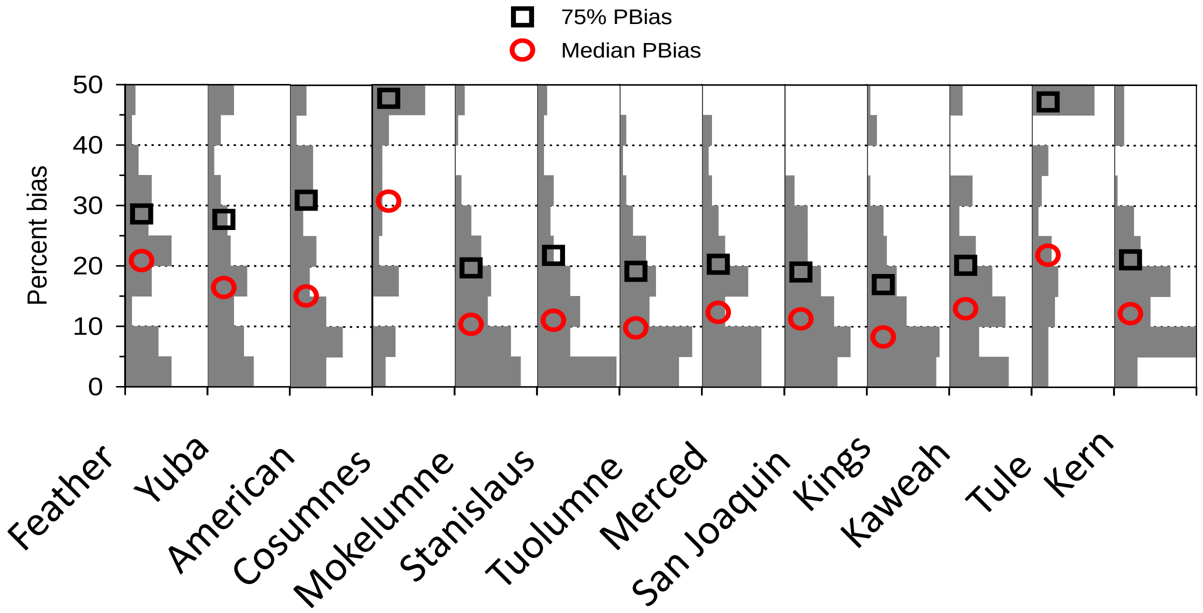


Figure 8. Tuolumne River 1 April percent bias categorized by runoff magnitude for each month of forecast period. Box is 25%, 75%, with median shown as a bar. Tics are 10% and 90% with outliers outside of that range.



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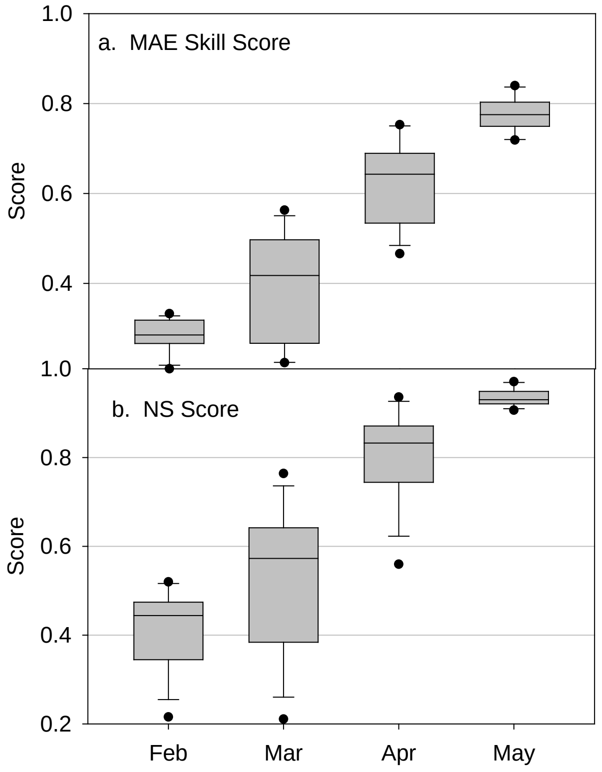
Histogram truncated with upper range of 45 to 50 containing any PBias 45 and above.



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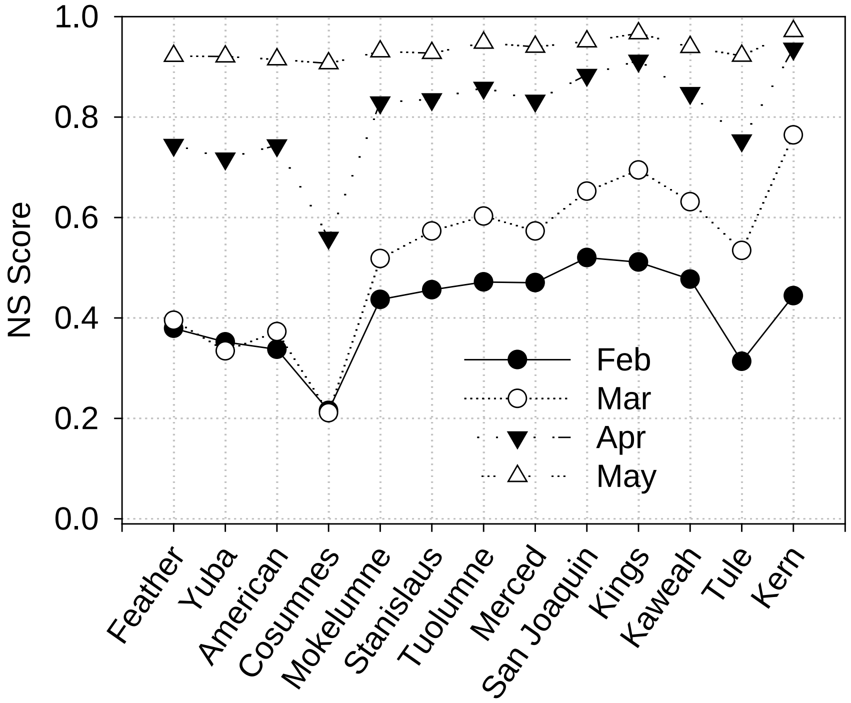

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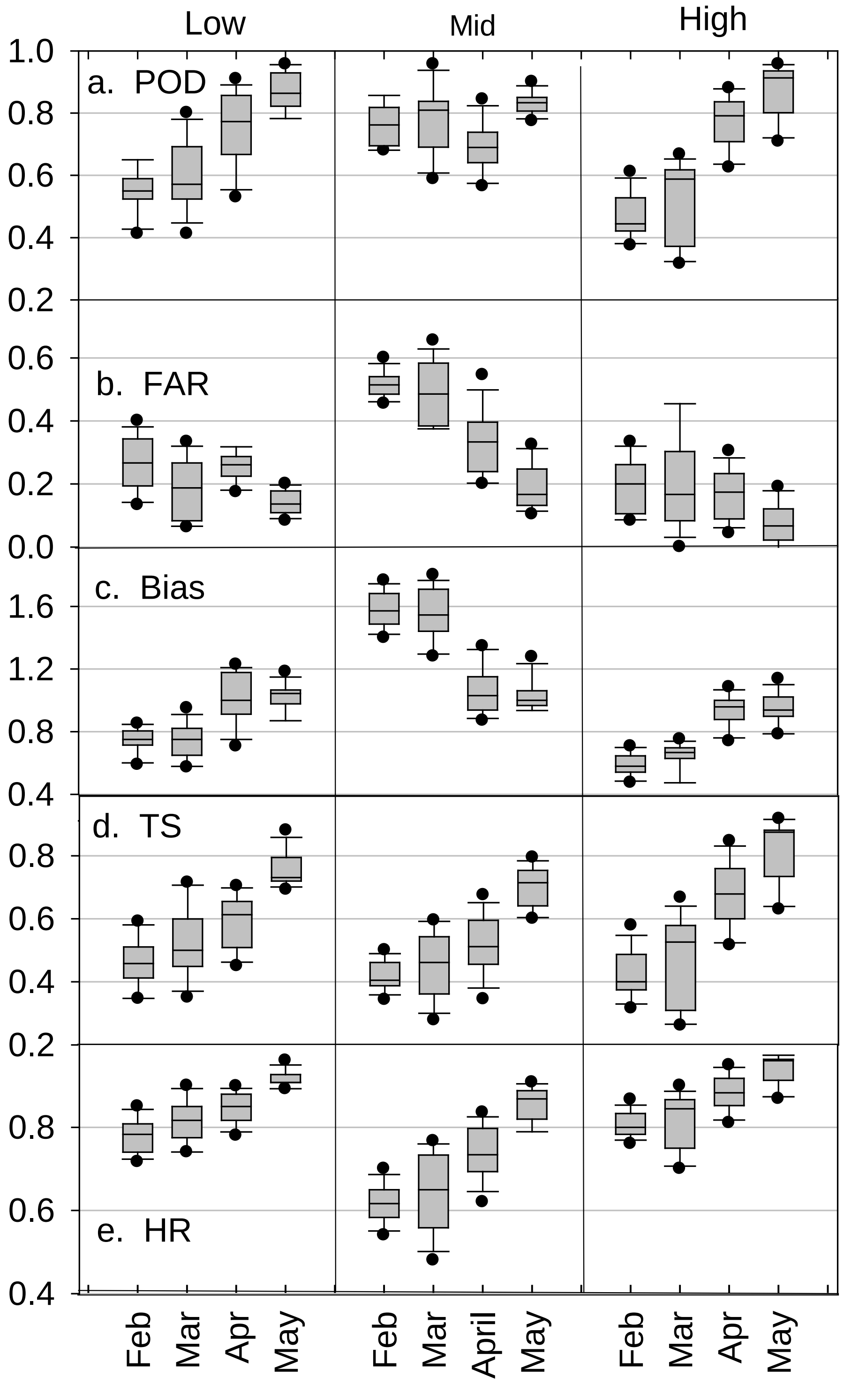


Figure 12. Categorical measures for western Sierra Nevada for each forecast month. The categories are low runoff, mid runoff and high runoff. The forecast months (February to May) are on the abscissa.

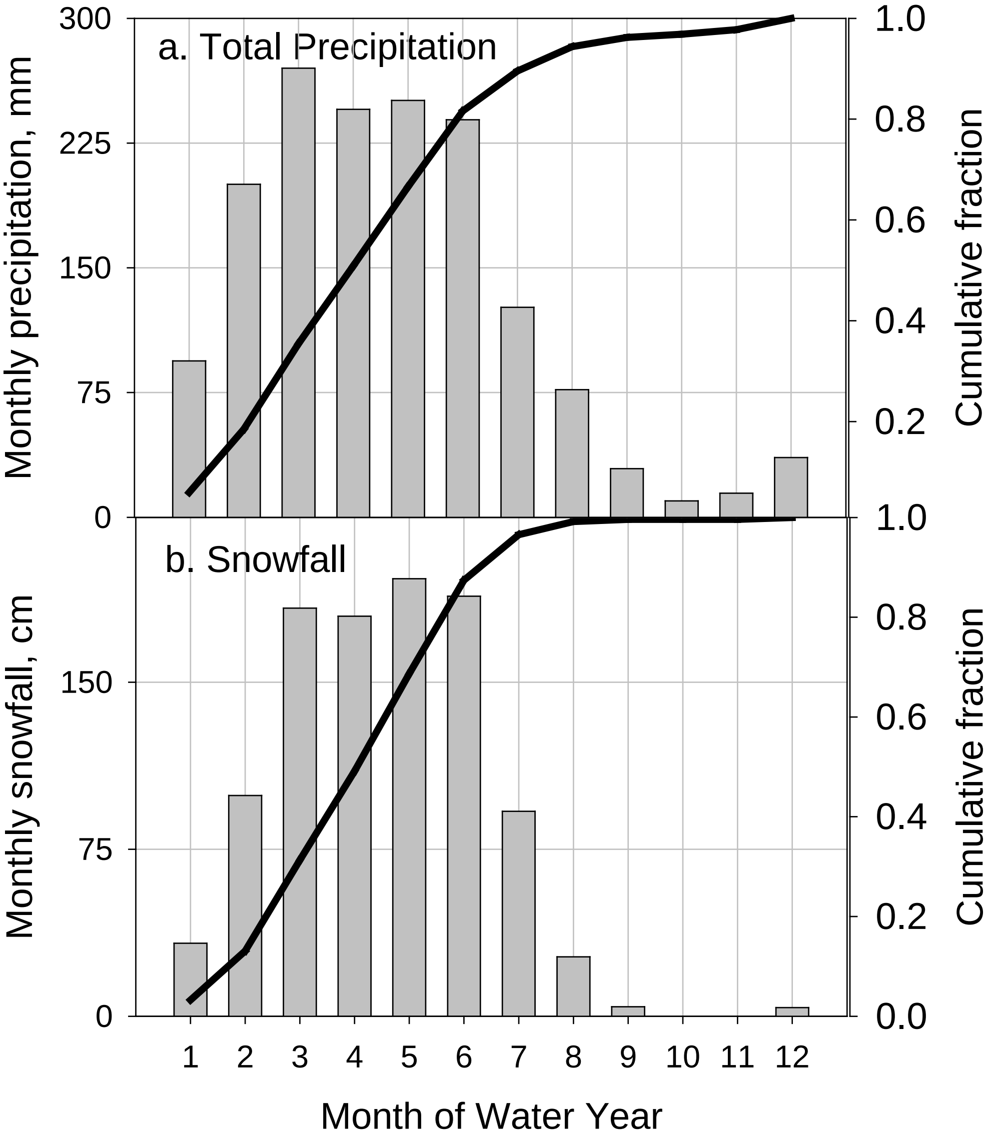
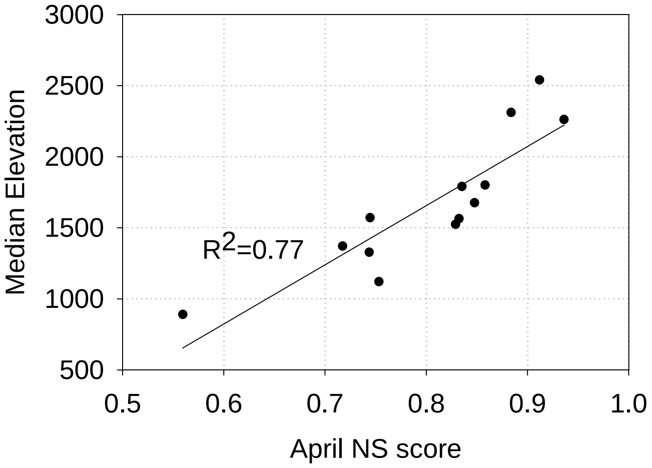


Figure 13 a. Mean precipitation and cumulative mean fraction precipitation.
b. Mean snowfall by month and cumulative mean fraction snowfall.
The location is the Central Sierra Snow Laboratory.



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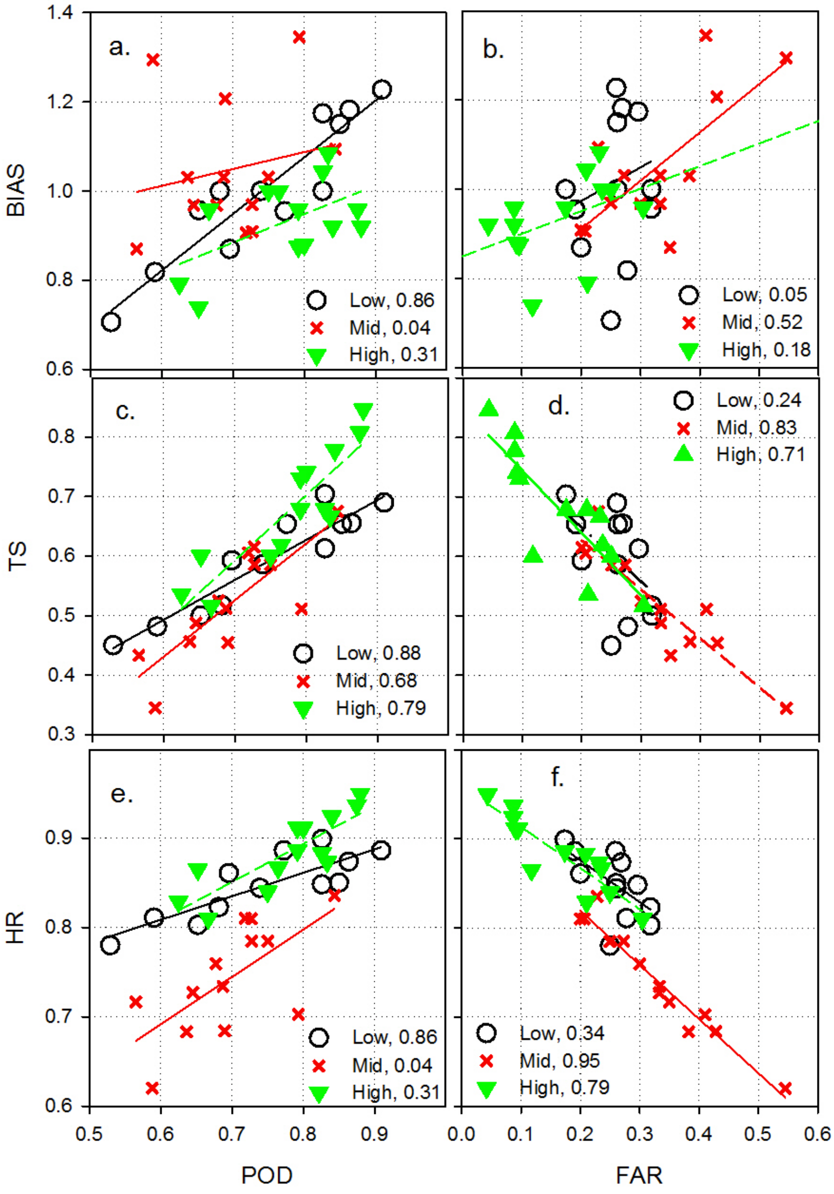

Figure 15. Correlation between categorical measures. Values in legend of each panel are R^2.

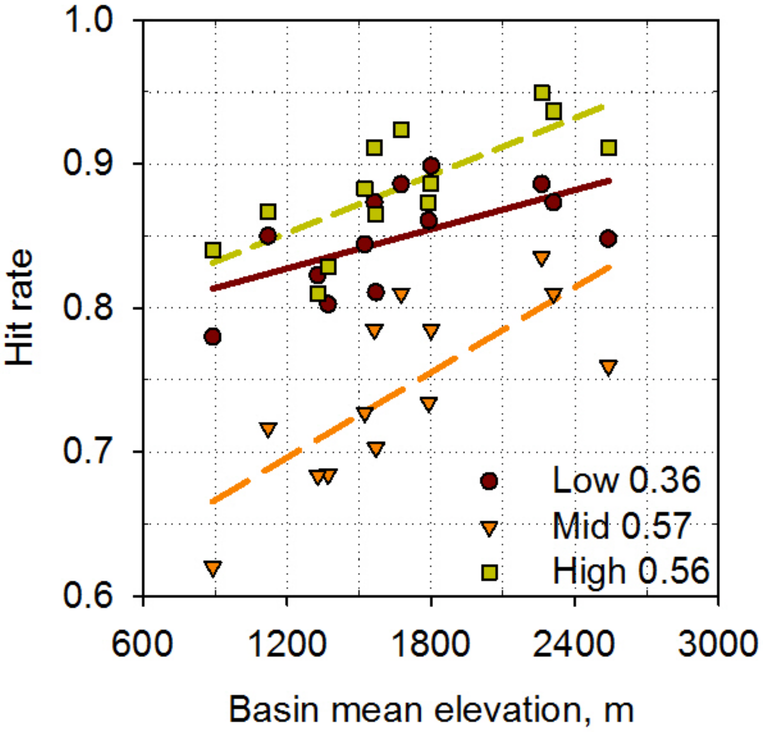

Figure 16. Hit rate versus elevation. Values in legend are R^2.

CHAPTER 3

Skill Assessment of Water Supply Outlooks in the Colorado River Basin

Brent Harrison [1,*], Roger Bales [2,†]

[1] Sierra Nevada Research Institute, University of California Merced, 5200 N. Lake Rd., Merced CA 95343, bharrison3@ucmerced.edu
[2] Sierra Nevada Research Institute, University of California Merced, 5200 N. Lake Rd., Merced CA 95343, rbales@ucmerced.edu

[†] This author contributed equally to this work.

[*] Author to whom correspondence should be addressed; E-Mail: bharrison3@ucmerced.edu;
Tel.: +1-209-228-7674 ; Fax: +1-209-228-4158.

Abstract:

Water-supply forecasts on various watersheds are intended to predict the April through July (snowmelt) runoff and assist in estimating the total water-year runoff, and are thus very important to users of water from those watersheds. Water-supply outlooks, a type of forecast, are made on major contributing watersheds of the Colorado River. This study reviewed the skill level of April through July forecasts at 28 forecast points within the Colorado River basin. All the forecasts were made after 1950, with considerable variation in time period covered. Evaluations of the forecasts were made using summary measures, correlation measures and categorical measures. The summary measure, a skill score for mean absolute error, indicated a steady increase in forecast skill through the forecast season of January to May. The width of the distribution for each monthly forecast over the 28 locations remained similar through the forecast season. The two correlation measures, R^2 and Nash-Sutcliffe score showed similar results, with the Nash-Sutcliffe median showing a 0.4 increase from 0.4 to 0.8 during the forecast season. The categorical measures used a three section partition of the April through July runoff. The Probability of Detection for low and high flows shows an increase in skill from approx. 0.4 to 0.8 during the forecast season. The same score for mid flow years shows limited increase in skill. The False Alarm Rate illustrates the under forecast of high flow years. The Bias of the mid runoff forecasts indicated over forecast early in the forecast season (January to March), with higher skill later in the forecast season (April and May), ending the forecast season at 1.0. Forecasts for both low and high runoff were under forecast early in the season with a Bias near 0.5, improving to nearly 1.0 by the end of the forecast season. The Hit Rate measure illustrated the difficulty of mid flow forecasts, starting at 0.5 in January and increasing to 0.75 in May due to the forecasting assumption of normal climatology for the remaining forecast period.

Keywords: forecast; runoff; skill

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1. Introduction

The Colorado River basin in the western United States encompasses one-fifth the area of the continental United States over seven states, with an area of 627,000 km^2. Snowmelt runoff from the seasonally snow-covered mountains that comprise the headwaters of watersheds within the Colorado River basin provide water to a significant area of the southwestern United States. Water managers use seasonal water-supply outlooks, which are prepared monthly during the snow accumulation and ablation periods, to effectively plan and schedule water deliveries, reservoir releases and transfers within the basin. The forecasts are prepared jointly by the Natural Resources Conservation Service (NRCS) and the National Weather Service (NWS) (Pagano et al. 2004). The basis for the forecasts is mainly the relations between snow conditions, precipitation and discharge, primarily naturalized flow in past years. This information on snowpack, and precipitation and hydrologic conditions is used to make statistical forecasts of runoff volume past the forecast point for a specified period of time. These water-supply outlooks have been prepared on some Colorado River watersheds since the 1950's. In much of the basin, the outlooks are issued from January to May and are intended to forecast runoff in the April through July period (Stacie Bender personal communication, 7 May 2013).

In addition to the water supply outlooks for the Colorado River Basin, water supply forecasts are also made on other watersheds in the western United States, including locations in California. Evaluations of the skill of these various forecasts have been made since the late 1950's on various subsets of the forecasts in the western United States. In 1958, one of the earliest comprehensive studies of forecast skill was prepared by Work and Beaumont (1958). They compared the forecast skill of NRCS and NWS forecasts and found that using snow survey data had some advantages over using precipitation when preparing forecasts. The next year Kohler (1959) produced an analysis favoring the use of precipitation. Following that work, Shafer and Huddleston (1984) reviewed historical seasonal volume forecasts based on regression techniques and found a small improvement in forecasting skill in recent years but cautioned that large improvements in skill are not to be expected in the future by refining regression techniques. Schaake and Peck (1985) partitioned error in water supply forecasts into three parts. They proposed that errors and uncertainty in forecasting arose from unknown future precipitation and temperature, data errors and uncertainty arose from difficulties in measuring inputs and outputs of the models, and errors in the models themselves produce forecast errors. They also presented analysis techniques to quantify those errors and uncertainty. Also Dracup et al. (1985) examined the accuracy of hydrologic forecasts on the Colorado River in the states of Arizona, Utah and Colorado by calculating and comparing various correlation coefficients and coefficients of prediction. They found trends in the accuracy of forecasts that were attributed to the amount of precipitation and the proportion of precipitation that was snow at the forecast location.

Again there was an absence of skill assessments until Hartmann et al. (2002) performed a regional assessment of hydrologic forecasts emphasizing the Colorado River Basin. One recommendation of the study was to make performance evaluations publicly available. Franz et al. (2003) evaluated the forecasts at 14 sites on the Colorado River and determined that the Ensemble Streamflow Prediction (ESP) system, developed by the National Weather Service (NWS), performed better than climatology forecasts.

Pagano et al. (2004) evaluated forecasts on 29 unregulated rivers in the western United States. The report also presented a historical review of skill assessment reports for water supply forecasts. Pagano found high skill for forecasts issued on 1 April. Forecasts made earlier in the season contained more uncertainty but were shown to still be skillful. Pagano also found that areas with wet winters and dry springs presented higher forecast improvement over the forecast season than areas with dry winters and wet springs. Pagano also found mixed changes in skill over time when comparing different areas of the study. Pagano noted that one challenge in forecast evaluation was to normalize forecast errors to allow a fair comparison between small streams and larger rivers. Pagano and his co-authors have stated that it is desirable that the evaluation measures be chosen carefully so they are understandable and relevant to forecast users.

Hartmann et al. (2006) and others performed an assessment of water-supply outlooks in the Colorado River basin, which established a baseline for identifying improvements in hydrologic forecasts. In a following working paper, Morrill et al. (2007) prepared an assessment of the strengths and weaknesses of seasonal water supply outlooks at fifty-four sites in the Colorado River basin using an assortment of skill measures. These measures included traditional scalar measures (e.g., correlation, root-mean square error and bias) and categorical measures (e.g., false alarm rate, threat score). They found that the examined water supply outlooks were an improvement over using average climatology. They also found that most of the forecasts were conservative, with above-average flows under predicted and below-average flows over predicted.

The questions addressed in this research are first, what is the skill of runoff forecasts in the Colorado River Basin using summary, correlation and categorical measures; and how do the various skill measures compare? Third, what measures are sensitive to the different input conditions, and what improvement in skill may be possible?

2. Methods and Data

2.1 Skill Measures

We introduce summary and correlation (Table 1) and categorical measures (Tables 2 and 3) of the skill of runoff forecasts. Summary measures indicate the error in forecasts as an arithmetic difference between the forecast and the observation. The Mean Absolute Error (MAE) has dimensions and depend on the magnitude of the runoff. For the current analysis we use a skill score (SS), i.e. normalizing by the difference of each observation from the mean (Table 1). A zero skill score indicates no skill over using the historical average observation as the forecast, a negative value indicates that using the average would be better than using the forecast, and a skill score of 1 indicates perfect skill (no error in the forecast).

For a correlation measure, we used the Nash-Sutcliffe score (NS). The Nash-Sutcliffe score is one minus the ratio of the variance of the forecasts about the observation divided by the variance of the observations about their mean. As with SS, a zero NS score indicates no skill over using the average, a negative value indicates that using the average would be better than using the forecast, and a skill score of 1 indicates perfect skill (no error in the forecast). As the NS score is normalized by a variance, it is dimensionless. It is also possible to use the coefficient of determination (R^2) but it was not used in the analysis as it is similar to the NS and shows the same response (not shown),

Categorical measures indicate the skill of the forecast in predicting the magnitude category of the runoff, in this case low, middle and high total-runoff categories. For example, if the forecast was for flows assigned to the low-flow category, did the low flow actually occur? Historical runoff records for each forecast point were divided into 3 runoff categories, the lower 30%, the mid 40% and highest 30% of flows. A 2 ×2 contingency table was used to count the results of forecasts versus observations in each category (Table 2) (Wilks, 2011). Five categorical measures were assessed (Table 3).

The Probability of Detection (POD) is intuitive, being the proportion of times the event was forecast compared to the times it occurred. The False Alarm Rate (FAR) is the proportion of forecast events that failed to occur to all forecasts; and has a negative orientation, ranging from zero (perfect) to 1.0 (poor). The Bias indicates if category is over forecast (>1) or under forecast (<1). The Threat Score (TS), also known as the Critical Success Index, is similar to the HR, except that it is only for yes forecasts, i.e. the “no” forecasts are not included. The Hit Rate (HR) is intuitive, in that it credits correct “yes” and “no” forecasts equally. The POD, TS and HR all range from zero (poor) to 1.0 (perfect).

2.2. Source of Data

Forecast and observation data for twenty-eight locations that currently forecast April to July runoff were obtained from the Colorado Basin River Forecast Center (Stacie Bender personal communication, 25 May 2013). The April through July forecast period was chosen because of the large amount of runoff during that time. Hydrologic information such as gage elevation, watershed area and map coordinates for each forecast point was obtained from the USGS NWIS system (USGS 2014). All the forecasts were made after 1950, and the record usually extended to 2012 but there was considerable variation in time period covered. The forecasts examined in this study were made monthly from January to May and were an estimate of the water volume to pass the forecast point during the forecast period. The actual forecast period at the various forecast locations showed considerable variation over the historical record. Many of the early forecasts were based on a forecast period from April through September. In the 1960’s, forecasts were made with the beginning of the forecast period corresponding with the month of forecast. In other words, a March forecast would be March through September, and an April forecast would be April through September. Since the 1980’s, most forecasts use an April through July forecast period, which corresponds with the April through July forecast period in the western Sierra Nevada of California. Data used in this study included the forecast period (for example April through July), month of forecast (January, February, March, April or May for this study), forecast flow in thousand acre feet (taf) and observed flow (taf)

The twenty–eight forecast locations are shown in Figure 1 along with state boundaries, a graphic delineation of watershed hydrology showing HUC designations, and a graphic representation of topography. Details of the forecast points are shown in Table 4. Observed flows are flows that can be directly observed and are generally found in headwater basins with very few diversions and no large reservoirs that impact the natural flow (Stacie Bender personal communication, 25 May 2013). Naturalized flows are calculated to estimate the unregulated flow at the measurement point, with allowance for diversions and/or reservoirs in the contributing watershed. Once the raw data for the 28 points were tabulated and checked for consistency, the data were analyzed and skill measures calculated for the forecasts.

3. Results

3.1 Watershed characteristics

The elevation histogram along with the median watershed elevation is shown in Figure 2 and ranges from 1984 m to 3364 m. The highest watershed was #10 - Blue River inflow to Dillon Reservoir, CO. at 3364 m. The lowest watershed was #1 – Virgin River at Virgin, UT at 1984 m. The largest watershed which also had the highest flow was #19 – Lake Powell at Glen Canyon Dam with an area of 289303 km^2, and average April to July flow of 8820 million m^3. The smallest watershed, which also had the smallest flow, was #15 – Ashley Creek near Vernal, UT with an area of 262 km^2, and an average flow of 61.4 million m^3.

In Figure 3, the mean precipitation for the Colorado River basin locations ranges from about 400 mm per year to about 900 mm per year. The interannual variability of water-year runoff and precipitation is shown in Figure 4. It is apparent that runoff has a higher variability than does precipitation. In Figure 5a, the increasing precipitation of the watershed is followed by the increasing water year runoff, with larger variability in the runoff also as seen in the previous figure. Figure 5b shows the precipitation along with the difference between precipitation and discharge which is mostly evapotranspiration. The evapotranspiration is fairly constant across the various locations, and is not correlated with elevation. In Figure 5c, the specific yield of water year runoff is shown. Specific yield is the fraction of precipitation expressed as the water year runoff. The specific yield appears quite uniform except for the driest watersheds. In Figure 6a, the watershed precipitation is shown to be correlated with median watershed elevation. In Figure 6b, the water year runoff is shown to be correlated with median elevation. This is a result of the fairly constant evapotranspiration amount removed from the precipitation, resulting in slightly increasing runoff.

3.2 Forecast skill - summary and correlation measures

The summary measure Skill Score for Mean Absolute Error (SSMAE) was computed for each of the five forecast months, January to May, for each of the 28 forecast locations. Boxplots of the skill scores are shown in Figure 7a. The forecast skill in January is quite low, with the SSMAE below 0.3 but with a tight distribution, as this early in the forecast season the forecasts are made using average climatology. The forecasts in February contain additional winter-storm information and thus have higher skill but a wider distribution. The figure indicates that the runoff forecast skill increases from the start to end of the forecast period, with the Skill Score in March around 0.4, 0.5 in April, and ending the forecasts season in May with a Skill Score of approximately 0.6. The distribution widens more in March with no increase in skill. The width of the distribution in May remains wide when compared to the width of the forecast distribution in other months, in spite of the availability of additional climatology. There are several outliers for each month of the forecast season.

The correlation measure computed for the forecasts was the Nash-Sutcliff score. The distributions of NS for the five forecast months at the 28 forecast locations are shown in Figure 7b. The median January NS starts at 0.4 and steadily increases to 0.8 for the median in May. The width of the distribution increases remains steady through the forecast season with the increasing information available from March to May. The increase in skill as the forecast season progresses is clearly shown, but no change in distribution width is apparent. Outliers are present for all forecast months. In Figure 8, a histogram of the NS for April is shown. It suggests that the NS scores are distributed with a central tendency but not in a normal distribution.

3.3 Forecast skill - categorical measures

The April-July runoff was categorized into low runoff years (0 to 0.3), mid runoff years (>0.3 to 0.7 and high runoff years (> 0.7), expressed as a fraction of the mean runoff for the period of record. The five categorical measures were calculated at each location for each of the three runoff categories. The first categorical measure is the Probability of Detection (POD) shown in Figure 9a. Mid runoff years show limited change in POD during the forecast season with the low and high runoff years showing some improvement during the season. The median April POD for all three categories is above 0.7, but several sites still have values below 0.5.

The False Alarm Rate (FAR) shown in Figure 9b reinforces the difficulty of forecasting mid-flow years, as each year looks mid-flow early in the forecast season. Both the low and mid runoff years have a fairly high FAR early in the season, with the FAR dropping below 0.3 by the end of the season, but above 0.4 for mid flows in April. Interestingly, the high flow FAR remains consistently low through the forecast season, potentially reflecting the lack of information and thus the reluctance of forecasting a “false alarm” for high runoff years.

The Bias shown (Figure 9c) illustrates the effect of increasing knowledge through the forecast season. The Bias results show under forecast of both low- and high-flow years early in the forecast season, with a movement to little or no Bias by April. The Bias results show the over-forecast of mid runoff years early in the season as average climatology is assumed for the remainder of the forecast season. The mid flow forecasts also end the season with little or no bias. The Bias scores for the high runoff years show slight improvement through the forecast season, but remain under forecast even in April and May.

The Threat Score (TS) is shown in Figure 9d. The TS scores in January for low runoff years start lower (0.25) than for mid (0.4) or high runoff years (0.35). The TS also rises rapidly through the season, with the mid-runoff years remaining less skillful than the low- or high-runoff years. This reflects the TS as solely a measure of correct forecasts.

The January Hit Rate (HR) (Figure 9e) starts higher in low runoff years (0.7) and high runoff years (0.75) than the January score for mid flow years (0.55). The HR increases through the forecast season and for the April forecasts the HR is 0.8 for low and high flows, but for mid flow years is approximately 0.65. The slightly lower scores for mid flow years may reflect the occurrence of low or high flows for the season even if average flows occur during the early part of the forecast season. Note that HR values for low- and mid-flow years are higher than for the TS, reflecting its use as an index of both correct forecasts and non-forecasts.

4. Discussion

The results of the study indicate that the various measures of forecast skill can give similar relative results in specific situations. The use of multiple skill measures enables certain measures to illustrate trends not highlighted by other measures. All measures during the forecast period show an increased in skill as more information becomes available. One of the measures, the SSMAE analysis, has the resolution necessary to pick up a widening distribution of forecast skill early in the forecast season through March. This trend may be related to the increase in difference between field conditions at the various forecast locations that can't be described by the limited increase in knowledge of monitored conditions at the forecast points.

No significant relationship was seen between watershed median elevation and increasing forecast skill, represented by April NS (Figure 10) or the categorical measures (not shown). This may be an indication that the Colorado watersheds may be similar in snow domination due to their sufficiently high elevation above the rain/snow transition during major storms to experience precipitation mainly as snow. Thus it is variable precipitation amounts across this large basin, with storms from different origins and paths, rather than rain versus snow storms that affects skill.

Of the categorical measures, POD and FAR are the simplest mathematically and conceptually straightforward. BIAS is correlated with POD for the high-flow category, suggesting that non-correct high-flow forecasts are not that important (Figure 11). However, the lack of correlation between BIAS and POD for mid-flows reflects the high number of incorrect mid-flow forecasts for April. The lower importance of incorrect high-flow forecasts is also reflected in the similar correlation between TS and POD, as between BIAS and POD. Note that TS differs from POD by including incorrect forecasts in the denominator. The higher correlations between TS and POD for high and mid flows, versus the correlations for BIAS and POD, also reflect the addition of incorrect forecasts. But in the case of TS, the incorrect forecasts are in the denominator, resulting in lower TS versus POD values. Note that slopes of the TS and POD correlations are near 1.0 for all flows. This is also shown in the high correlation between TS and FAR for low and mid flows. HR differs from TS by including correct non-forecasts in both the numerator and denominator. The HR values vary less than POD values, illustrating the effect of correct non-forecasts. Note also a very high correlation between HR and FAR for all categories, because of the influence of correct non-forecasts.

Comparisons between the two types of flow conditions in the Colorado Basin, observed flow and the naturalized flow, are shown in Table 5. On the Colorado River, 9 of the 28 points were locations with forecasts of observed flow. The remaining 19 points were locations with forecasts of naturalized flow. As expected, the locations with observed flow were on small, high-elevation watersheds with limited runoff. In Table 6, the mean NS score for the two types of watersheds in the Colorado River basin are listed for the five month of forecasts. It is interesting to note that the forecast skill at the start and end of the season is approximately the same for the two very different flow types, but the mid-period forecasts (February to April) appear more skillful for the observed flow locations. This result probably reflects the complicating effects of diversions and storage on flow measurements during the late winter and early spring high runoff periods.

5. Conclusions

The summary and correlation skill measures such as SSMAE and NS can appraise forecast skill over seasonal time periods as forecast skill improves during the yearly forecast period. The use of both measures increases the probability that the skill measures may have the resolution necessary to capture the increased forecast uncertainty early in the forecast season. The categorical skill measures can appraise forecast skill for three different flow scenarios and show changes over a forecast period. Measurements such as the FAR clearly show a tendency to under forecast high flows.

Various changing climate scenarios present the possibility of an increase in temperature. As a result, users of water supply forecasts may consider use of forecasting tools and data that are based on principles of mass balance and on the spatially distributed data needed to drive the models. Although current modeling tools are sufficiently flexible to incorporate immediate and larger future changes in climate that are outside the current stationarity assumption, data for those models are largely lacking. One other effect of changing climate is projected to be an increase in the amount of total precipitation falling as rain, emphasizing the potential of distributed, representative rainfall, as well as snowfall measurements to enhance forecasts. Future increases in skill level could be enabled by incorporating snow cover data estimated by remote sensing blended with representative ground measurements into the forecasting process. Increased forecast skill earlier in the water year, if new measurements can facilitate that, can provide significant economic benefits to water users, and introduce flexibility and resiliency into water-management decisions.

Acknowledgments

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Table 1. Summary and correlation measures of forecast skill

Skill measure	**Equation**[a]
Mean Absolute Error (MAE)	MAE= $\frac{\sum\lvert f_i - o_i\rvert}{n}$
Mean Square Error (MSE)	$\text{MSE} = \frac{\sum(f_i - o_i)^2}{n}$
MAE skill score	SS_{MAE} = 1-MAE/MAE$_{\text{cl}}$, where MAE$_{\text{cl}}$= $\frac{\sum\lvert\bar{o} - o_i\rvert}{n}$
MSE skill score[b]	SS_{MAE} = 1-MSE/MSE$_{\text{cl}}$ where MSE$_{\text{cl}}$ = $\frac{\sum(\bar{o} - o_i)^2}{n}$

[a] Variables: o_i is the observation, $\bar{o}$ is the mean of the observations, f_i is the forecast, $\bar{f}$ is the mean of the forecasts
n is the number of observations

[b] Equivalent to Nash-Sutcliffe (NS) score

Table 2. Variables for 2 x 2 contingency table

	Observed	**Not observed**
Forecast	a	b
Not forecast	c	d

Table 3. Categorical measures

Measure	**Explanation**	**Equation**	**Range**
Probability of Detection (POD)	Correct forecasts divided by observations	a/(a+c)	0-1 (perfect)
False Alarm Rate (FAR)	Incorrect forecasts divided by forecasts	b/(a+b)	1-0 (perfect)
Bias	Correct and non-correct forecasts divided by observations	(a+b)/(a+c)	>1 over; and <1 under forecast
Threat Score or Critical Success Index (TS)	Correct forecasts divided by the forecasts plus non-forecast observations	a/(a+b+c)	0-1 (perfect)
Hit Rate (HR)	Correct forecasts and correct non-forecasts, divided by total forecasts and observations	(a+d)/(a+b+c+d)	0-1 (perfect)

Table 4a. Forecast point locational information

No.	Location	NWS	USGS	Lat.	Long.
1	Virgin River at Virgin, UT	VIRU1	9406000	37.204	113.180
2	Colorado River below Lake Granby, CO	GBYC2	9019000	40.140	105.835
3	Eagle River below Gypsum, CO	GPSC2	9070000	39.649	106.953
4	Green River at Warren Bridge, near Daniel, WY	WBRW4	9188500	43.019	110.119
5	East River at Almont, CO	ALEC2	9112500	38.664	106.848
6	Gunnison River inflow to Blue Mesa Reservoir	BMDC2	9124800	38.451	107.332
7	Colorado River near Cameo, CO	CAMC2	9095500	39.239	108.266
8	Uncompahgre River at Colona, CO	CLOC2	9147500	38.331	107.779
9	Colorado River near Cisco, UT	CLRU1	9180500	38.811	109.293
10	Blue River inflow to Dillon Reservoir, CO	DIRC2	9050700	39.626	106.066
11	Dolores River at Dolores, CO	DOLC2	9166500	37.473	108.497
12	Gunnison River near Grand Junction, CO	GINC2	9152500	38.983	108.450
13	Blue River inflow to Green Mountain Reservoir, CO	GMRC2	9057500	39.880	106.333
14	Roaring Fork at Glenwood Springs, CO	GWSC2	9085000	39.544	107.329
15	Ashley Creek near Vernal, UT	ASHU1	9266500	40.578	109.621
16	San Juan River near Bluff, UT	BFFU1	9379500	37.147	109.864
17	New Fork River near Big Piney, WY	BPNW4	9205000	42.567	109.929
18	Animas River at Durango, CO	DRGC2	9361500	37.279	107.880
19	Lake Powell at Glen Canyon Dam, AZ	GLDA3	9379900	36.937	111.483
20	Green River at Green River, UT	GRVU1	9315000	38.986	110.151
21	Yampa River near Maybell, CO	MBLC2	9251000	40.503	108.033
22	Piedra River near Arboles, CO	PIDC2	9349800	37.088	107.397
23	Rock Creek near Mtn Home, UT	ROKU1	9279000	40.493	110.578
24	Strawberry River near Duchesne, UT	STAU1	9288180	40.155	110.554

25	Yampa River at Steamboat Springs, CO	STMC2	9239500	40.484	106.832
26	Duchesne River near Tabiona, UT	TADU1	9277500	40.300	110.602
27	White River near Meeker, CO	WRMC2	9304500	40.034	107.862
28	Whiterocks River near Whiterocks, UT	WTRU1	9299500	40.594	109.932

Table 4b. Forecast basin hydrological information

No.	Location	Runoff Records	Runoff Type	Median Elev., m	Area, km^2	April-July runoff, million m^3
1	Virgin River at Virgin, UT	1958-2012	O	1984	2476	71.6
2	Colorado River below Lake Granby, CO	1954-2013	N	3120	808	272.5
3	Eagle River below Gypsum, CO	1975-2012	N	2971	2445	414.2
4	Green River at Warren Bridge, near Daniel, WY	1958-2012	O	2768	1212	299.4
5	East River at Almont, CO	1957-2012	N	3135	749	224.8
6	Gunnison River inflow to Blue Mesa Reservoir	1972-2012	N	3023	9091	833.5
7	Colorado River near Cameo, CO	1957-2012	N	2776	20850	2906.2
8	Uncompahgre River at Colona, CO	1954-2012	N	2807	1160	168.3
9	Colorado River near Cisco, UT	1957-2012	N	2636	62419	5475.0
10	Blue River inflow to Dillon Reservoir, CO	1972-2012	N	3364	868	200.4
11	Dolores River at Dolores, CO	1954-2012	O	2984	1305	304.1
12	Gunnison River near Grand Junction, CO	1954-2012	N	2783	20534	1821.9
13	Blue River inflow to Green Mountain Reservoir, CO	1954-2012	N	3260	1551	339.1
14	Roaring Fork at Glenwood Springs, CO	1954-2012	N	3026	3763	853.2
15	Ashley Creek near Vernal, UT	1954-2012	O	2746	262	61.4
16	San Juan River near Bluff, UT	1957-2012	N	1985	59570	1350.1
17	New Fork River near Big Piney, WY	1975-2012	O	2452	3186	437.7
18	Animas River at Durango, CO	1954-2012	O	3167	1792	514.2
19	Lake Powell at Glen Canyon Dam, AZ	1964-2012	N	2135	289303	8822.1
20	Green River at Green River, UT	1957-2012	N	2135	116162	3649.7
21	Yampa River near Maybell, CO	1957-2012	N	2316	8832	1154.1
22	Piedra River near Arboles, CO	1972-2012	O	2604	1629	257.7
23	Rock Creek near Mtn Home, UT	1965-2012	N	3121	381	109.0
24	Strawberry River near	1954-2012	N	2435	2375	154.1

	Duchesne, UT					
25	Yampa River at Steamboat Springs, CO	1954-2012	N	2695	1471	318.2
26	Duchesne River near Tabiona, UT	1954-2012	N	2707	914	133.0
27	White River near Meeker, CO	1954-2012	O	2763	1955	342.9
28	Whiterocks River near Whiterocks, UT	1954-2012	O	3194	282	66.6

O = observed

N = naturalized

Table 5: Type of forecast locations

	No of Points	Mean Elev. m	Mean Discharge million m^3	Mean Area km^2
Naturalized	19	1852	1540	33470
Observed	9	1933	261	1567

Table 6: Type of forecasting location and NS score

	NS Score				
	Jan	Feb	Mar	Apr	May
Naturalized	0.37	0.47	0.49	0.59	0.74
Observed	0.39	0.51	0.57	0.67	0.78

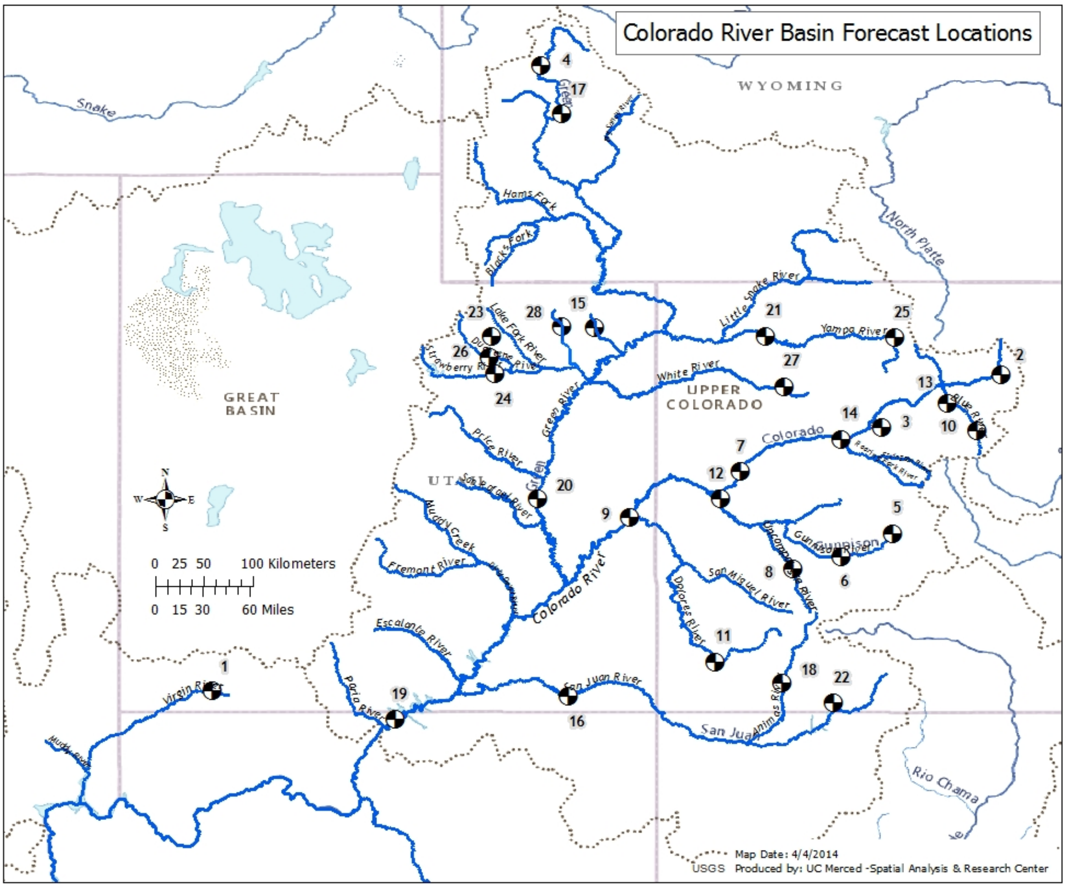

Figure 1: Map of the forecast points in the Colorado River basin

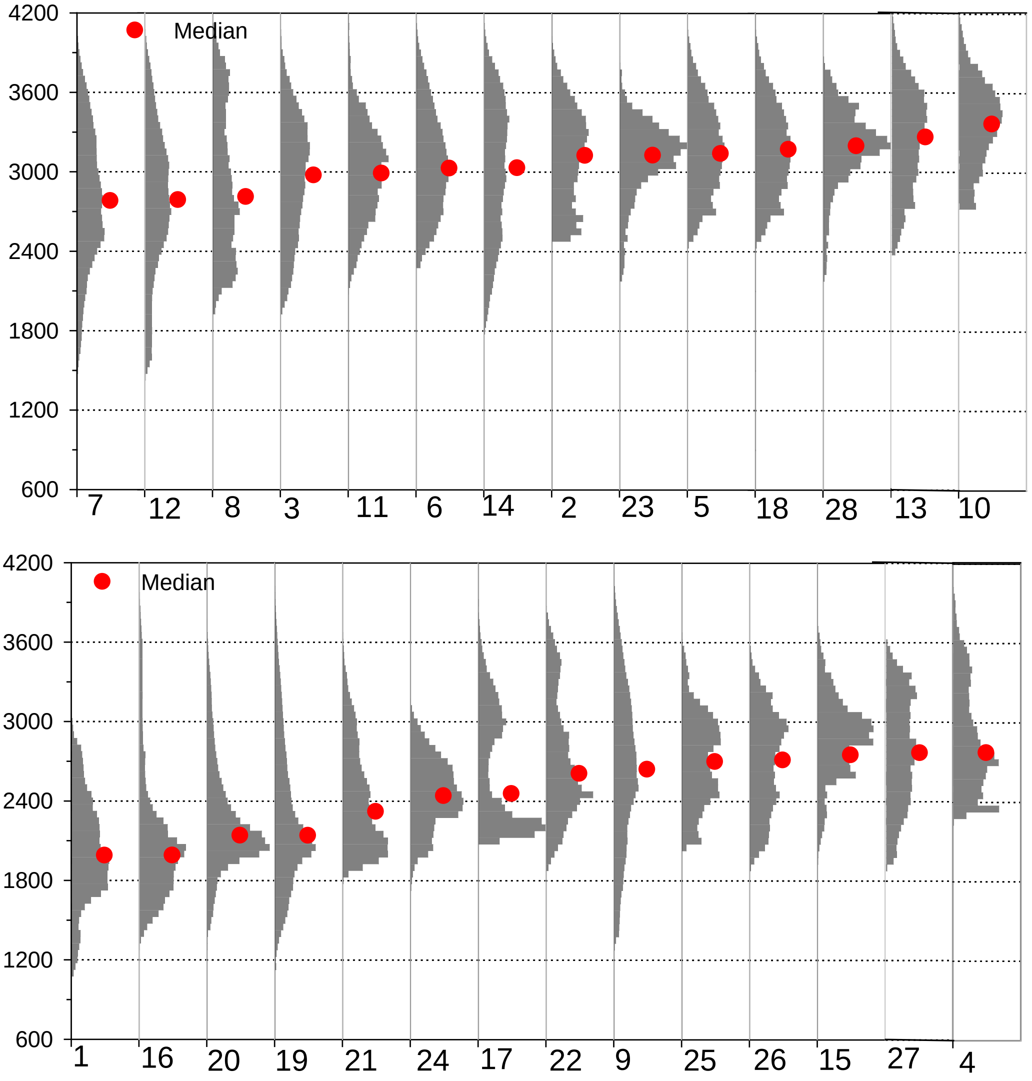

Figure 2: Elevation histogram and median elevation for the 28 watersheds, sorted by elevation. Forecast location on abscissa (Table 4).

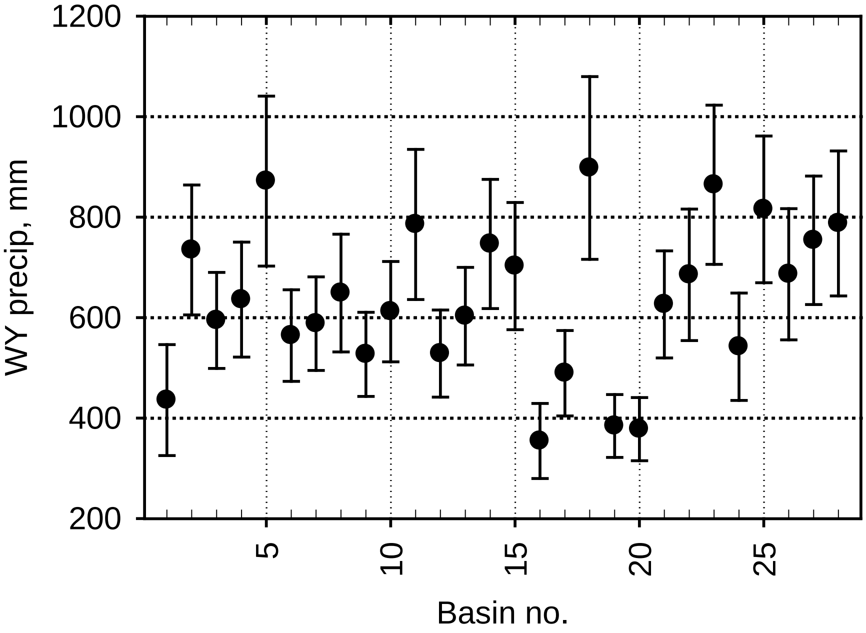

Figure 3: Mean annual precipitation for 28 Colorado River basin watersheds +/- one standard deviation (PRISM data)

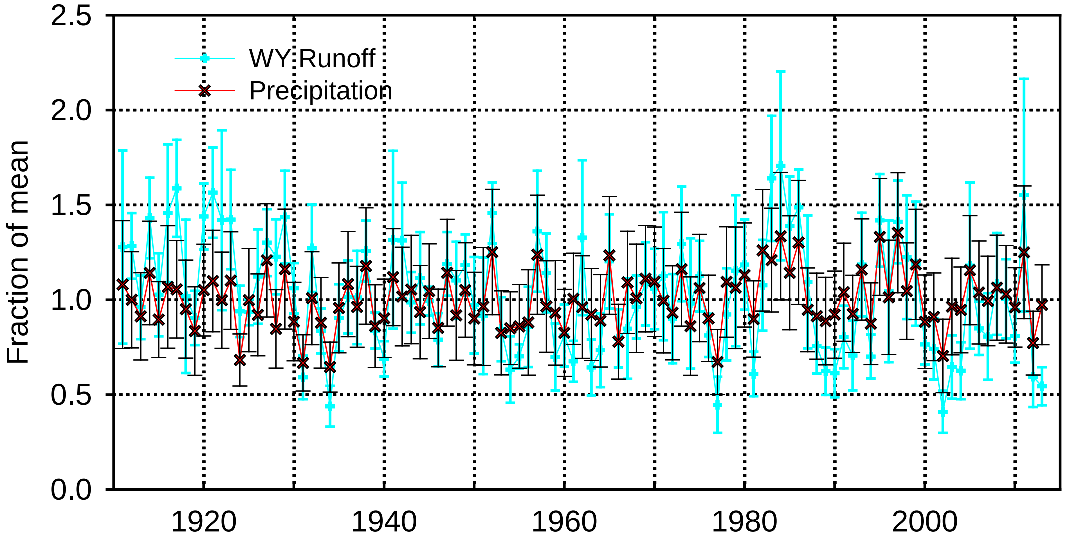

Figure 4: Fraction of mean water year runoff and precipitation across all basins. Error bars are +/- 1 standard deviation for both plots.

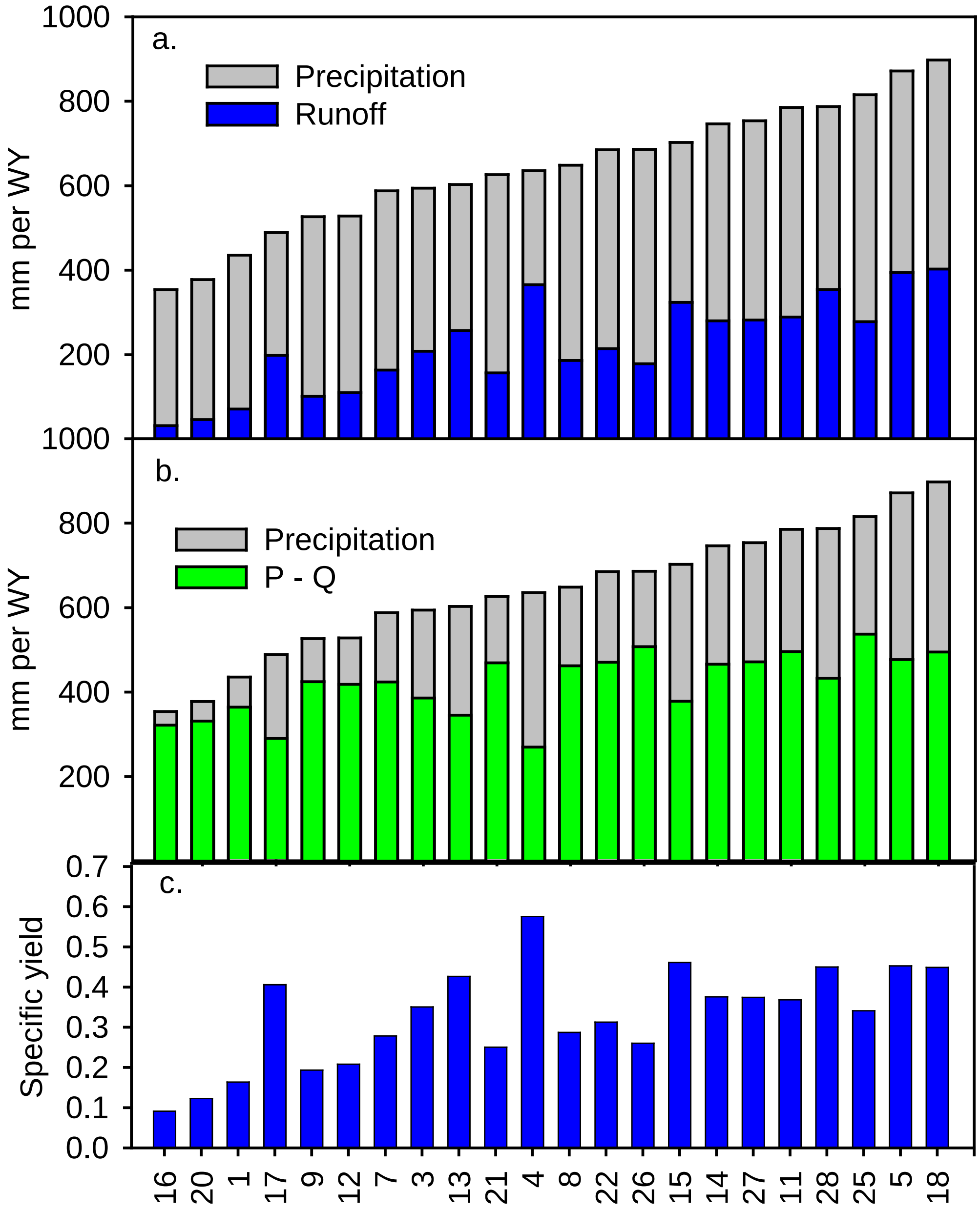

Figure 5: a. Mean water year precipitation and runoff' b. Mean water year precipitation and mean precipitation – mean water year runoff. c. Water year specific yield. All plotted by increasing precipitation with the basin indicated on the abscissa (Table 4). Six basins, not shown, had missing or inconsistent water year data in the NWIS database (2, 6, 10, 19, 23, 24).

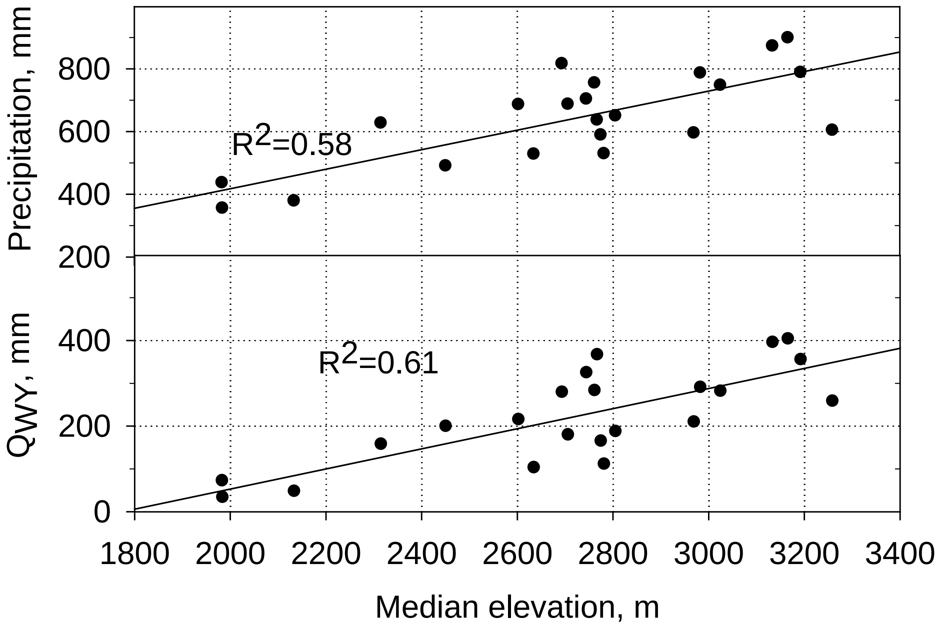

Figure 6: a. Water year precipitation vs. watershed median elevation
b. Water year runoff vs. watershed median elevation.

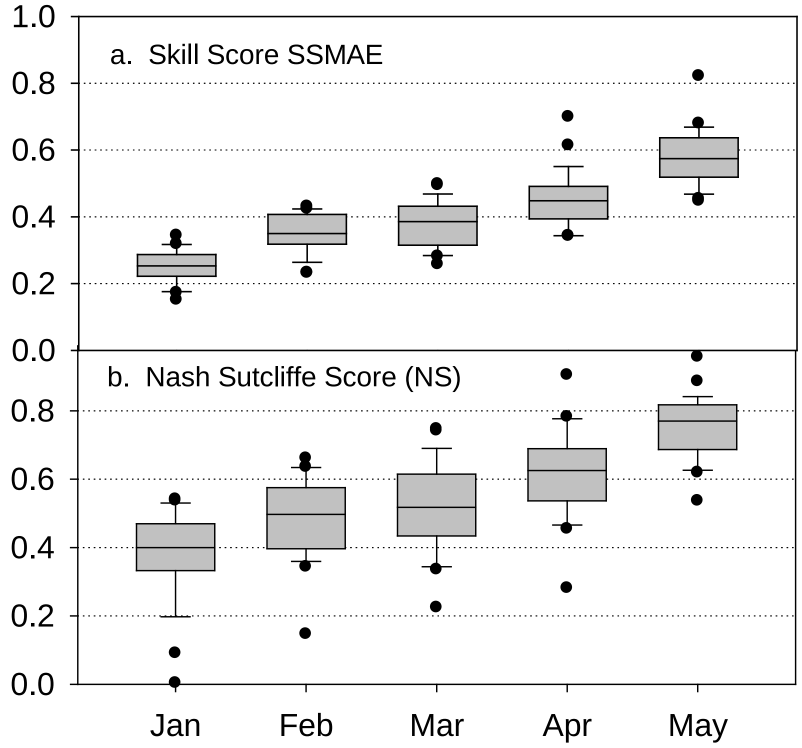

Figure 7: The skill scores for the Colorado River locations. a. SSMAE. b. NS score. The horizontal line within each box is the median of the 28 skill scores, with the box containing 25% to 75% of the scores. The two bars outside are 10% to 90% with the remaining points of the distribution shown as outliers.

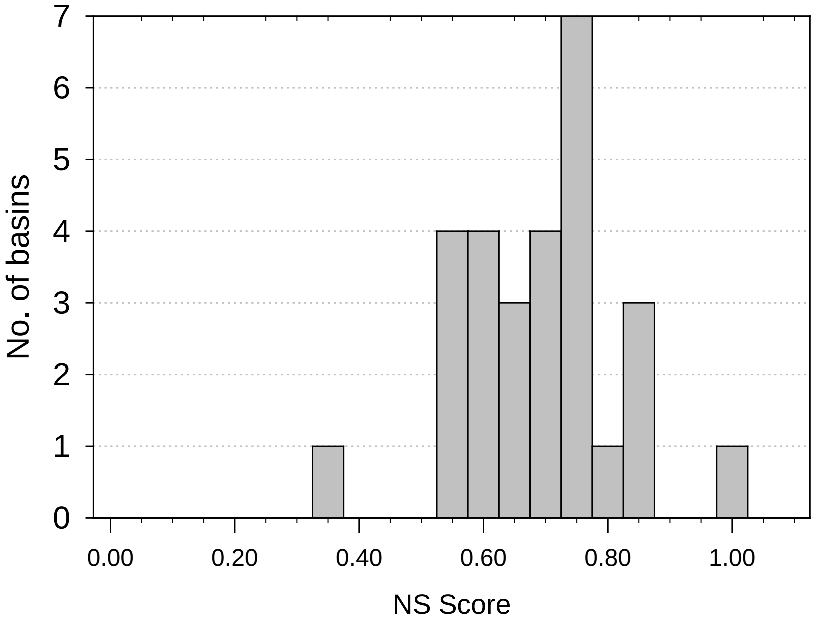

Figure 8: NS score distribution for April

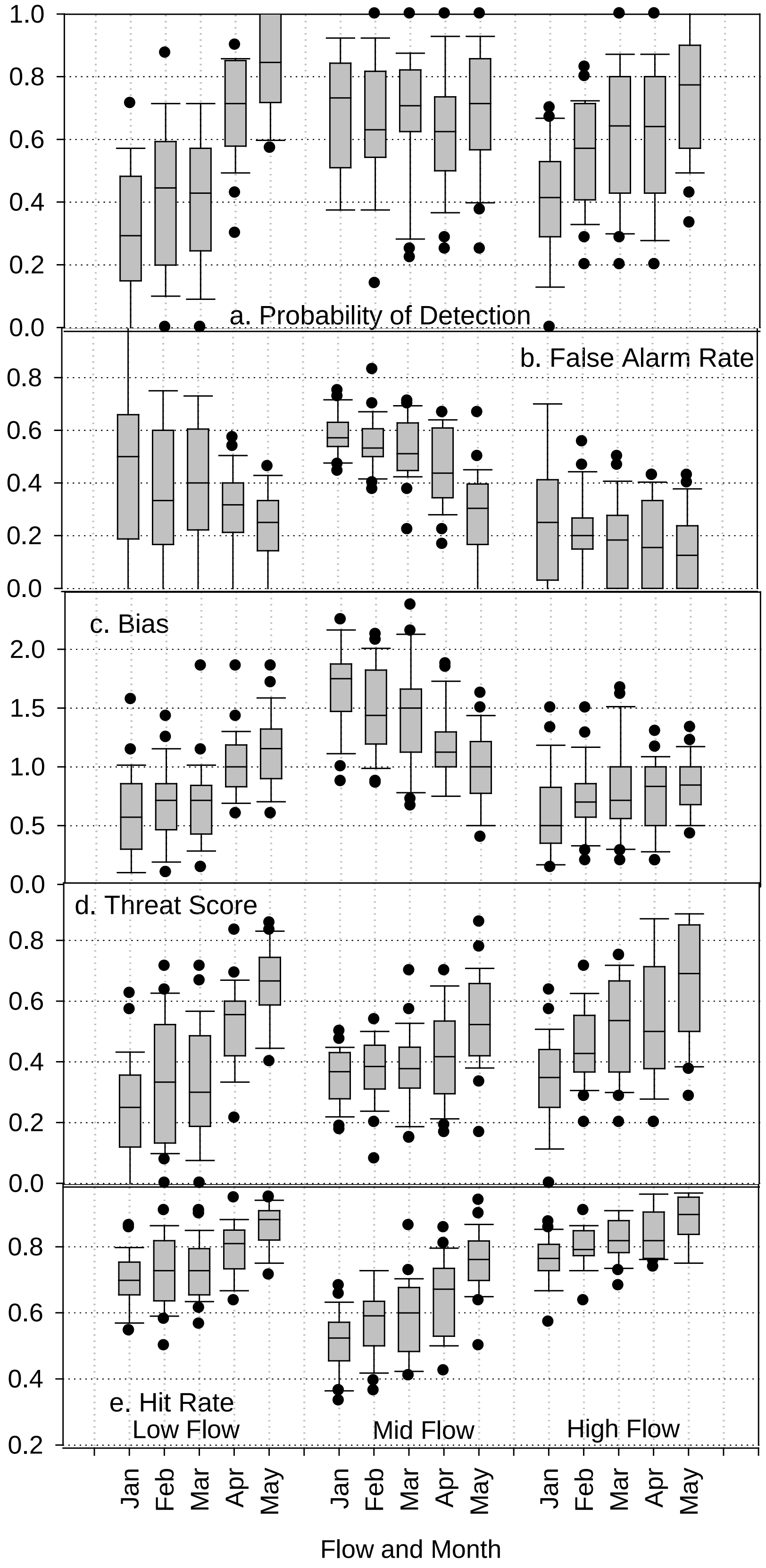

Figure 9: Categorical skill measures for Colorado River basin

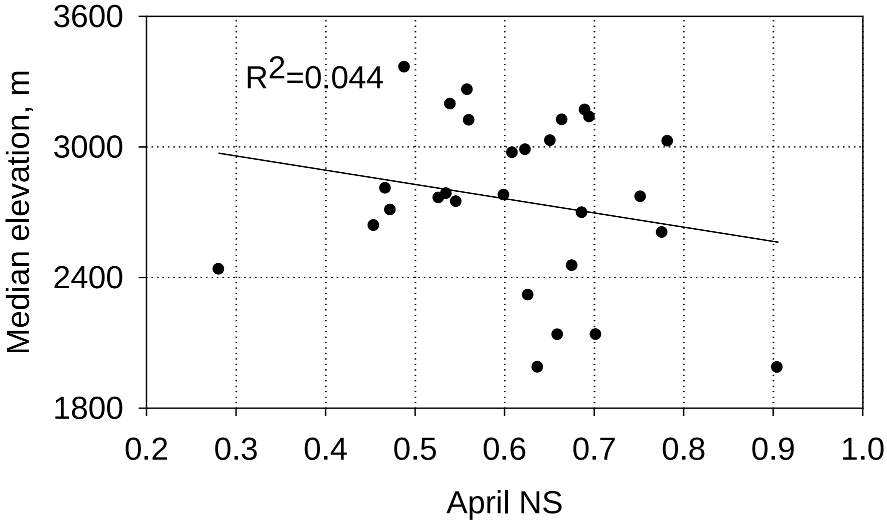

Figure 10: Relationship between April 1 NS and watershed median elevation

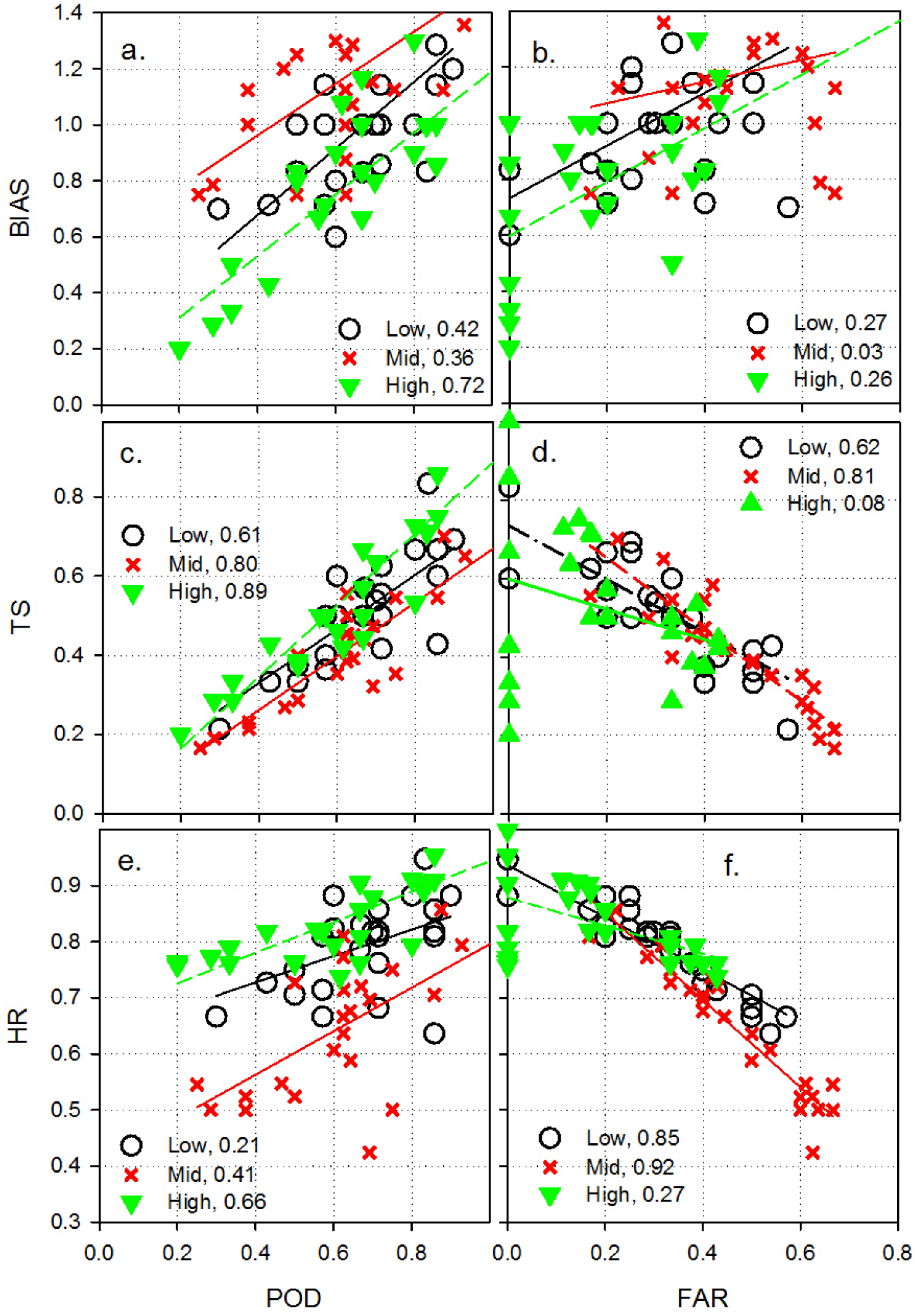

Figure 11. Correlation between categorical measures. Values in legend of each panel are R^2.

CHAPTER 4

PERCENT BIAS ASSESSMENT OF WATER-SUPPLY OUTLOOKS IN THE COLORADO RIVER BASIN

Brent Harrison[1] and Roger Bales[2]

ABSTRACT

Water-supply forecasts on various watersheds are intended to predict the April through July (snowmelt) runoff and assist in estimating the total water-year runoff, and are thus are very important to users of water from those watersheds. Water-supply outlooks, a type of forecast, are made on major contributing watersheds of the Colorado River. This study reviewed the characteristics of twenty-eight watersheds on the Colorado River. During that review, a strong linear relationship was found between watershed elevation and yield. As elevation increased, the runoff yield increased in a linear fashion. When studying the relationship between runoff and area, it was found that there was a non-linear relationship between increasing area and increasing runoff. The skill level of April to July forecasts was examined using percent bias as a representative summary measure of forecast skill. Review of percent bias of forecasts during dry, near normal and wet years indicates that in dry years the forecasts have a positive bias while those in wet years have a negative bias. Forecasts for near normal runoff years show limited or no bias toward over or under prediction. Seventy percent of the values for the absolute value of percent bias for individual forecasts were 40 percent or less. (KEYWORDS: water; forecast; runoff; skill)

INTRODUCTION

The Colorado River basin in the western United States encompasses one-fifth the area of the continental United States over seven states, with an area of 242,000 square miles. Snowmelt runoff from the seasonally snow-covered mountains that comprise the headwaters of watersheds within the Colorado River basin provide water to a significant area of the southwestern United States. Water managers use seasonal water-supply outlooks, which are prepared monthly during the snow accumulation and ablation periods to effectively plan and schedule water deliveries, releases and transfers within the basin. The forecasts are prepared jointly by the Natural Resources Conservation Service (NRCS) and the National Weather Service (NWS) (Pagano et al. 2004). The basis for the forecasts is mainly the relations between snow conditions, precipitation and discharge, primarily naturalized flow in past years. These predictions use primarily information on snowpack, and precipitation and hydrologic conditions to make statistical forecasts of runoff volume past the forecast point for a specified period of time. These water-supply outlooks have been prepared on some Colorado River watersheds since the 1950's. In much of the basin, the outlooks are issued from January to May and are intended to forecast runoff in the April through July period (CBRFC 2013). The investigation of the skill of water-supply forecasts in the Colorado River basin reported here assesses patterns across the basin and identifies characteristics of forecast points with different skill levels.

Evaluations of forecast skill

In addition to the water-supply outlooks for the Colorado River Basin, water-supply forecasts are also made on other watersheds in the western United States, including locations in California. Evaluations of the skill of these various forecasts were made in the late 1950's on various subsets of these forecasts. Additional work to evaluate forecast skill was done again in the mid 1980's. Starting in 2002, the latest work was initiated to evaluate the skill of water-supply forecasts in the western United States.

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[1] Brent Harrison, Sierra Nevada Research Institute, University of California Merced, 5200 N. Lake Rd., Merced CA, 95343, bharrison3@ucmerced.edu

[2] Roger Bales, Sierra Nevada Research Institute, University of California Merced, 5200 N. Lake Rd., Merced CA, 95343, rbales@ucmerced.edu

In 2004, Pagano evaluated forecasts using Nash-Sutcliffe scores and other measures on 29 unregulated rivers in the western United States (Pagano et al. 2004). The report also presented a historical review of skill assessment reports for water-supply forecasts. Pagano found high skill for forecasts issued on 1 April. Forecasts made earlier in the season contained more uncertainty but were shown to still be skillful. Pagano also found that areas with wet winters and dry springs presented higher forecast improvement over the forecast season than areas with dry winters and wet springs. Pagano also found mixed changes in skill over time when comparing different areas of the study. In 2006, Hartmann and others performed an assessment of water-supply outlooks in the Colorado River Basin which established a baseline for identifying improvements in hydrologic forecasts (Hartmann et al. 2006). The following work by Morrill and others was an assessment of the strengths and weaknesses of seasonal water-supply outlooks at fifty-four sites in the Colorado River basin using an assortment of skill measures (Morrill et al. 2007). Morrill found that the water-supply outlooks were an improvement over climatology during the historical record for most sites. They also found that most of the forecasts were conservative, with above-average flows under predicted and below-average flows over predicted. The reports of Pagano, Hartmann and Morrill provide an excellent starting point for the skill evaluation of seasonal water-supply outlooks for the Colorado River basin.

In order to evaluate the skill of the forecasts, a method of quantitatively evaluating the forecasts versus the observed flows was needed. Pagano noted that one challenge in forecast evaluation was to normalize forecast errors to allow a fair comparison between small streams and larger rivers. Pagano maintained that it is desirable that the evaluation measures be chosen carefully so they are understandable and relevant to forecast users. A set of Matlab scripts developed to calculate various forecast skill measures which were used during the Morrill investigation were reviewed. Based on these criteria, the Percent Bias was chosen for this introductory review of forecast skill.

$$Percent\ bias\ = \left(\frac{forecast - observation}{observation}\right) x\ 100 \qquad (1)$$

As shown in Equation 1, percent bias (pbias) is the error in the forecast (forecast – observation) normalized by the observation. The best percent bias is zero, with positive scores indicating over forecast (forecasts exceeding the observation) and negative scores indicating under forecast (forecasts less than the observation).

ANALYTIC PROCEDURE

Source of Data

Forecast and observation data for twenty-eight locations that currently forecast April to July runoff were obtained from the Colorado Basin River Forecast Center (CBRFC) (CBRFC 2013). The April through July forecast period was chosen to enable comparison between similar forecast periods at the various locations in the western United States, including California. Hydrologic information such as gage elevation, watershed area and map coordinates for each forecast point was obtained from the USGS NWIS system (USGS, National Water Information System). All the forecasts were made after 1950, and the record usually extended to 2012 but with considerable variation in time period covered. The forecasts examined in this study were made monthly from January to May. The forecasts were an estimate of the water volume in thousands of acre-feet (taf) passing the forecast point during the forecast period. The actual forecast period at the various forecast locations showed considerable variation over the historical record. Many of the early forecasts were based on a forecast period from April through September. In the 1960’s, forecasts were made with the beginning of the forecast period corresponding with the month of forecast. In other words, a March forecast would be March through September, and an April forecast would be April through September. Since the 1980’s, most forecasts use an April through July forecast period, which corresponds with the April through July forecast period in the western Sierra Nevada of California. Data used in this study included the forecast period (for example April through July), month of forecast (January, February, March, April or May for this study), forecast flow in thousand acre feet (taf), observed flow (taf), “reasonable” maximum and minimum flow percent of average for forecast period, and mean flow for the forecast period.

The twenty–eight forecast locations are shown in Figure 1 along with state boundaries, a graphic representation of watershed hydrology showing HUC designations, and a graphic representation of topography. Details of the forecast points are shown in Table 1. The table shows the site number, the descriptive location of the gage, the NWS designation, the USGS designation, the measurement characteristic of the location (observed or naturalized flow), the elevation of the gage, the start year and end year of the data at that location, and the decimal latitude and longitude of the location. Observed flows are flows that can be directly observed and are generally found in headwater basins with very few diversions and no large reservoirs that impact the natural flow (personal communication, CBRFC 2013). Naturalized flows are calculated to estimate the unregulated flow at the measurement point, with allowance for diversions and/or reservoirs in the contributing watershed.

Results and Discussion

Basin characteristics

The forecast points covered a wide range of elevation and areas across the upper and lower Colorado River basin and the basin characteristics add context to the percent-bias analysis. The highest forecast point was #10 - Blue River inflow to Dillon Reservoir, CO. at 8760 feet. The lowest forecast point was #1 – Virgin River at Virgin UT at 3500 ft. The largest watershed which also had the highest flow was #19 – Lake Powell at Glen Canyon Dam with an area of 111,700 square miles, and average forecast flow of 7155 (taf). The smallest watershed, which also had the smallest flow, was #15 – Ashley Creek near Vernal, UT with an area of 101 sq. miles, and an average flow of 50 taf.

The mean volume of flow for the latest forecast period was obtained from the forecast and observation data set, and area of the drainage area in square miles was obtained from the USGS records for the twenty-eight sites, as shown in Table 1. These data enabled calculation of the watershed yield in feet for the locations. The April through July yields range from a low of 0.07 feet on the relatively low elevation #16-San Juan River to a maximum of 1.11 feet on the relatively high #2-Lake Granby inflow.

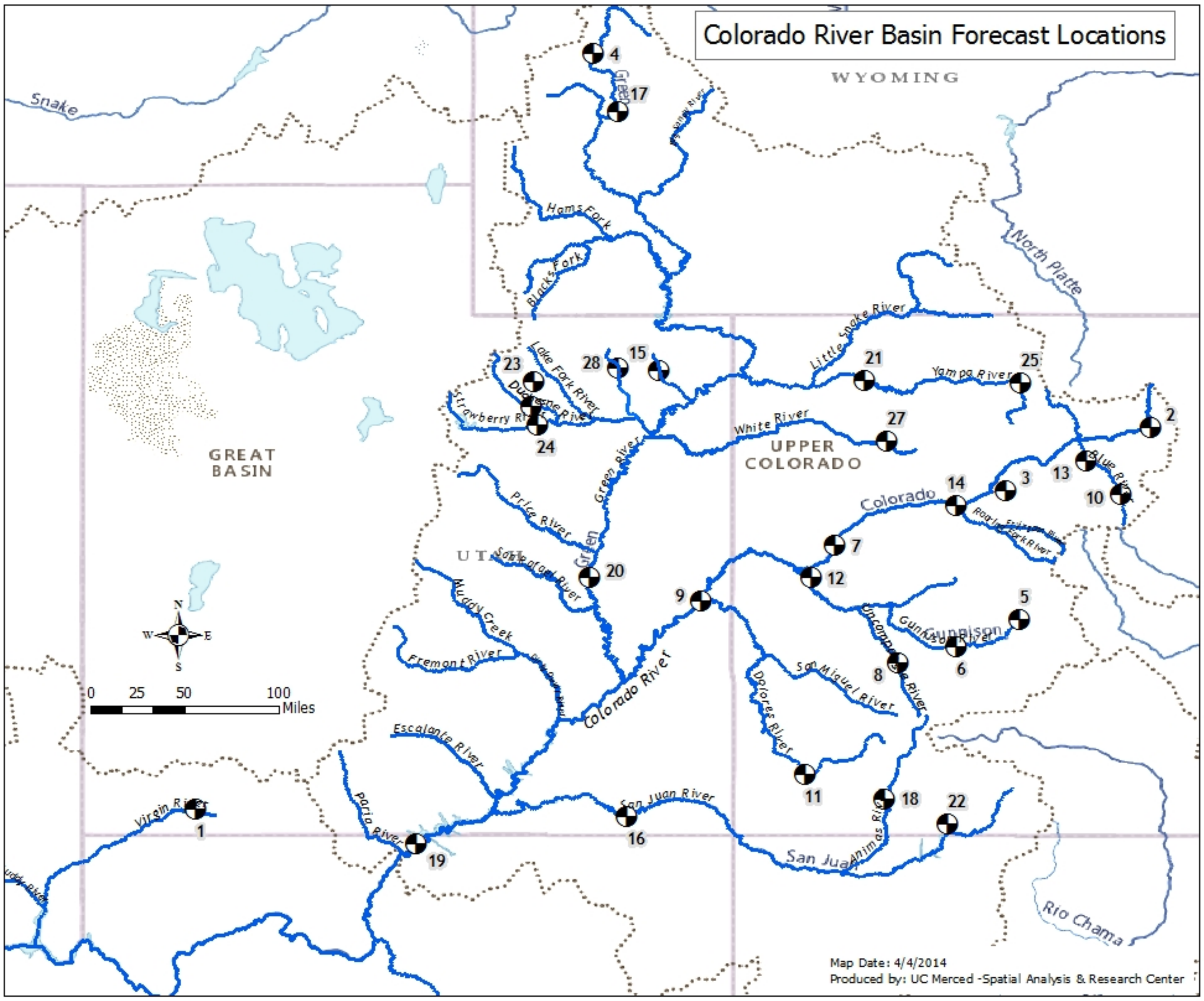

Figure 1: Map of Forecast Points – See Table 1 for names and characteristics

Table 1: Location summary and yield calculation

Site No.	Location	NWS	USGS	Type	Elevation Ft.	Start Year	End Year	Lat.	Long.	April July Mean TAF	Area Sq Miles	Calc Yield Ap-Jul Ft.
1	VIRGIN RIVER AT VIRGIN, UT	VIRU1	9406000	Observed	3,500	1958	2012	37.204	-113.180	58	956	0.09
2	COLORADO RIVER BELOW LAKE GRANBY, CO.	GBYC2	9019000	Naturalized	8,050	1954	2013	40.140	-105.835	221	312	1.11
3	EAGLE RIVER BELOW GYPSUM, CO	GPSC2	9070000	Naturalized	6,275	1975	2012	39.649	-106.953	336	944	0.56
4	GREEN RIVER AT WARREN BRIDGE, NEAR DANIEL, WY	WBRW4	9188500	Observed	7,469	1958	2011	43.019	-110.119	243	468	0.81
5	EAST RIVER AT ALMONT, CO	ALEC2	9112500	Naturalized	8,006	1957	2012	38.664	-106.848	182	289	0.99
6	GUNNISON RIVER INFLOW TO BLUE MESA RESERVOIR	BMDC2	9124800	Naturalized	7,519	1972	2012	38.451	-107.332	676	3,510	0.30
7	COLORADO RIVER NEAR CAMEO, CO	CAMC2	9095500	Naturalized	4,814	1957	2012	39.239	-108.266	2,357	8,050	0.46
8	UNCOMPAHGRE RIVER AT COLONA, CO	CLOC2	9147500	Naturalized	6,319	1954	2012	38.331	-107.779	137	448	0.48
9	COLORADO RIVER NEAR CISCO, UT	CLRU1	9180500	Naturalized	4,090	1957	2012	38.811	-109.293	4,440	24,100	0.29
10	BLUE RIVER INFLOW TO DILLON RESERVOIR,CO	DIRC2	9050700	Naturalized	8,760	1972	2012	39.626	-106.066	163	335	0.76
11	DOLORES RIVER AT DOLORES, CO	DOLC2	9166500	Observed	6,940	1954	2012	37.473	-108.497	247	504	0.76
12	GUNNISON RIVER NEAR GRAND JUNCTION, CO	GINC2	9152500	Naturalized	4,628	1954	2012	38.983	-108.450	1,478	7,928	0.29
13	BLUE RIVER INFLOW TO GREEN MOUNTAIN RESERVOIR, CO	GMRC2	9057500	Naturalized	7,683	1954	2012	39.880	-106.333	275	599	0.72
14	ROARING FORK AT GLENWOOD SPRINGS, CO	GWSC2	9085000	Naturalized	5,721	1954	2012	39.544	-107.329	692	1,453	0.74
15	ASHLEY CREEK NEAR VERNAL, UT	ASHU1	9266500	Observed	6,231	1954	2012	40.578	-109.621	50	101	0.77
16	SAN JUAN RIVER NEAR BLUFF, UT	BFFU1	9379500	Naturalized	4,048	1957	2012	37.147	-109.864	1,095	23,000	0.07
17	NEW FORK RIVER NEAR BIG PINEY, WY	BPNW4	9205000	Observed	6,800	1975	2012	42.567	-109.929	355	1,230	0.45
18	ANIMAS RIVER AT DURANGO, CO	DRGC2	9361500	Observed	6,502	1954	2012	37.279	-107.880	417	692	0.94
19	LAKE POWELL AT GLEN CANYON DAM, AZ	GLDA3	9379900	Naturalized	3,715	1964	2012	36.937	-111.483	7,155	111,700	0.10
20	GREEN RIVER AT GREEN RIVER, UT	GRVU1	9315000	Naturalized	4,040	1957	2012	38.986	-110.151	2,960	44,850	0.10
21	YAMPA RIVER NR MAYBELL, CO	MBLC2	9251000	Naturalized	5,900	1957	2012	40.503	-108.033	936	3,410	0.43
22	PIEDRA RIVER NEAR ARBOLES, CO	PIDC2	9349800	Observed	6,148	1972	2012	37.088	-107.397	209	629	0.52
23	ROCK CREEK NEAR MTN HOME, UT	ROKU1	9279000	Naturalized	7,250	1965	2012	40.493	-110.578	88	147	0.94
24	STRAWBERRY RIVER NEAR DUCHESNE, UT	STAU1	9288180	Naturalized	5,722	1954	2012	40.155	-110.554	125	917	0.21
25	YAMPA RIVER AT STEAMBOAT SPRINGS, CO	STMC2	9239500	Naturalized	6,695	1954	2012	40.484	-106.832	258	568	0.71
26	DUCHESNE RIVER NEAR TABIONA, UT	TADU1	9277500	Naturalized	6,190	1954	2012	40.300	-110.602	108	353	0.48
27	WHITE RIVER NEAR MEEKER, CO	WRMC2	9304500	Observed	6,300	1954	2012	40.034	-107.862	278	755	0.58
28	WHITEROCKS RIVER NEAR WHITEROCKS, UT	WTRU1	9299500	Observed	7,200	1954	2012	40.594	-109.932	54	109	0.77

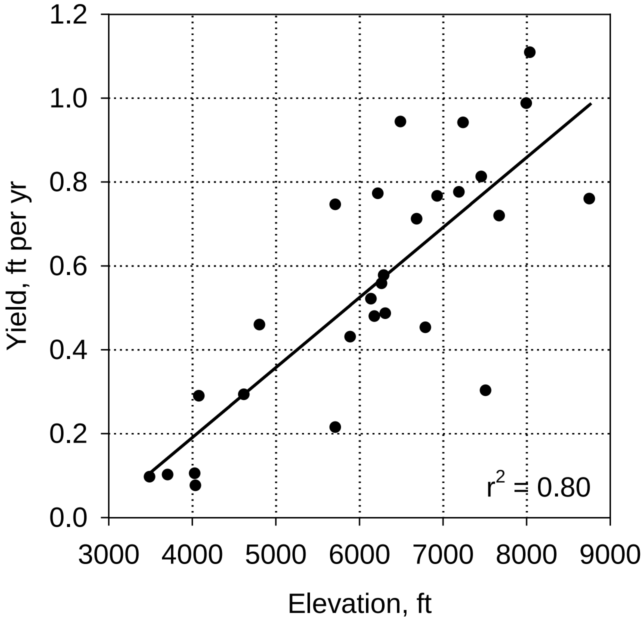

Figure 2 shows that yield increases with increasing elevation at the 28 gage locations, with the least-squares line illustrating this relationship, with an r^2 of 0.80. This relationship may be due to increased orographic precipitation at higher elevation, increased impervious substrate at higher elevation, fewer trees or vegetation at higher elevation, or a combination of the above factors. There are random components of each calculated yield as shown by the moderate amount of scatter in the graph. These random components may be due to watershed vegetation cover, rock cover, aspect (direction the watershed faces), plus possibly the influence of neighboring topography on the usual storm direction.

Figure 2: Watershed yield and elevation – data from Table 1

Figure 3 presents a relationship between increasing watershed area and increasing watershed runoff during the April through July period. Both the runoff and area are represented on a linear scale in the left panel of the graph. In the right panel, the area is represented by a logarithmic scale. The relationship between area and runoff is strong with an r^2 of 0.93. The non-linearity in the relationship observed in the left panel and also shown in the right panel may arise from the information that as the area of the watershed increases, increasing areas of low elevation or desert areas are included in the watershed, thus the reduction in increased runoff as the size increases. There is an increase in variability of runoff in the mid to higher discharges, which may attenuate at the highest discharges. This may be explained by noting that the mid-sized watersheds may contain a more heterogeneous mix of characteristics than the smaller watersheds. The largest watersheds would have a more expected or "average" mix of characteristics.

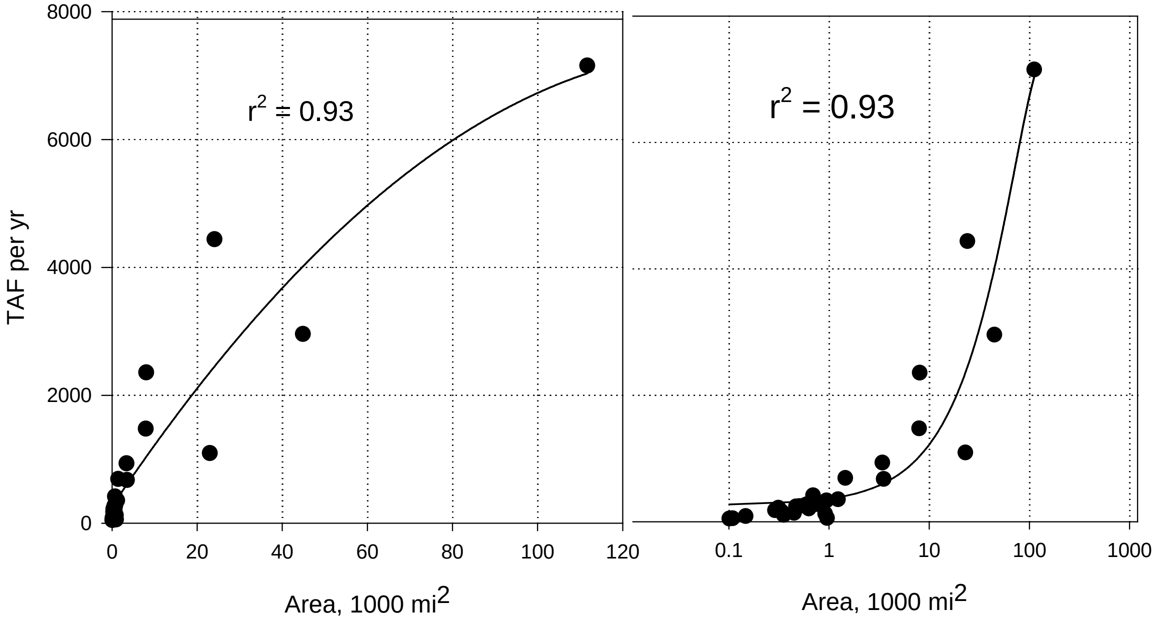

Figure 3: Runoff as function of watershed area – Data from Table 1

Forecast Skill

Figure 4 consists of two panels of information on site #4, the Green River. The bottom panel shows the anomaly of the April through July runoff separated into three flow magnitudes. The first set is the years with a fraction of less than or equal to 0.30 which are the "low" flows. The "mid" flows have a fraction of greater than 0.30 and less than or equal to 0.70. The "high" flows have a fraction of greater than 0.70. The interannual variability of runoff is shown clearly in the bottom panel along with multi-year flow regimes. There is a tendency for a dry year to follow a dry year for up to two years and wet years to follow wet years for up to four years. The top panel shows the time series of percent bias categorized by these three types of runoff years. Using the year 1970 as an example, the bottom panel indicates that the observed runoff was slightly drier than normal, yet still classified as a mid-flow year. The top panel shows that there was no bias in the forecast; the forecast was equal to the observation. Another observation is that there are really a limited number of years with very small (less than +/-5%) percent bias.

A summary of the percent-bias analysis from the top panel is contained in Table 2. It indicates that the low flows have a mixed tendency to over forecast (7 occurrences) or under forecast (5 occurrences). There are more over forecasts for mid flow than under forecasts. The high flows are definitely under forecast with 12 under forecasts and only 2 over forecasts.

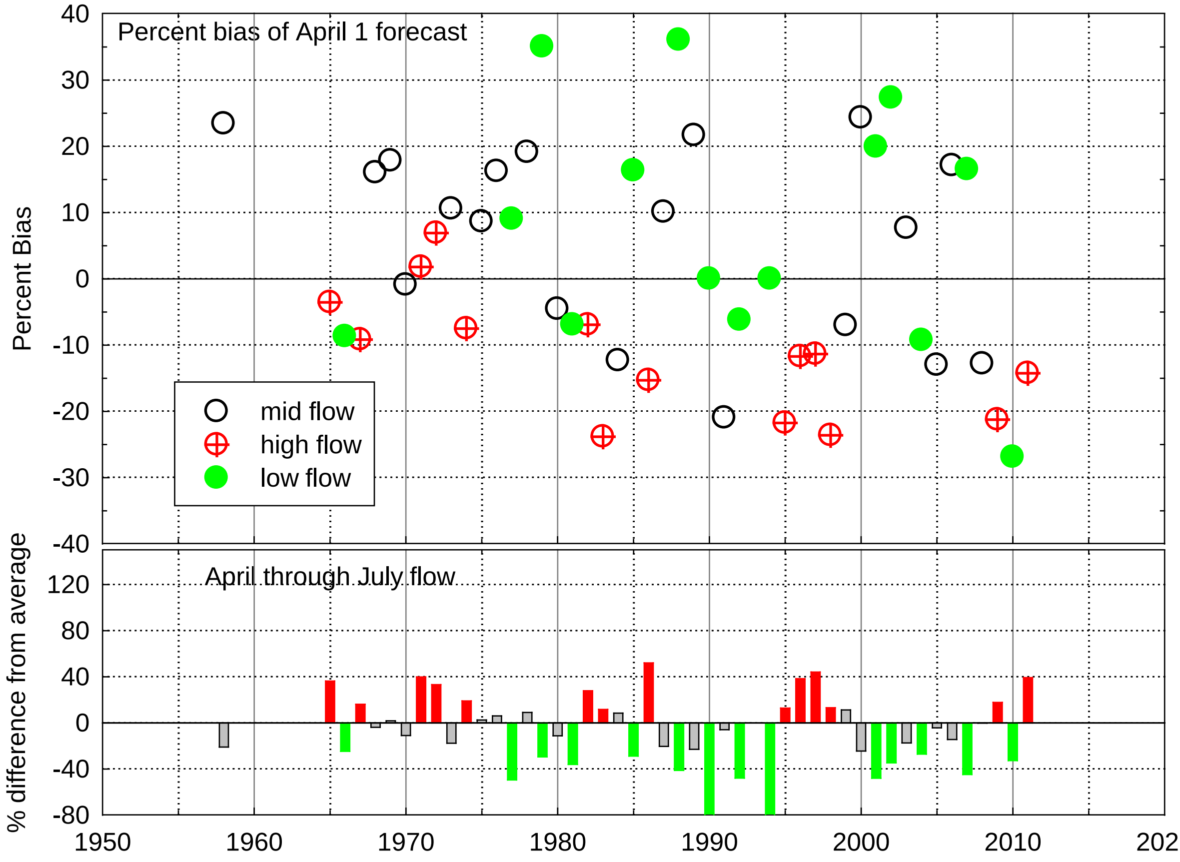

Figure 4: Percent Bias time series for #4 - Green River

Table 2 - Summary of percent bias for #4 – Green River

	Low	Mid	High
Over forecast (+)	7	12	2
Under forecast(-)	5	6	12

Figure 5 is similar to the previous figure but is for the East River. At this location, there is a tendency for dry years to follow dry year for up to four years and wet years to follow wet years for up to four years. The summary contained in Table 3 indicates that the low flows are over forecast (13 to 0). According to the top panel in Figure 5, forecasts for years with mid flows appear equally located around zero bias with a tighter distribution than seen on the Green River. The information for mid flows in Table 3 does not indicate a tendency toward over or under forecasting. There is a definite tendency to under forecast the high flows (3 over forecast to 13 under forecast). Review of the percent bias graphs for the remaining 26 forecast points indicates that the remaining point have similar distributions as Figure 5 and the information from Figure 5 and Table 3 is representative of other locations.

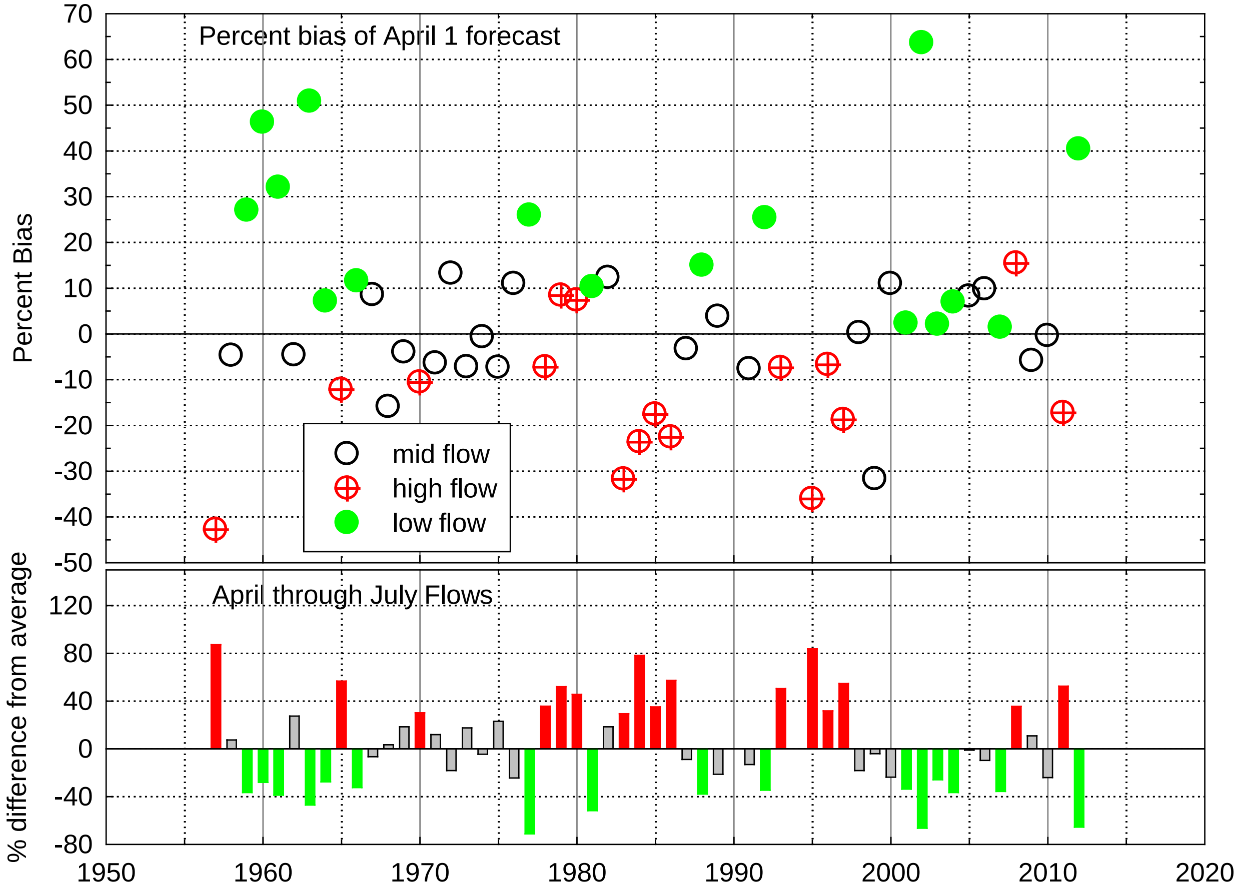

Figure 5: Percent Bias time series for #5 - East River

Table 3 - Summary of percent bias for #5 – East River

	Low	Mid	High
Over forecast (+)	13	8	3
Under forecast(-)	0	11	13

It has been seen that the percent-bias values are distributed around zero. It is therefore helpful to calculate the absolute value of the percent bias as a measure of the magnitude of forecast bias. Figure 6 shows the mean and dispersion of the absolute value of the pbias scores for each of the watersheds in the study. The box graphs are interpreted as follows. The highlighted bar extends from the 25th percentile to the 75th percentile, with the median shown as a vertical line. The vertical tics are the 10th percentile and the 90th percentile. The table entries are ranked top to bottom by increasing April through July flows. Most of the scores are contained within the range of 0 to 30%, with #24 – Strawberry River appearing to be an outlier. Upon review of the data for #24, the high pbias scores for the location were determined likely be correct as they appear when there is a very dry year and the forecasting process lags to some extent the deteriorating water supply. The width of the 25/75 percentile box in the box plot is similar in span (30%) for most of the forecast locations. There is a somewhat variable upper tail of the distribution, which is especially visible in the smaller watersheds. Another conclusion from reviewing the graph is the median percent bias exhibits more variability than the width of the 25/75 percentile box.

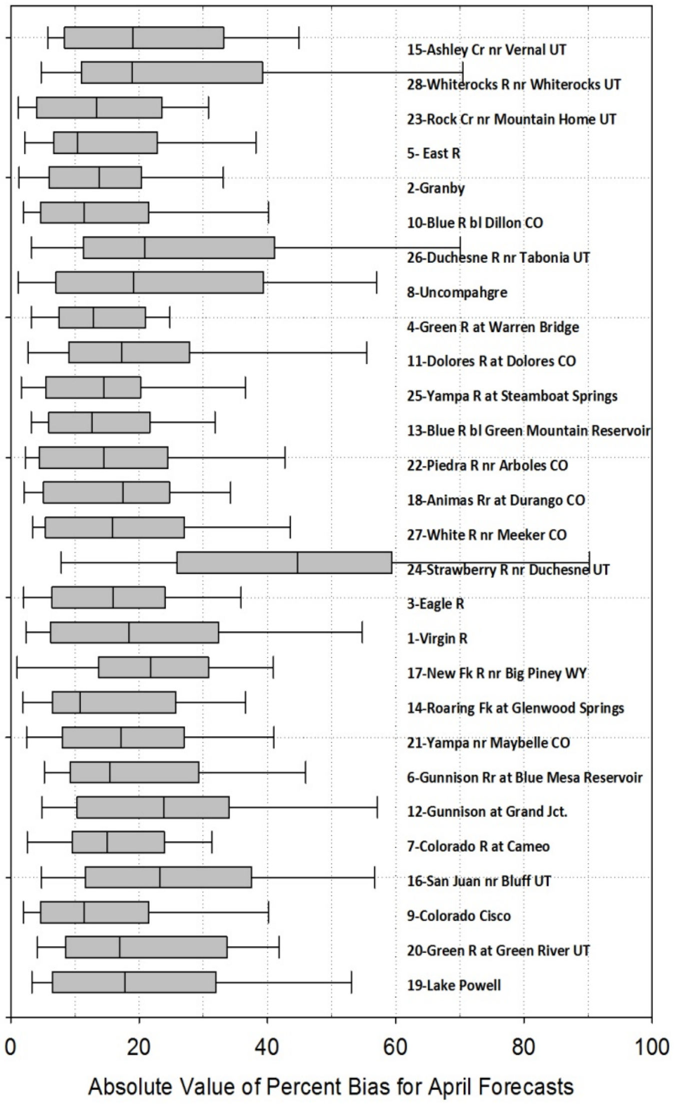

Figure 6: Absolute value of April 1 percent bias arranged by increasing flow; top to bottom

Figure 7 is a two-panel graphic with the distribution of percent bias shown in the lower panel, and the distribution of the absolute value of percent bias in the top panel. Each of the 28 locations is a separate line. The percent bias scores in the lower panel are approximately centered on the median at 0 pbias with a disproportionate increase on the high pbias scores. The traces in the lower panel show the fairly tight distribution of percent bias due to the plus and minus scores. The apparent outlier visible in the negative percent bias score portion of the graphic is again location #24.

The upper panel of Figure 7 shows the distribution of the absolute value of pbias. The graphic shows that approximately 70 percent of the absolute values of percent bias for the individual forecasts are 40 percent or less. Again, one watershed, #24- Strawberry appears as an outlier with high absolute value of pbias scores in the upper panel. The same explanation for the outlier as on Figure 6 seems reasonable. The extensive upper tail in both panels is a more clear visualization of the upper tail appearing in the box graphs of Figure 6.

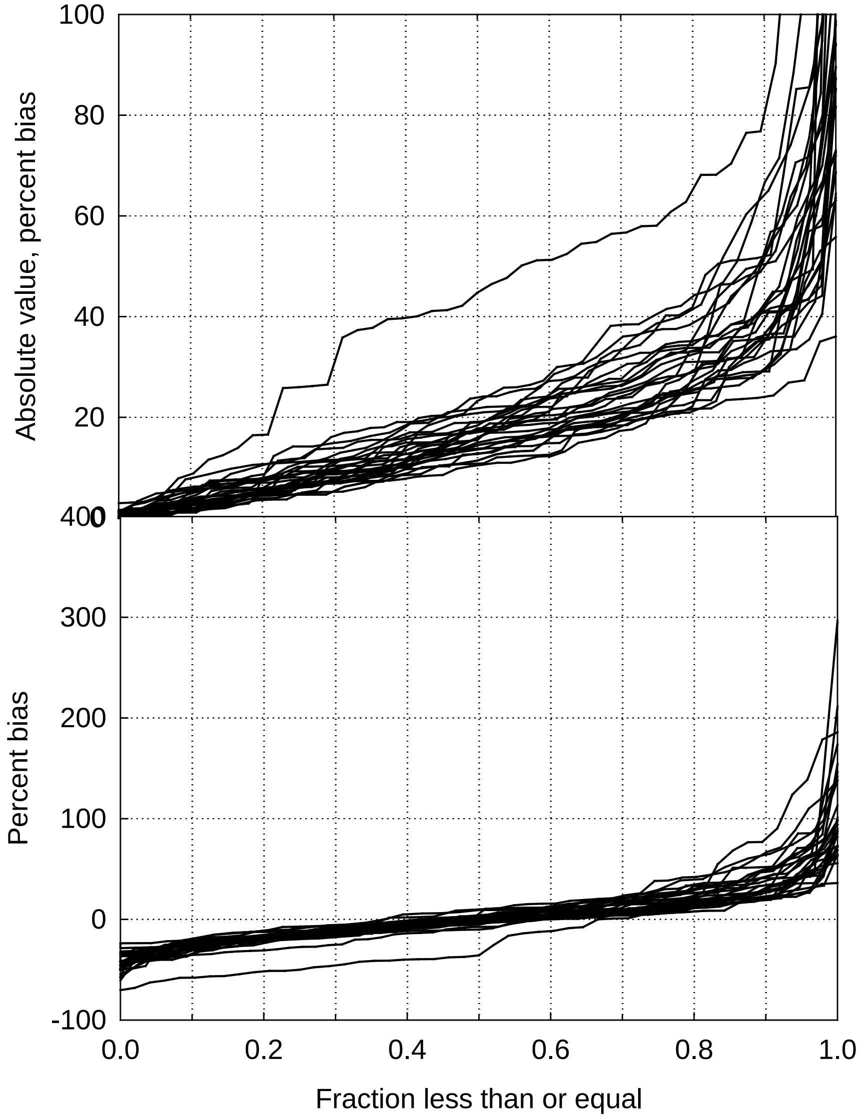

Figure 7: Percent Bias and Absolute Value of Percent Bias distributions

Figure 8 shows the distribution of percent bias for low, mid and high flows on six representative watersheds. The box plot is interpreted similarly as discussed for Figure 6. The pbias scores for the low flow years have considerable variability, with the median varying from nearly zero to nearly 40%. There are long upper tails for the pbias in low flow years, primarily due to the magnification of the error when dividing by a smaller observed flow. The percent bias for mid flow years exhibits the tightest distribution, with the median around zero. For the high flow forecast years, the median percent bias is negative, roughly around -20%. The high flow pbias also exhibit a tight distribution with the 10th percentile about -40%.

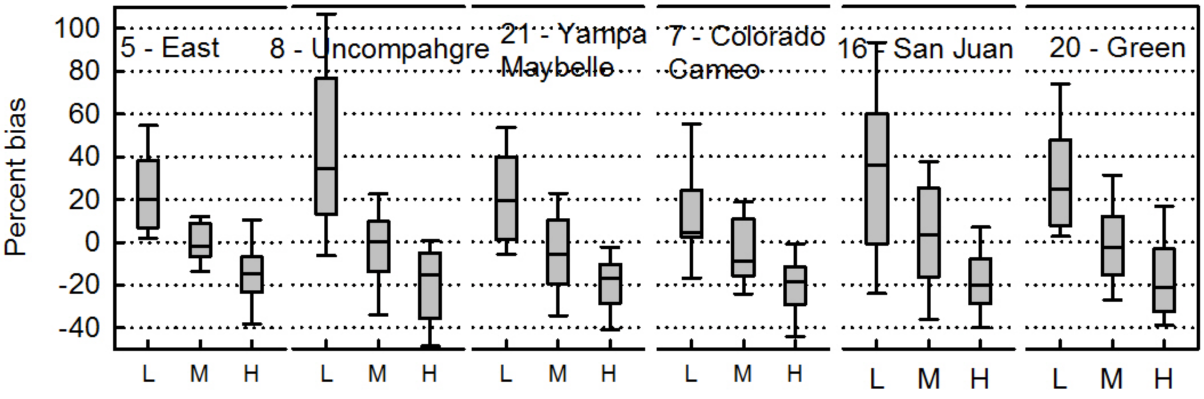

Figure 8: Percent Bias for selected watersheds

CONCLUSIONS

This investigation has illustrated several important characteristics of watersheds and runoff forecasts within the Colorado River Basin. The data assembled for the study presented an opportunity to calculate the runoff yield for twenty-eight of the watersheds. A strong relationship between increasing watershed yield and increasing watershed elevation was demonstrated. In addition, a relationship between increasing watershed area and increasing runoff was shown but with a decreasing contribution to runoff as the size increased. This may be due to increasing areas of low runoff that are included in the watershed as the size of the watershed increases. Examination of the percent bias time series for two of the watersheds indicated strongly that forecasts in wet years tend to under forecast runoff. Conversely, forecasts in dry years tend to over forecast runoff. Forecasts for mid flow years are shown to be somewhat challenging as the year may end up slightly wet or dry and the forecasting process is expected to reflect that result. Investigation of the percent bias for the various watersheds shows that 70% of the absolute values of pbias scores are 40 percent or less. This similarity between watersheds would be expected as all the forecasts use similar types of information although the forecast locations are different and with different physical characteristics at each watershed.

One interesting observation is the absence of any trend toward decreasing percent bias through the advance of the historical record. This observation stands in contrast to the years of increasing institutional experience in forecasting runoff and the advance of computational machinery. A possible explanation could be that the percent bias measures the human contribution to the forecasting process, which leads to the production of conservative forecasts that are familiar and useful to water resource decision makers.

Acknowledgments

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CHAPTER 5

Comparison of Skill Assessments of Water Supply Forecasts for the Western Sierra Nevada and the Colorado River Basin

Brent Harrison [1,*], Roger Bales [2,†]

[1] Sierra Nevada Research Institute, University of California Merced, 5200 N. Lake Rd., Merced CA 95343, bharrison3@ucmerced.edu
[2] Sierra Nevada Research Institute, University of California Merced, 5200 N. Lake Rd., Merced CA 95343, rbales@ucmerced.edu

† *This author contributed equally to this work.*

***** Author to whom correspondence should be addressed; E-Mail: bharrison3@ucmerced.edu;
Tel.: +1-209-228-7674 ; Fax: +1-209-228-4158.

Abstract: The skill of runoff forecasts for thirteen watersheds in the western Sierra Nevada and twenty-eight watersheds in the Colorado River basin were compared. The summary measures included a skill scores based on Mean Absolute Error which showed clearly the increase in skill during the forecast season, with both the skill scores starting at 0.3 for both regions. The skill of the western Sierra forecasts end the season somewhat higher at 0.8 compared to 0.6 for the Colorado Basin. Some widening of the skill scores for the Sierra locations is visible. This is evidence of an increase in uncertainty of March and April forecasts. The monthly increase in NS score was higher at 0.19 for the western Sierra watersheds when compared to watersheds elsewhere in the western United States, which ranged from 0.08 to 0.12 per month. A correlation between PBias and watershed median elevation was also visible. The April 1 categorical measures indicated a low FAR (0.2) for high runoff forecasts and a higher FAR (0.4-0.5) for mid flow forecasts. Bias scores indicated over-forecast of mid flows and under-forecast of high flows. The conservatism in forecasting high runoff years was illustrated in both the FAR and the Bias categorical measures. The over forecast of mid-flow years was shown in the high April FAR of 0.3 for the Sierra locations and 0.4 for the Colorado locations. Illustrating the difficulty in making mid-flow forecasts, the HR for mid-flow forecasts (0.7) was lower than the HR for high flow or low flow. Examination of SWE and precipitation records from 5 sites showed a level accumulation of SWE and precipitation. This may explain the lower skill level of forecasts in the Colorado River basin.

Keywords: forecast; runoff; skill

1. Introduction

1.1 Runoff Forecasts

The water from seasonally snow covered watersheds is used for agricultural, municipal, industrial, recreational and environmental purposes. In order to properly apportion the water to their many customers, the agencies responsible for the water rely on runoff forecasts prepared during the snow accumulation and ablation period to estimate water supplies for the remainder of the water year. These forecasts use information on snowpack, precipitation and other hydrologic conditions to make these projections of runoff. In the Sacramento-San Joaquin basin of California, the Cooperative Snow Survey Program, part of California Department of Water Resources (DWR), coordinates the collection of data and prepares the forecasts. These forecasts have been prepared on watersheds in California since the 1930's. The forecasts predict April through July runoff and estimate runoff for the water year. The forecasts are issued monthly starting in February and ending in May of each year.

Snowmelt runoff from the seasonally snow-covered mountains that comprise the headwaters of watersheds within the Colorado River basin provide water to a significant area of the southwestern United States. Water managers use seasonal water-supply outlooks, which are prepared monthly during the snow accumulation and ablation periods to effectively plan and schedule water deliveries, releases and transfers within the basin. The forecasts are prepared jointly by the Natural Resources Conservation Service (NRCS) and the National Weather Service (NWS) (Pagano et al. 2004). These predictions use primarily information on snowpack, precipitation and hydrologic conditions to make statistical forecasts of runoff volume past the forecast point for a specified period of time.

1.2 Evaluations of Forecast Skill

Water supply forecasts are also made on other watersheds in the western United States. Evaluations of the skill of these various forecasts have been made since the late 1950's on various subsets of these forecasts. In 1958, one of the earliest comprehensive studies of forecast skill was prepared by Work and Beaumont (1958). They compared the forecast skill of NRCS and NWS forecasts and found that using snow survey data had some advantages over using precipitation when preparing forecasts. The next year Kohler (1959) produced an analysis favoring the use of precipitation. Shafer and Huddleston (1984) reviewed historical seasonal volume forecasts based on regression techniques and found a small improvement in forecasting skill in recent years but cautioned that large improvements in skill are not to be expected in the future by refining regression techniques. Schaake and Peck (1985) partitioned error in water supply forecasts into three parts. They proposed that errors and uncertainty in forecasting arose from unknown future precipitation and temperature, data errors and uncertainty arose from difficulties in measuring inputs and outputs of the models, and errors in the models themselves produce forecast errors. They also presented analysis techniques to quantify those errors and uncertainty. Also Dracup et al. (1985) examined the accuracy of hydrologic forecasts on the Colorado River in the states of Arizona, Utah and Colorado by calculating and comparing various correlation coefficients and coefficients of prediction. They found trends in the accuracy of forecasts that were attributed to the amount of precipitation and the proportion of precipitation that was snow at the forecast location.

Again there was an absence of skill assessments until Hartmann et al. (2002) performed a regional assessment of hydrologic forecasts emphasizing the Colorado River Basin. One recommendation of the study was to make performance evaluations publicly available. Franz et al. (2003) evaluated the forecasts at 14 sites on the Colorado River and determined that the Ensemble Streamflow Prediction (ESP) system, developed by the National Weather Service (NWS), performed better than climatology forecasts.

Pagano et al. (2004) evaluated forecasts on 29 unregulated rivers in the western United States. The report also presented a historical review of skill assessment reports for water supply forecasts. Pagano found high skill for forecasts issued on 1 April. Forecasts made earlier in the season contained more uncertainty but were shown to still be skillful. Pagano also found that areas with wet winters and dry springs presented higher forecast improvement over the forecast season than areas with dry winters and wet springs. Pagano also found mixed changes in skill over time when comparing different areas of the study. Pagano noted that one challenge in forecast evaluation was to normalize forecast errors to allow a fair comparison between small streams and larger rivers. Pagano and his co-authors have stated that it is desirable that the evaluation measures be chosen carefully so they are understandable and relevant to forecast users.

Hartmann et al. (2006) and others performed an assessment of water-supply outlooks in the Colorado River Basin which established a baseline for identifying improvements in hydrologic forecasts. In a following working paper, Morrill et al. (2007) prepared an assessment of the strengths and weaknesses of seasonal water supply outlooks at fifty-four sites in the Colorado River basin using an assortment of skill measures. These measures included traditional scalar measures (e.g., correlation, root-mean square error and bias) and categorical measures (e.g., false alarm rate, threat score). They found that the examined water supply outlooks were an improvement over using average climatology. They also found that most of the forecasts were conservative, with above-average flows under predicted and below-average flows over predicted.

This investigation of the forecast skill level is intended to assist water managers and other interested water resource professionals to effectively plan and schedule water releases, delivery and transfers in the region.

The issues to be addressed in this research include comparison of the skill levels of runoff forecasts for the western Sierra Nevada and the Colorado River basin using summary, correlation and categorical measures and what basin and climate characteristics contribute to these differences.

2. Methods and Data

Previous investigators have used an assortment of summary, correlation and categorical measures to determine skill levels of runoff forecasts. Harrison and Bales (2014a) published forecast skill level at 28 locations within the Colorado River basin, as measured by April 1 percent bias. The PBias data includes a time series of April through July forecasts and a three partition breakdown of the PBias based on runoff magnitude. Harrison and Bales (2014b) published summary, correlation and categorical measures of forecast skill in the western Sierra Nevada. The data available include skill scores based on Mean Absolute Error (MAE). PBias time series for April 1 forecasts are available along with a three partition breakdown of PBias based on runoff magnitude. The correlation measure available is the Nash Sutcliff score. Five categorical measures based on three partitions of runoff are also available. Harrison and Bales (2014c) published the forecast skill at 28 locations within the Colorado River basin using summary, correlation and categorical measures of forecast skill. The data available include skill scores based on Mean Absolute Error (MAE). The correlation measure available is the Nash Sutcliff score. Five categorical measures based on three partitions of runoff are also available. The reader is referred to the papers for details on the skill measures, procedures for calculation and information on interpretation of the skill measurements. Also available in each paper are a map of the forecast locations and details of each site.

3. Results

Figures 1 and 2 are the maps of the two study areas, with details of each site listed in Tables 1 and 2. The Colorado study area (Figure 2) is larger as it includes watersheds that are up to 30 times larger than the largest basin in the Sierra Nevada. The span of basin elevation (from smallest to largest) is approximately the same, 1649 m for the Sierra and 1380 m for the Colorado basins. The median elevation of the highest Colorado basin (3364 m) is higher than the median elevation of the highest Sierra basin (2540 m). These differences may be expected to present higher variability in runoff in the Colorado basins.

Figure 3 is the comparison of skill scores between the two regions. The skill score based on MAE is shown in Figure 3a. In the Sierra, the median starting score for the February forecasts is 0.3. The median increases to 0.4 in March but the distribution of skill scores is much wider. The skill scores increases to 0.6 for April, with a decrease in width of the distribution. For May, the median score increases again to nearly 0.8 but with a tight distribution. The forecast skill in February is quite low, but with a tight distribution as this early in the forecast season the forecasts are made using average climatology. The forecasts in March contain additional winter-storm information and thus have higher skill but a much wider distribution. The forecasts in April and May are made with nearly complete information and thus have higher skill and less uncertainly. In the Colorado River basin, the skill in February is about the same as the Sierra and the same consistent increase in skill is noted over the forecast season. However, the skill of the forecasts for April and May are higher in the western Sierra, with the skill of the western Sierra forecasts ending near 0.8 with the Colorado basin ending near 0.6 in May. There is no increase in uncertainty for the Colorado forecasts in March, but outliers are present in March and April

Figure 3b shows the Nash Sutcliffe scores for the two regions. The NS scores and patterns for the two regions are similar to the SSMAE but there are more distinct outliers in the scores for the Colorado basin. There are slightly higher scores in the western Sierra from March to May which ends with a compact distribution around 0.9. The NS for the Colorado River basin starts at 0.5 (February) and ends near 0.8 (May), which is lower than the comparable NS for the western Sierra in March, April or May. The snow dominance of the California runoff may be a reason for the higher ending forecast skill in the Sierra and may contribute to the wider distributions and increased number of outliers in the Colorado basin.

There is a visible correlation between increasing elevation and absolute value of PBias value for the Sierra basins but it may be weaker in the Colorado locations (Figure 4a). Three headwater basins in Utah and the 6 large integrating basins in Colorado and Utah were removed from the sample. The absolute value of percent bias for these sites is shown in Figure 4b. There is little difference in the absolute value of the April 1 PBias for the two locations, with even the non-conforming watersheds (4-Cosumnes, 12-Tule, and 24-Strawberry) similar in offset and range in skill. The absolute value of PBias ranges from 0 to 40 percent for most of the locations, the outliers excepted. The complicating samples shown in Figure 4b also show the same range for PBias, with a possible tendency for more uncertainty as exhibited by a wider distribution.

The categorical skill measures are similar for March and April between the Sierra locations and the Colorado locations (Figure 5). The Probability of Detection scores for both regions are shown in Figure 5a. The appearances of the boxplots are very similar, with a slight drop in POD for the mid runoff years shown clearly in both regions. This can be attributed to the assumption of average climatology through the forecast season which increases the expectation of mid flows for the March forecasts.

The False Alarm Rates for both regions are shown in Figure 5b. The low FAR for the high runoff years in both regions is clearly shown, along with higher scores for the other runoff types. This reflects the conservative nature of high runoff forecasts. Also, the mid runoff years have fairly high FAR due to the assumption of normal climatology for the remaining runoff period.

The Bias scores of the forecasts are shown in Figure 5c. In March, low runoffs are shown under forecast in both regions, with the mid runoff forecasts strongly over forecast, again due to the assumption of average climatology early in the forecast season. The high flow forecasts are strongly under forecast in March, reflecting a conservative approach to forecasting high runoff years.

The Threat Score (Figure 5d) shows a consistent increase in skill from March to April. The Sierra watersheds seem to have slightly higher scores for all the years.

The Hit Rate for the two regions (Figure 5e) illustrate the lower skill of forecasts made for mid runoff years, due to the assumption of average climatology for the remaining runoff. The low flow scores are higher for the Sierra locations.

The POD for the 19 select Colorado basins shows a slightly tighter distribution for the March high flow when compared to all the Colorado basins (not shown). There is an increase in FAR for all Sierra locations in the March and April high flow FAR. The Bias, TS and HR appear nearly identical between the 19 select basins and all the Colorado basins.

In order to evaluate a possible elevation contribution to forecast skill, three representative watersheds of varying elevation in the Western Sierra were chosen (Figure 6). The Cosumnes watershed is at a relatively low elevation, the American is higher, the Kings watershed is the highest. Five locations were chosen for the Colorado. The Duchesne is located in the Utah headwaters, the Yampa, Roaring, and Animas are North to South in Colorado. The Green river is a colder location in Wyoming. Median percent bias scores for April 1 forecasts were plotted for each of the select watersheds and a strongly decreasing PBias is visible as the elevation in the Sierra increases. A similar pattern of decreasing PBias is visible in with the representative Colorado locations. This increase in forecast skill with increasing elevation is also shown in the increasing skill scores SSMAE and NS for both the representative Sierra and Colorado watersheds

4. Discussion

There are three separate studies of runoff forecast skill in the literature with usable data for comparison, as shown in Table 3. There were 29 locations in the western United States with observed flows studied by Pagano et al., (2004). Harrison and Bales (2014b) studied 13 locations on western slope of the Sierra Nevada consisting of mainly naturalized flows. Harrison and Bales (2014c) also studied 28 locations within the Colorado River basin with a mixture of naturalized and observed flows. The study of western watersheds by Pagano reported NS scores from 0.35 in January to 0.70 in April. The study of the western Sierra Nevada watersheds reported a February score of 0.44 rising to 0.83 in April. The Colorado basin NS scores were 0.40 (January) rising to 0.63 in April. The Sierra Nevada scores are higher in April when compared to the western US or the Colorado River. The forecast skill scores of the Colorado River locations were similar to what was found by Pagano in the western United States.

The increase in skill from the beginning month of forecasts to the April forecasts may be related to the relative percent of yearly precipitation received during the period January to March according to Pagano. The monthly fraction of SWE and precipitation and the accumulation of each at five locations in the Colorado basin area are shown in Figure 7 (NRCS 2014). The locations varied in elevation from 2865 m at Columbine Pass to 3444 m at Berthoud Summit. At the Columbine Pass location, the snow season is short, extending from November to February, with a short cut off in March. At the other sites the snow accumulation season generally starts in October and extends into April, all with sharp endings. The accumulation is nearly linear through the main part of the season. The total precipitation shows nearly linear accumulation during the winter with smaller but fairly even accumulation during the summer. There appears to be a leveling effect on both the monthly SWE and precipitation as the elevation increases.

At these sites, the accumulation traces for both snow and rain have linear accumulation periods, suggesting an even accumulation of snow and precipitation during the year. This explains a lower skill level as there is not a sharp accumulation of snow and subsequent sharp snowmelt quantity that can be measured and used in forecasting. As shown in Table 3, the California forecasts have the largest increase in skill (0.19 per month) when normalized for the number of months of forecasts before the April prediction. The California scores are also significantly higher in April. These steeper increases for California scores and higher April skill may be related to California's watersheds being more snow dominated.

5. Conclusions

Skill in making runoff forecasts from two very different watersheds in the western United States can be compared using summary, correlation and categorical measures. The magnitude of the scores and the time dependent trends of the scores are comparable between watersheds. The slightly lower scores for the watersheds in the Colorado River basin may be the result of a more even distribution of precipitation and snow during the year.

The results of this investigation of forecast skill are consistent with previous investigations such as the 2004 work by Pagano and others. This work has shown high skill for the April forecasts, with lesser but significant skill earlier in the season. Pagano's work predicted that watersheds with wet winters and dry springs would exhibit higher skill, precisely what was found for the western Sierra Nevada. The summary measures were normalized to unit less measures as recommended by Pagano, thus aiding in understanding the significance of the measure across watersheds of various sizes and configurations.

The institutional assumptions that go into the forecasting process shape the final skill measures and are detectable during analysis. The assumption of average precipitation and normal climatology early in the forecast season clearly shapes the skill scores. High flows are under forecast throughout the forecast season. The conservative nature of the forecasts is clear in the skill analysis of False Alarms and Bias.

Increased knowledge of conditions in the field would be useful to reduce the width of forecasts distributions, especially early in the forecast season. This would enable users of the water supply forecasts to make better and timelier decisions on allocation of water supplies.

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Table 1. Forecast points and river basins in western Sierra Nevada

No.	Location	Median elev., m	Area, km^2
1	Feather River at Oroville	1571	9386
2	Yuba River near Smartsville plus Deer Creek	1372	3085
3	American River inflow to Folsom Lake	1328	4921
4	Cosumnes River at Michigan Bar	891	1373
5	Mokelumne River at Mokelumne Hill (Pardee)	1524	1489
6	Stanislaus River at Goodwin Dam	1791	2422
7	Tuolumne River at La Grange Dam	1801	3963
8	Merced River at Merced Falls	1564	2642
9	San Joaquin River at Friant Dam	2311	4248
10	Kings River at Pine Flat Dam	2540	3989
11	Kaweah River below Terminus Reservoir	1676	1458
12	Tule River below Lake Success	1121	1010
13	Kern River inflow to Lake Isabella	2262	5387

Table 2. Colorado River basin forecast locations

No.	**Location**	**Median Elev., m**	**Area, km^2**
1	Virgin River at Virgin, UT	1984	2476
2	Colorado River below Lake Granby, CO	3120	808
3	Eagle River below Gypsum, CO	2971	2445
4	Green River at Warren Bridge, near Daniel, WY	2768	1212
5	East River at Almont, CO	3135	749
6	Gunnison River inflow to Blue Mesa Reservoir	3023	9091
7	Colorado River near Cameo, CO	2776	20850
8	Uncompahgre River at Colona, CO	2807	1160
9	Colorado River near Cisco, UT	2636	62419
10	Blue River inflow to Dillon Reservoir, CO	3364	868
11	Dolores River at Dolores, CO	2984	1305
12	Gunnison River near Grand Junction, CO	2783	20534
13	Blue River inflow to Green Mountain Reservoir, CO	3260	1551
14	Roaring Fork at Glenwood Springs, CO	3026	3763
15	Ashley Creek near Vernal, UT	2746	262
16	San Juan River near Bluff, UT	1985	59570
17	New Fork River near Big Piney, WY	2452	3186
18	Animas River at Durango, CO	3167	1792
19	Lake Powell at Glen Canyon Dam, AZ	2135	289303
20	Green River at Green River, UT	2135	116162
21	Yampa River near Maybell, CO	2316	8832
22	Piedra River near Arboles, CO	2604	1629
23	Rock Creek near Mtn Home, UT	3121	381
24	Strawberry River near Duchesne, UT	2435	2375
25	Yampa River at Steamboat Springs, CO	2695	1471
26	Duchesne River near Tabiona, UT	2707	914
27	White River near Meeker, CO	2763	1955
28	Whiterocks River near Whiterocks, UT	3194	282

Table 3: Comparison of NS scores for April-July forecast period

Forecast Month	Pagano	Sierra Nevada	Colorado River
January	0.35	-	0.40
February	0.50	0.44	0.50
March	0.65	0.57	0.52
April	0.70	0.83	0.63
May	-	0.93	0.77
Number of sites	29	13	28
April through July Forecast Improvement (April)	Jan to April	Feb to April	Jan to April
NS Increase	0.35	0.39	0.23
No. of Changes	3	2	3
NSchg/month	0.12	0.19	0.08

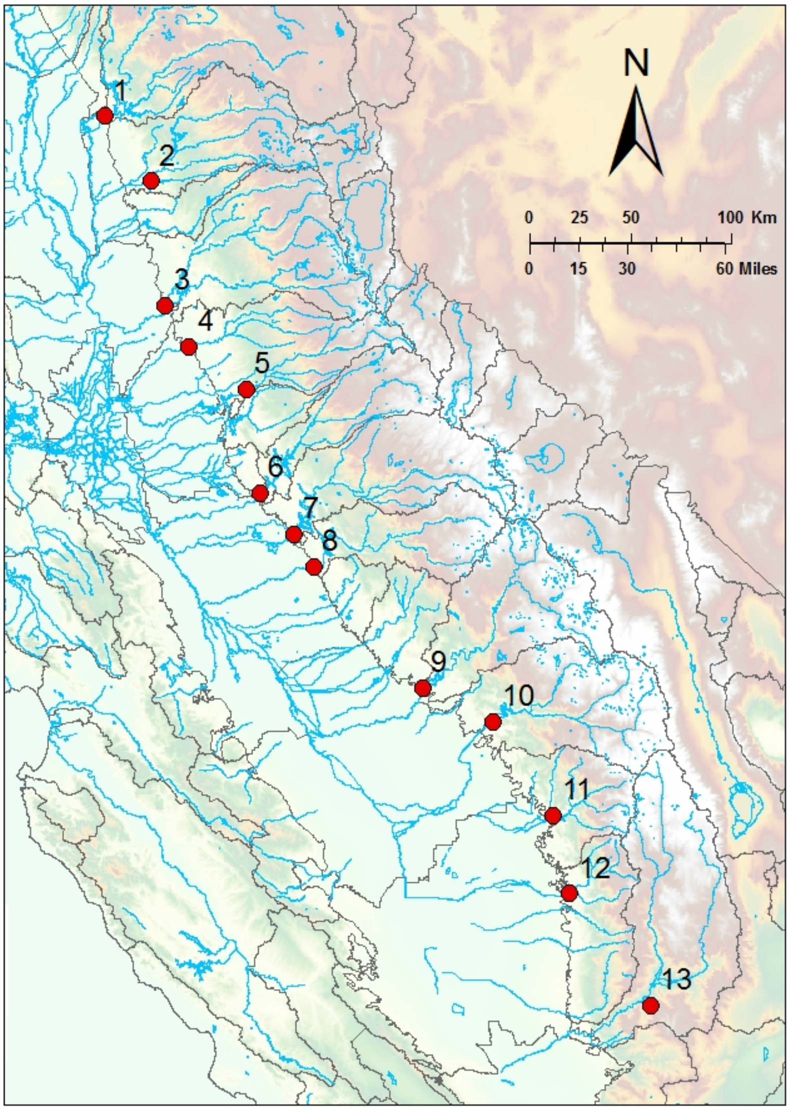


Figure 1: Map of Sierra Nevada forecast locations

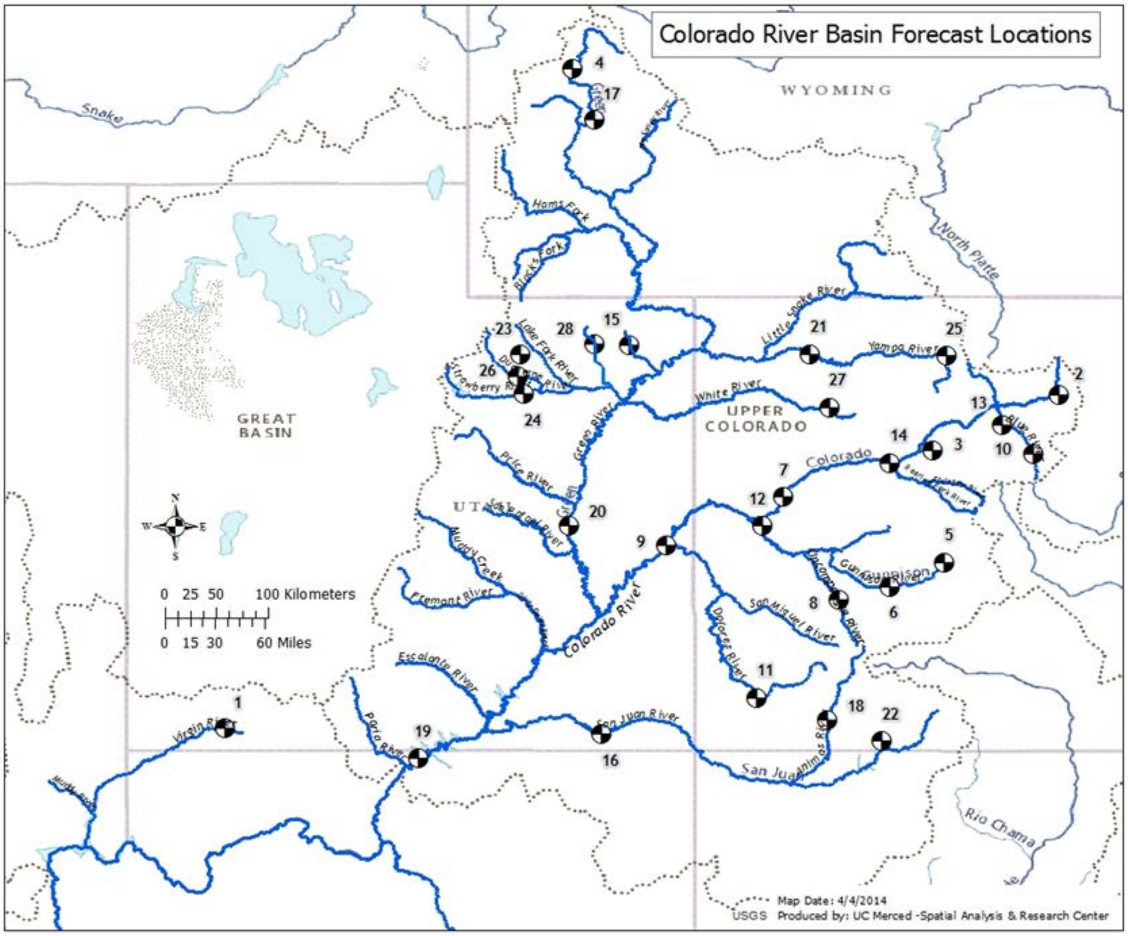


Figure 2: Map of Colorado River basin forecast locations

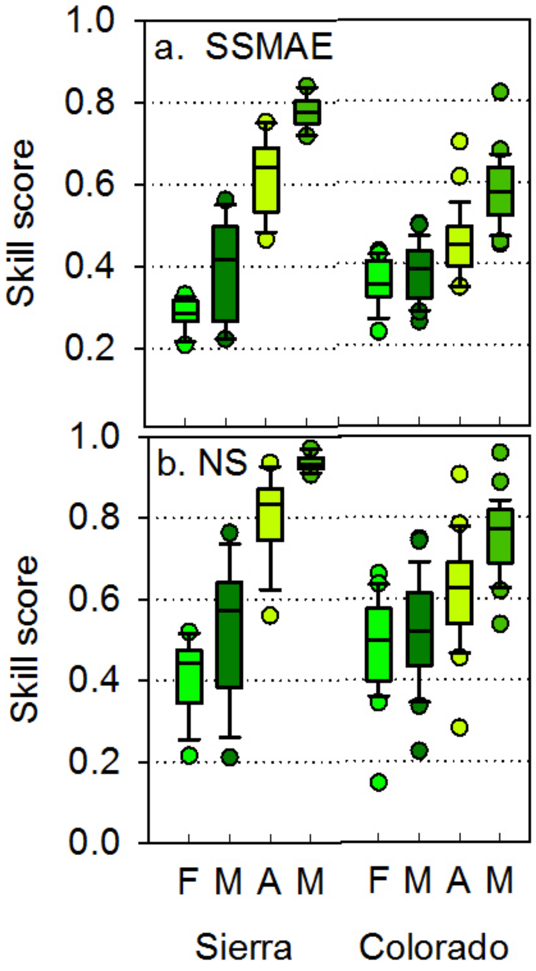


Figure 3: Skill scores for western Sierra and Colorado basin (Feb to May). The median is the line in the box. The boxes are 25 and 75 percentile with the tics at 10 and 90 percentile

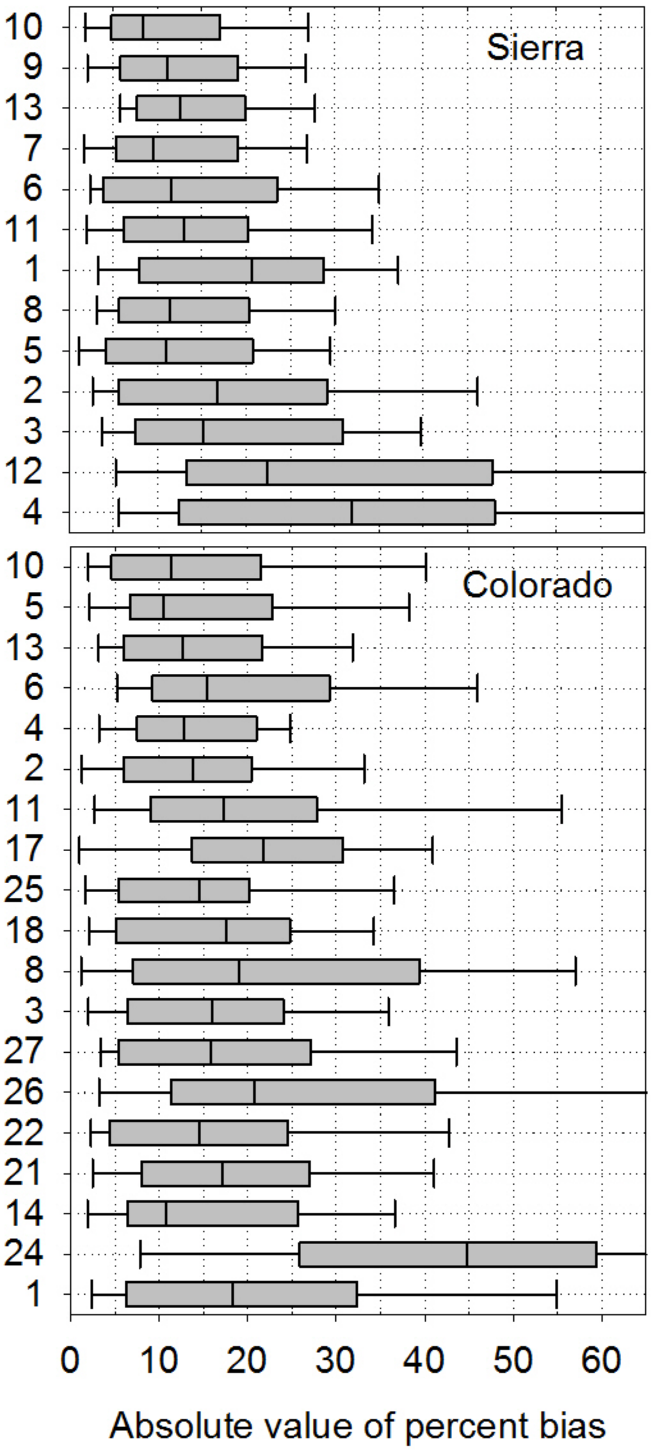


Figure 4a. April 1 absolute value of percent bias for Sierra and Colorado basins, arranged in order of increasing elevation from bottom to top. Colorado basins have area between 700-10000 km^2. Three headwater basins in Utah and the 6 large integrating basins in Colorado and Utah were removed before plotting.

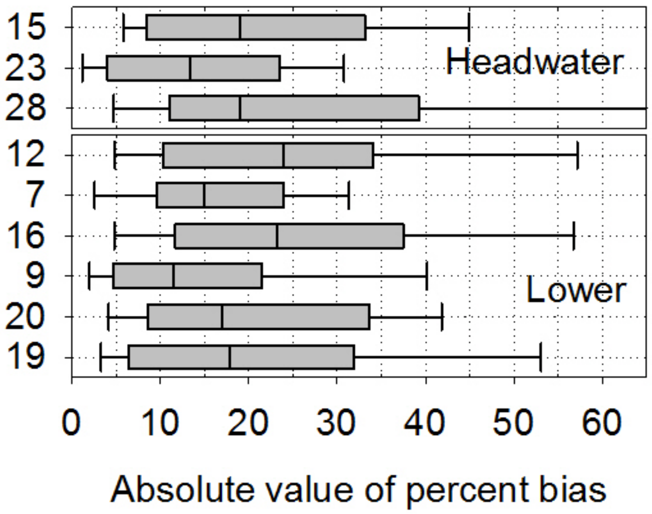


Figure 4b. Absolute value of April 1 percent bias for the three headwater and 6 large integrating basins .

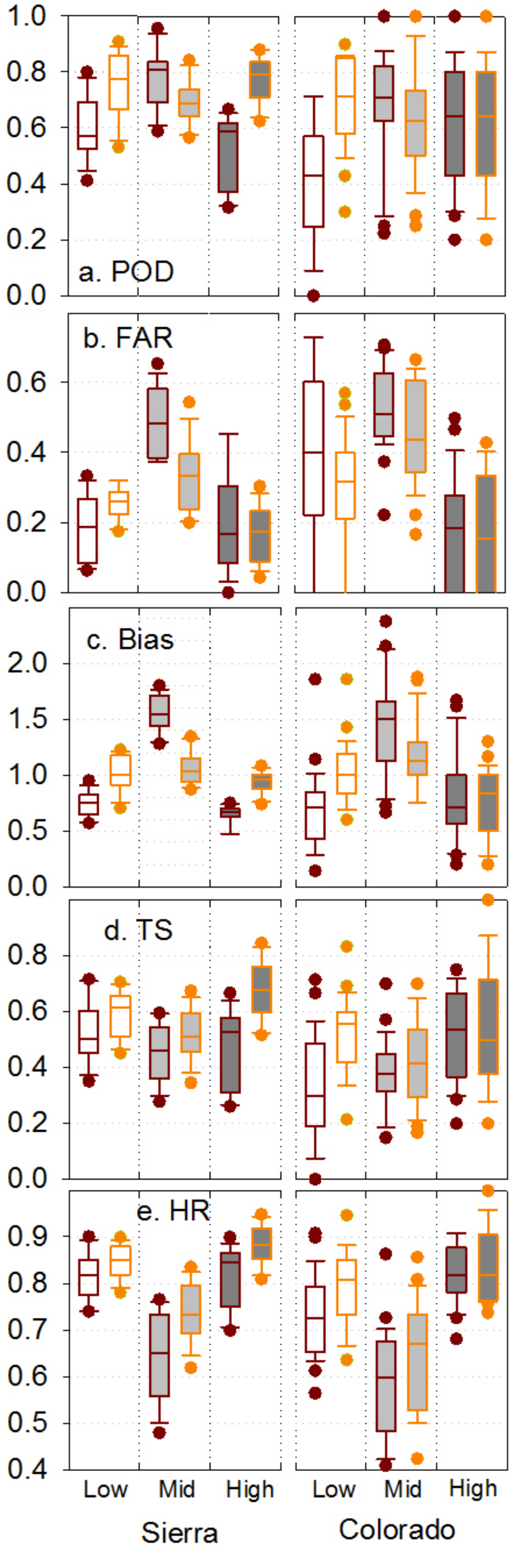


Figure 5. Categorical measures for March and April for Sierra and Colorado locations

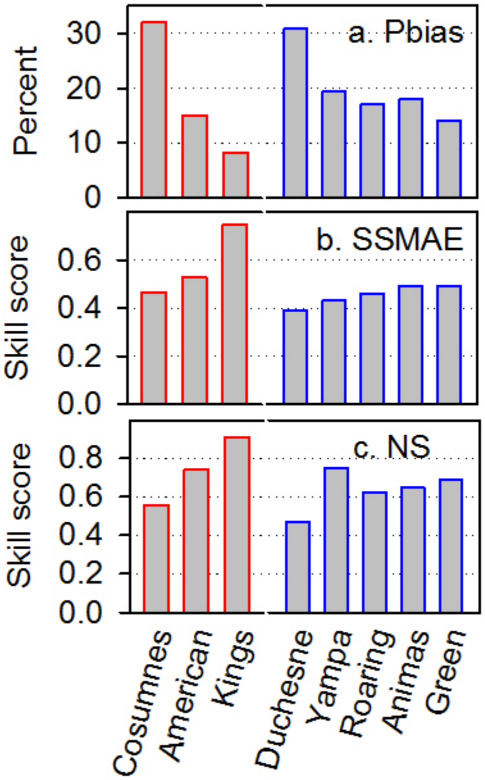


Figure 6. Median PBias skill scores for three representative watersheds in the Sierra Nevada and five watersheds in the Colorado River basin.

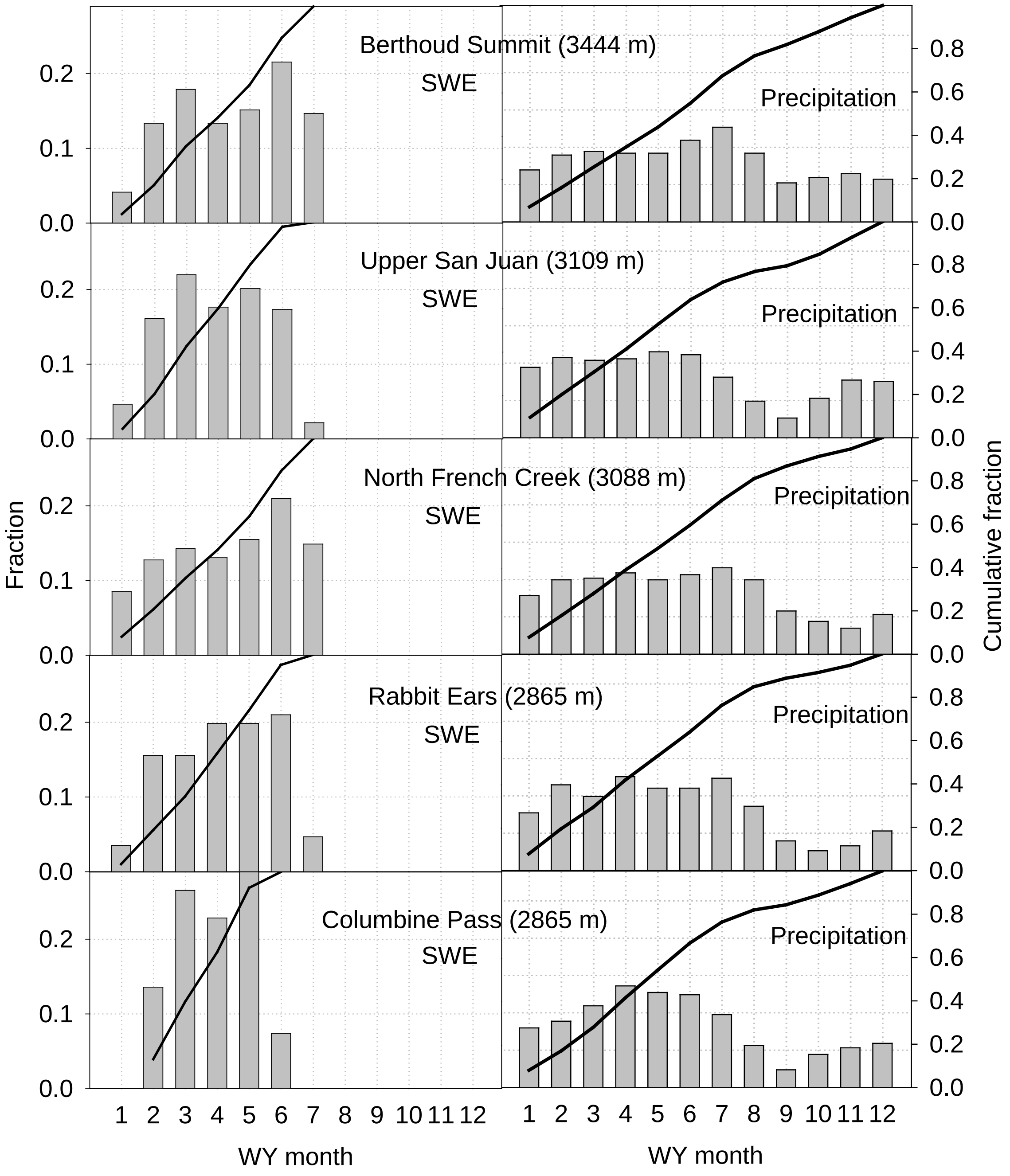


Figure 7. Monthly SWE and precipitation with accumulation. Data from NRCS, 1981-2010.

CHAPTER 6

Conclusions

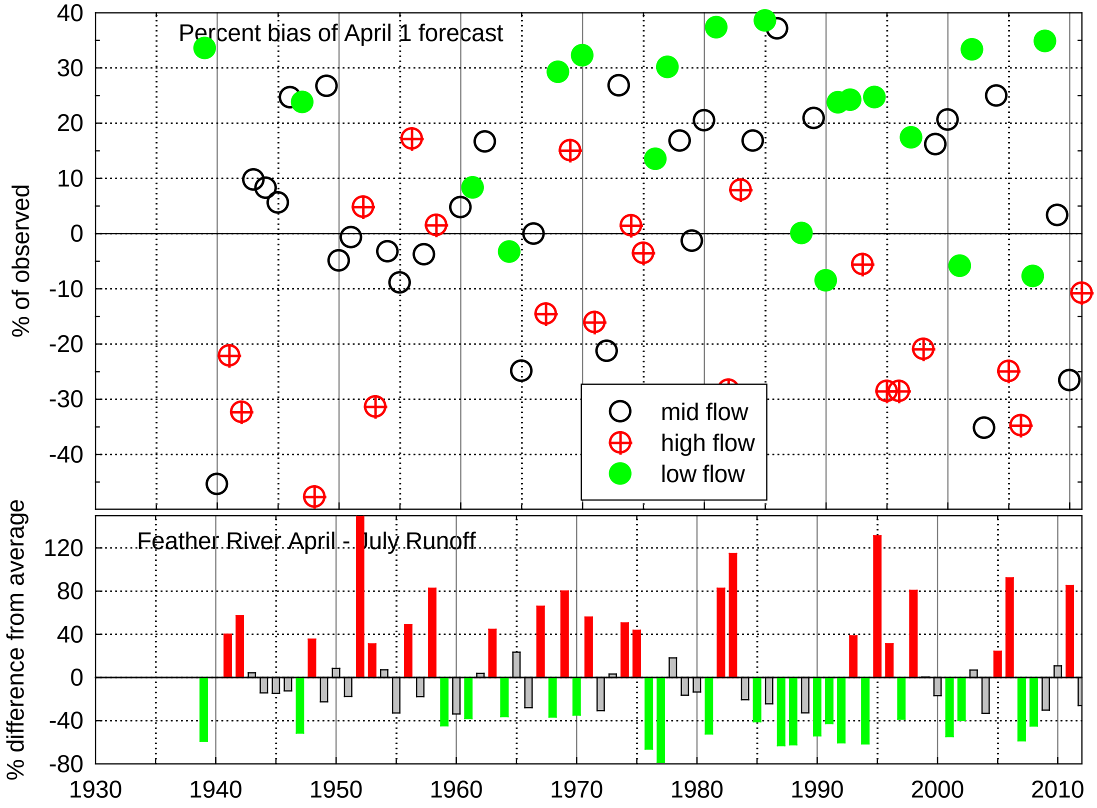
This work to quantify the skill of water supply forecasts and to identify watershed features that affect those skill measures can assist water resource professionals in preparing for the challenges of a changing climate. An increase in the proportion of precipitation falling as rain in the Sierra Nevada may reduce the forecast skill in the northern Sierra as the snow dominance of the runoff from those watersheds decreases. In contrast, the higher central and southern Sierra Nevada may maintain their snow dominated runoff and retain their current forecast skill. In a like manner, changes in total precipitation may affect the northern and southern Sierra differently. A portion of any increase in precipitation will be expressed as increased snow in the southern Sierra, with a lesser expression of snow in the northern Sierra. These changes will shift the April to July runoff portion of the water year runoff to earlier in the season, and require an adjustment in forecast procedures and computations. Climate changes in other parts of the western United States may also be expected, the exact form of the change depending on the physical characteristics of the watershed. The time series of skill measures examined in this study indicate no increase in skill over the time period of record. This static result exists in spite of improvements in computational techniques and hardware over the period of the historical record. This indicates that the human contribution to forecasting influences the forecasts and that users of the forecasts are familiar with the assumptions and conventions instituted during the forecasting process.

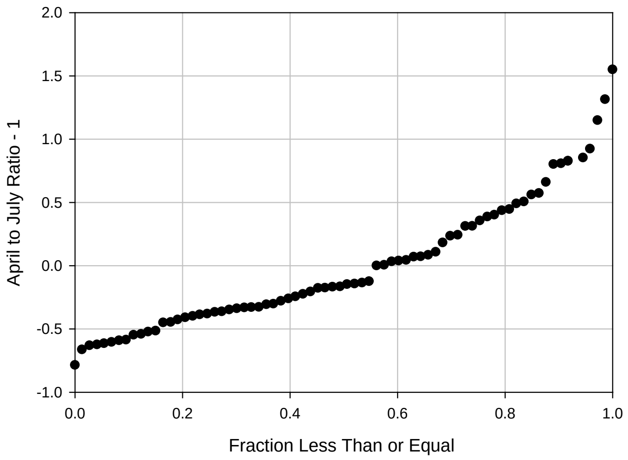
The assumptions that go into the forecasting process shape the final skill measures and are detectable during analysis. The assumption of average precipitation and normal climatology early in the forecast season clearly shapes the skill scores, particularly for mid-flow forecasts. High flows are under forecast throughout the forecast season. The conservative nature of the forecasting process is clear in the skill analysis of False Alarms and Bias, which show consistent under forecast of high flows.

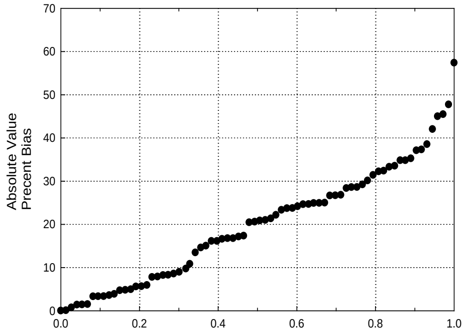
Increased knowledge of conditions in the field would be useful to reduce the uncertainty of forecast distributions. Accordingly, a denser grid of snow and meteorological stations will improve forecasting information thus building confidence in the forecasts. The lower skill level in forecasting high runoff years may be improved by utilization of modern data collection, storage and retrieval systems, which will provide the forecasting process more information throughout the forecast season. Adding data collection points and denser sensor networks will improve the data availability earlier in the forecast season. These changes may improve the forecasts earlier in the forecast season which may benefit users of the water supply forecasts. Future increases in skill level could be enabled by incorporating snow cover data estimated by remote sensing blended with representative ground measurements into the forecasting process.

Appendix A

Percent bias information on Sierra Nevada forecast locations







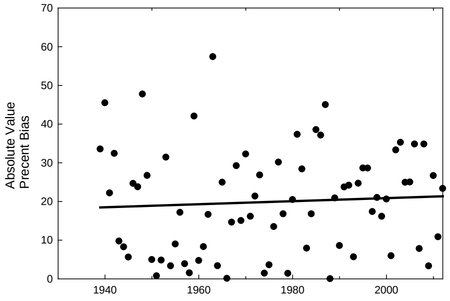
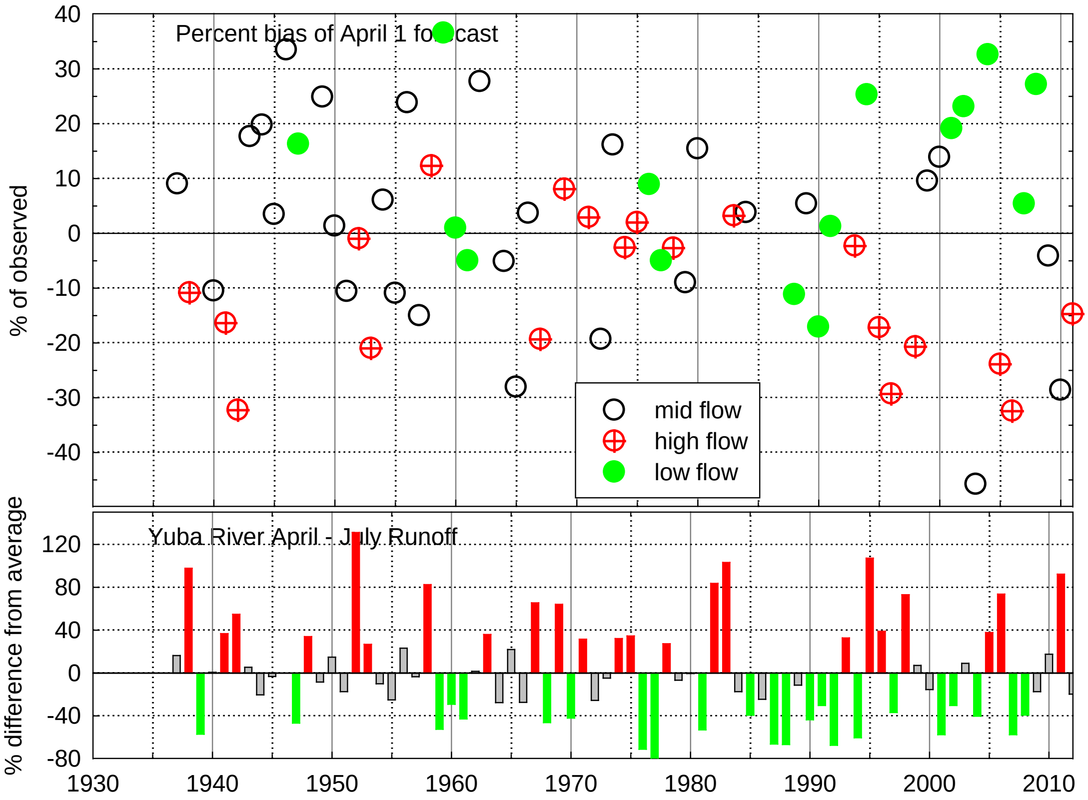
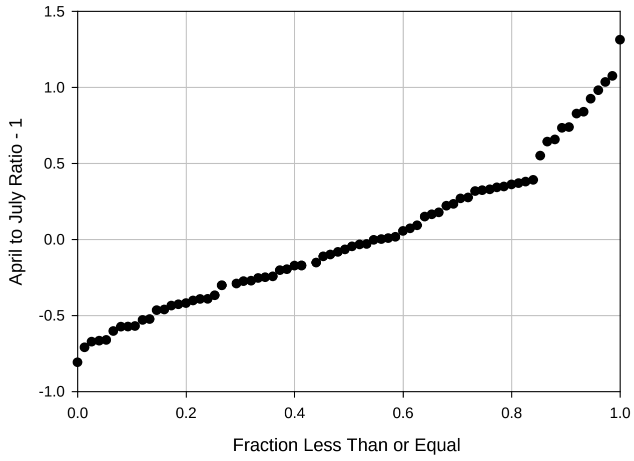
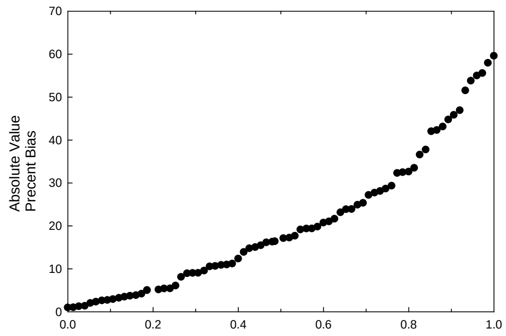


Figure A1: Feather River. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.







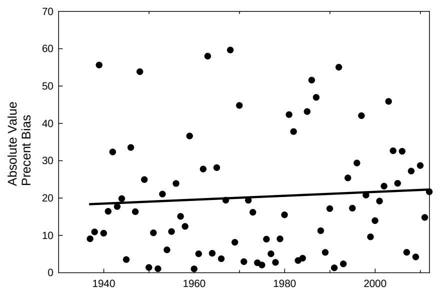
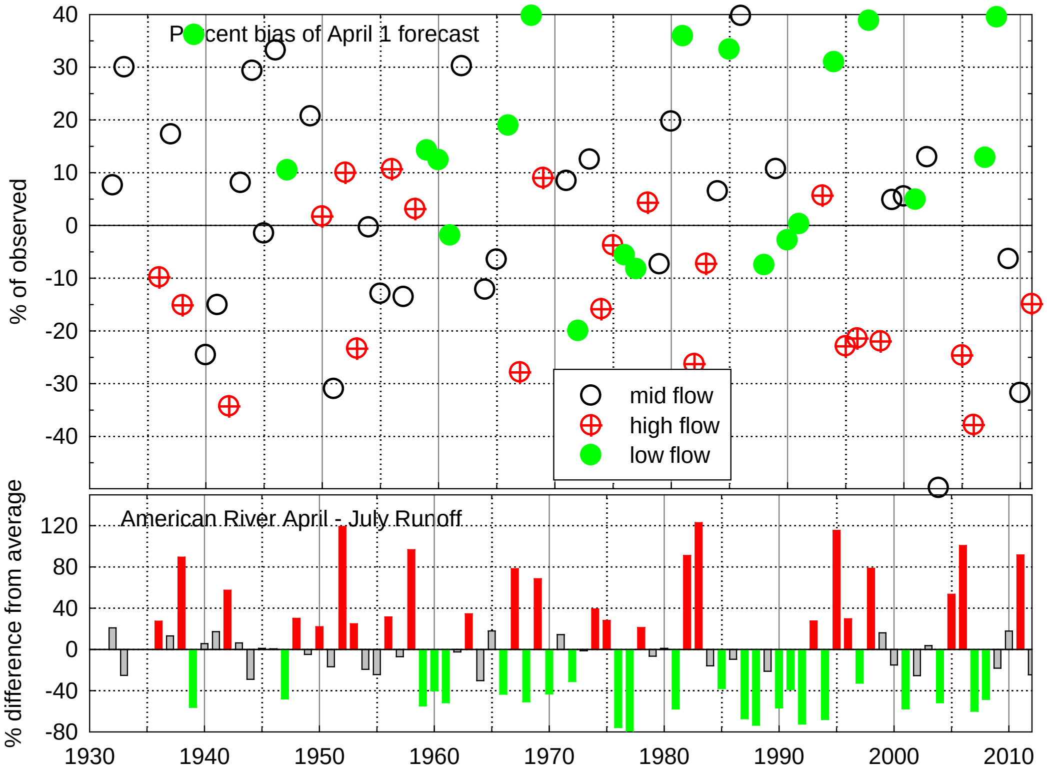
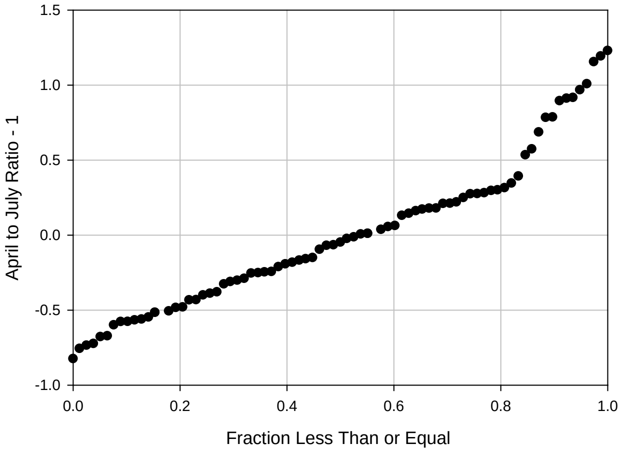
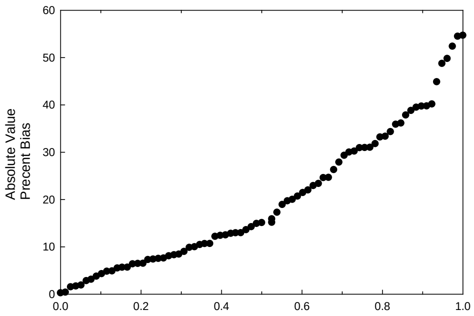


Figure A2: Yuba River. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.







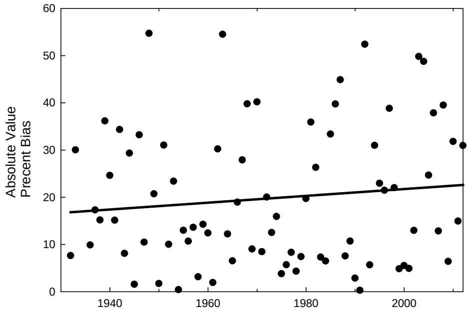
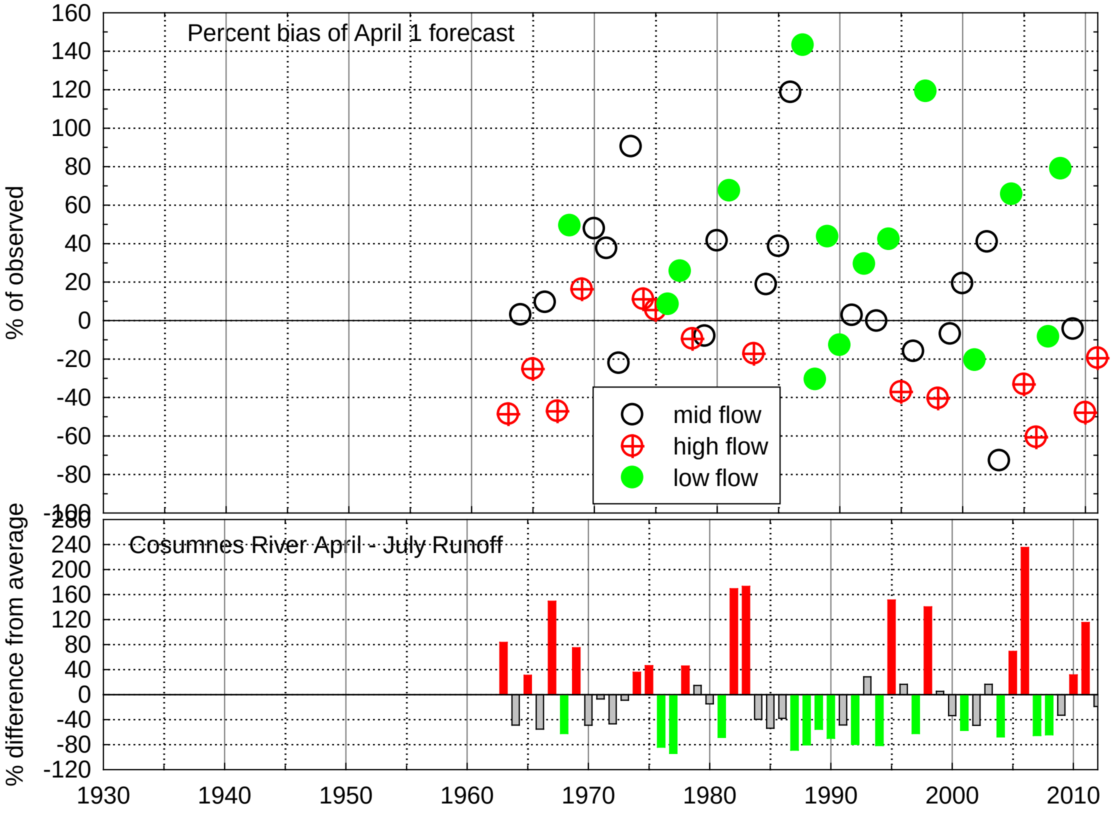
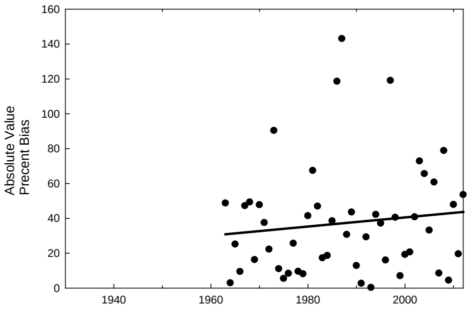
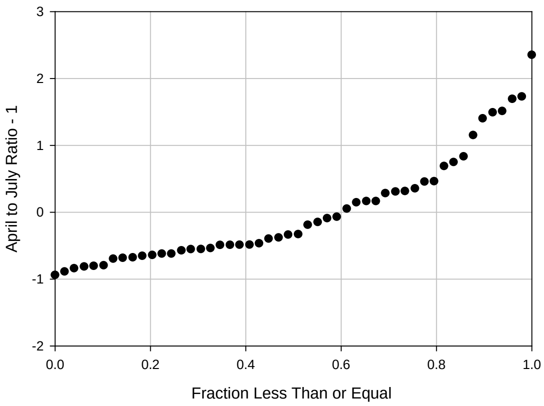


Figure A3: American River. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.







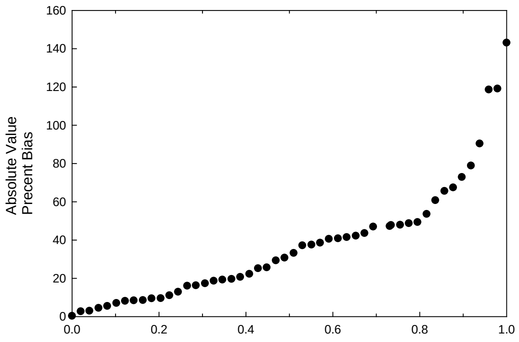
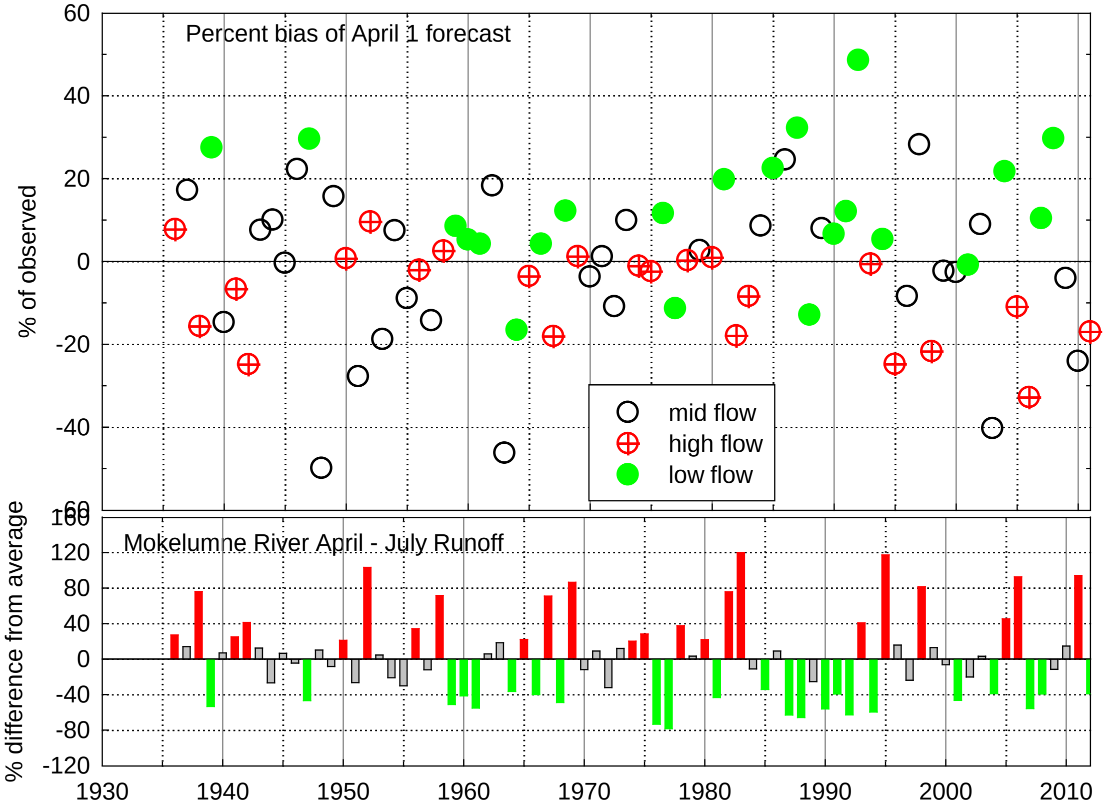
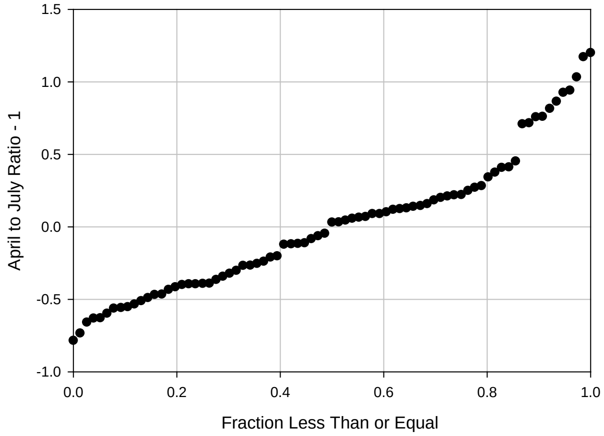
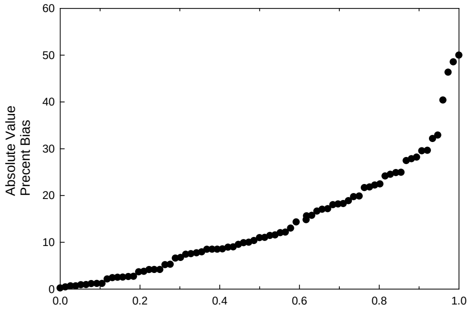


Figure A4: Cosumnes River. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.







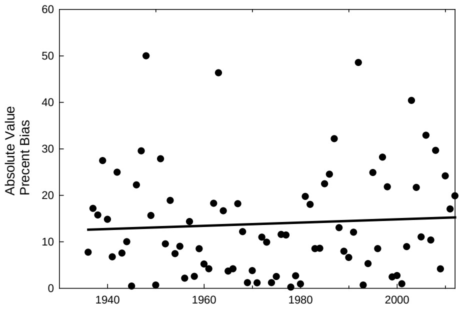
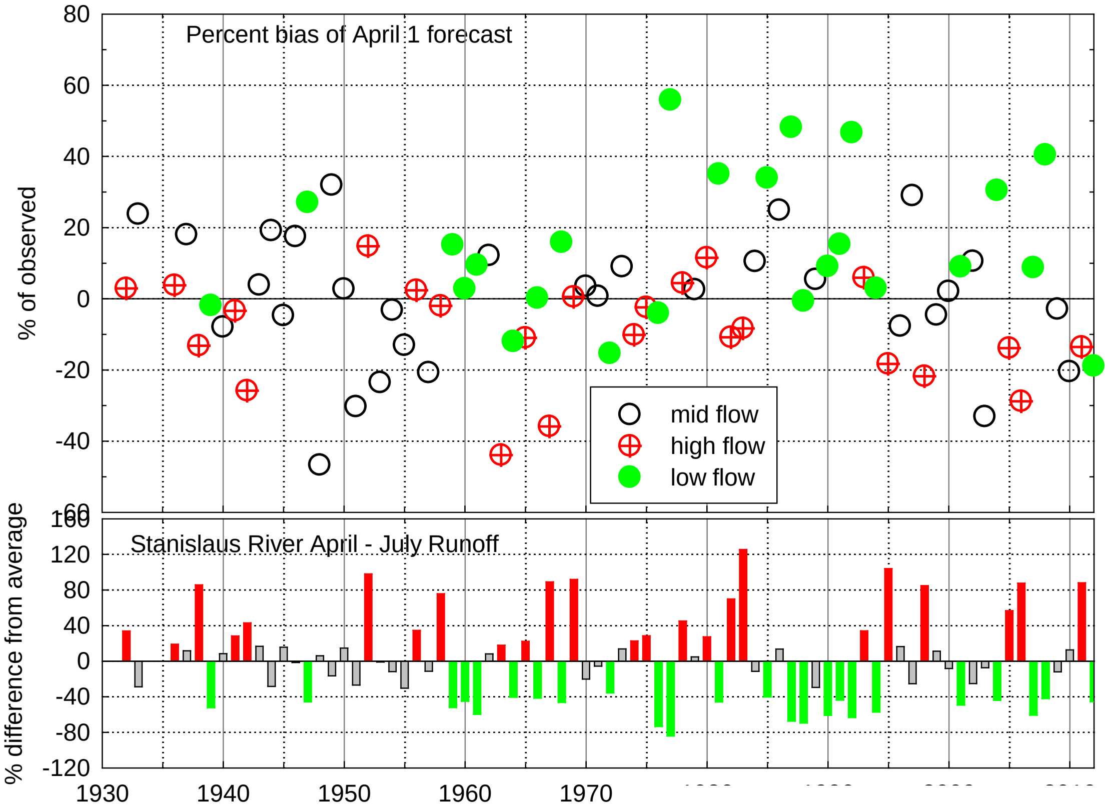
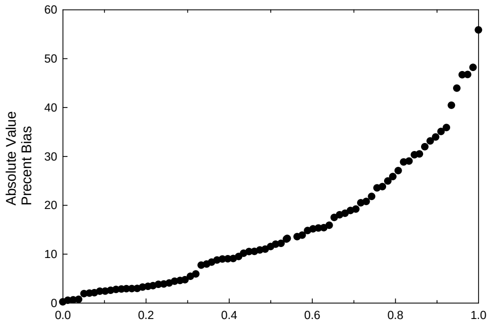
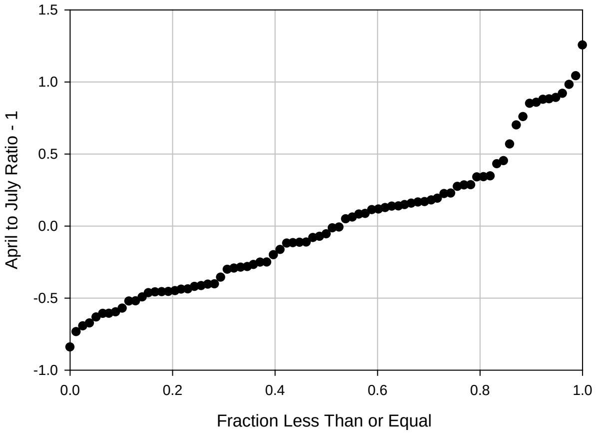


Figure A5: Mokelumne River. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.







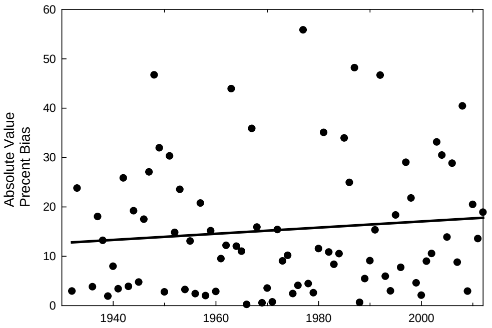
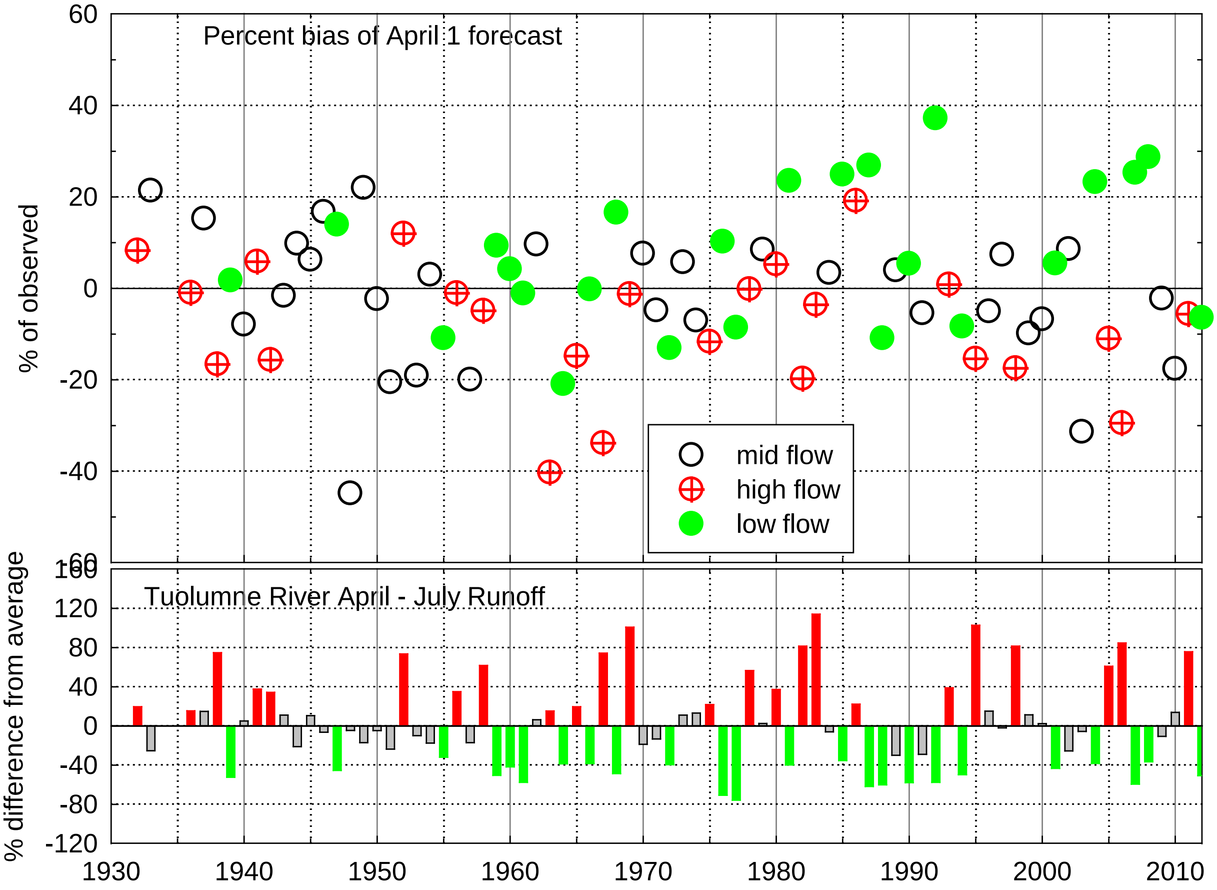
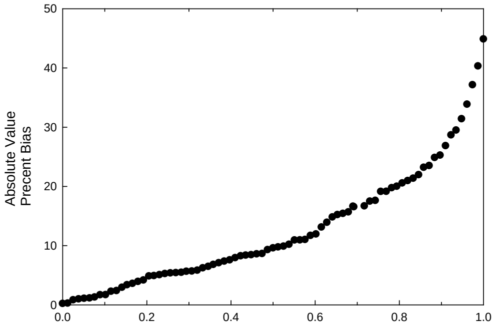
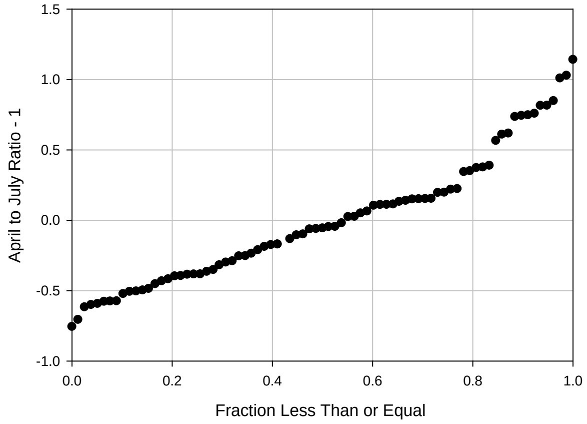


Figure A6: Stanislaus River. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.







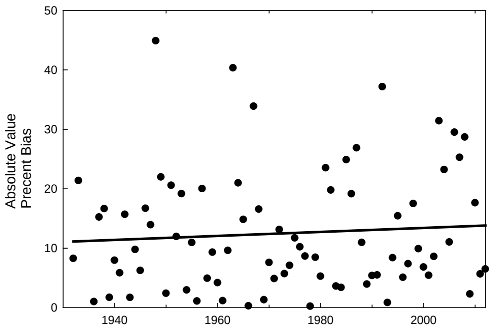


Figure A7: Tuolumne River. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.

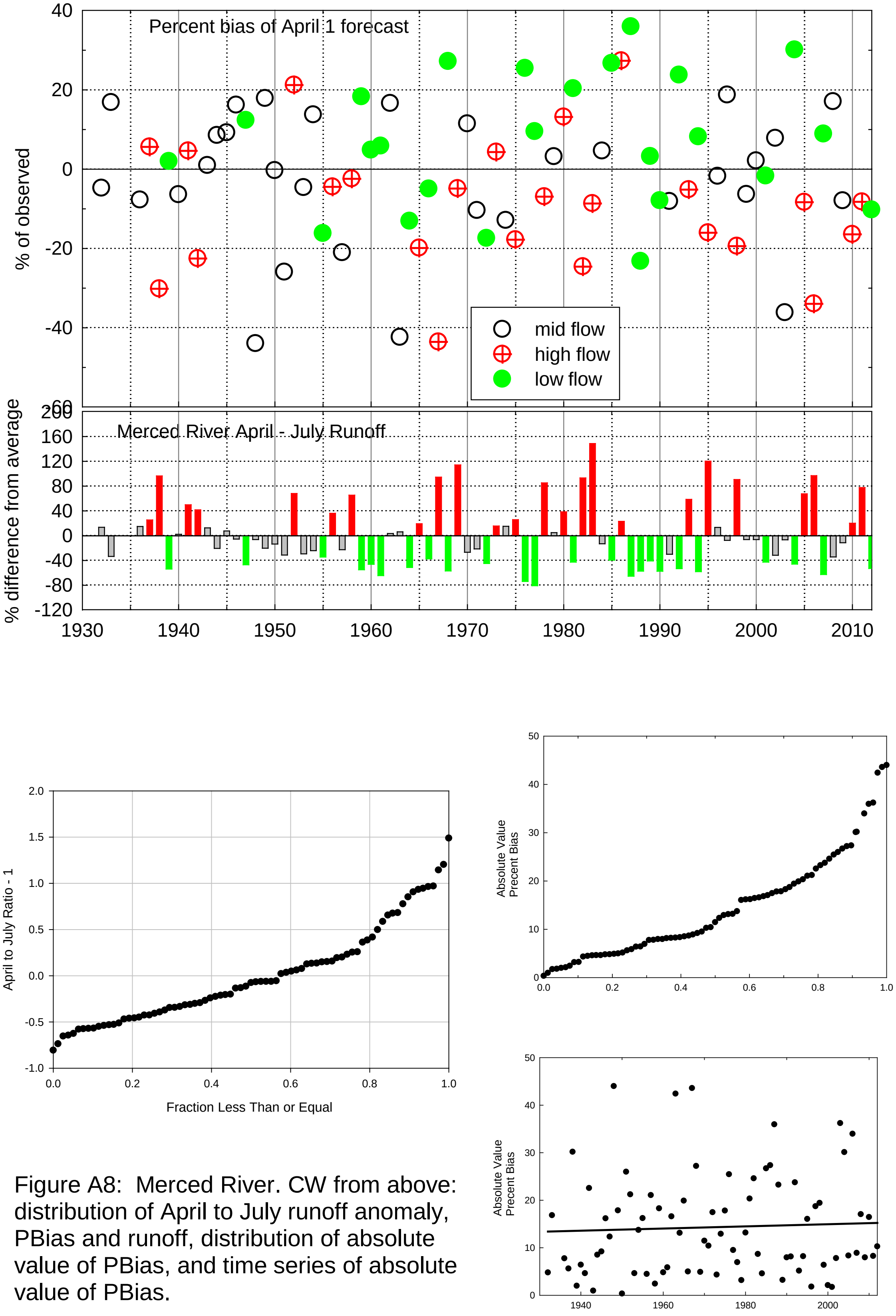
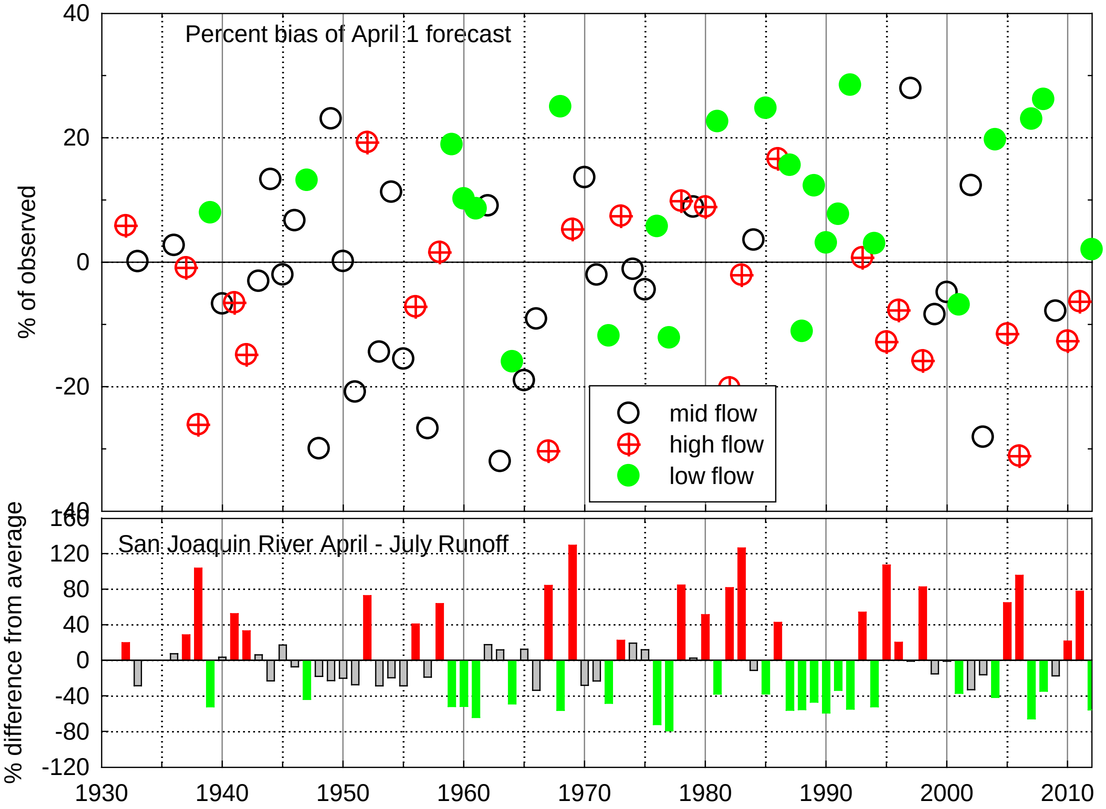
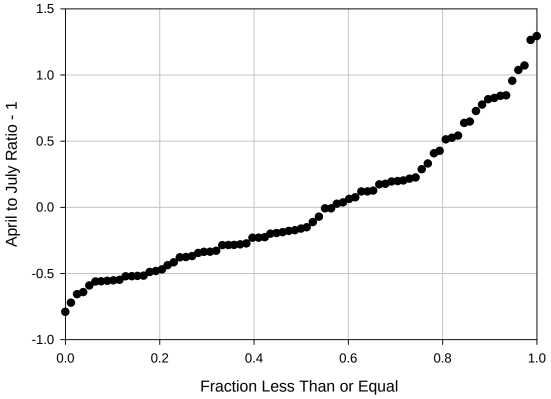
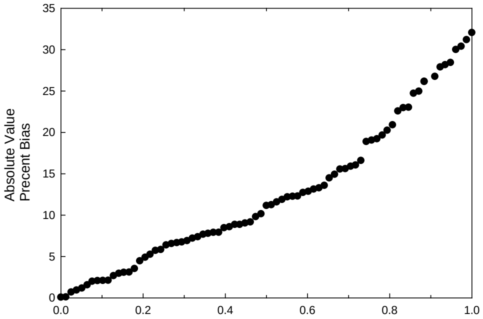


Figure A8: Merced River. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.







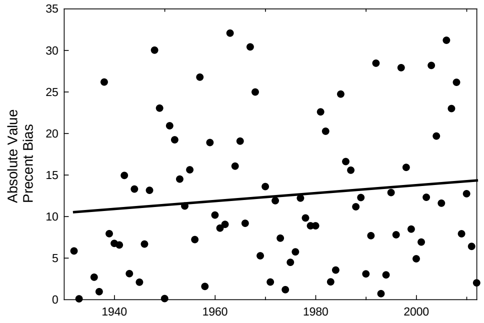
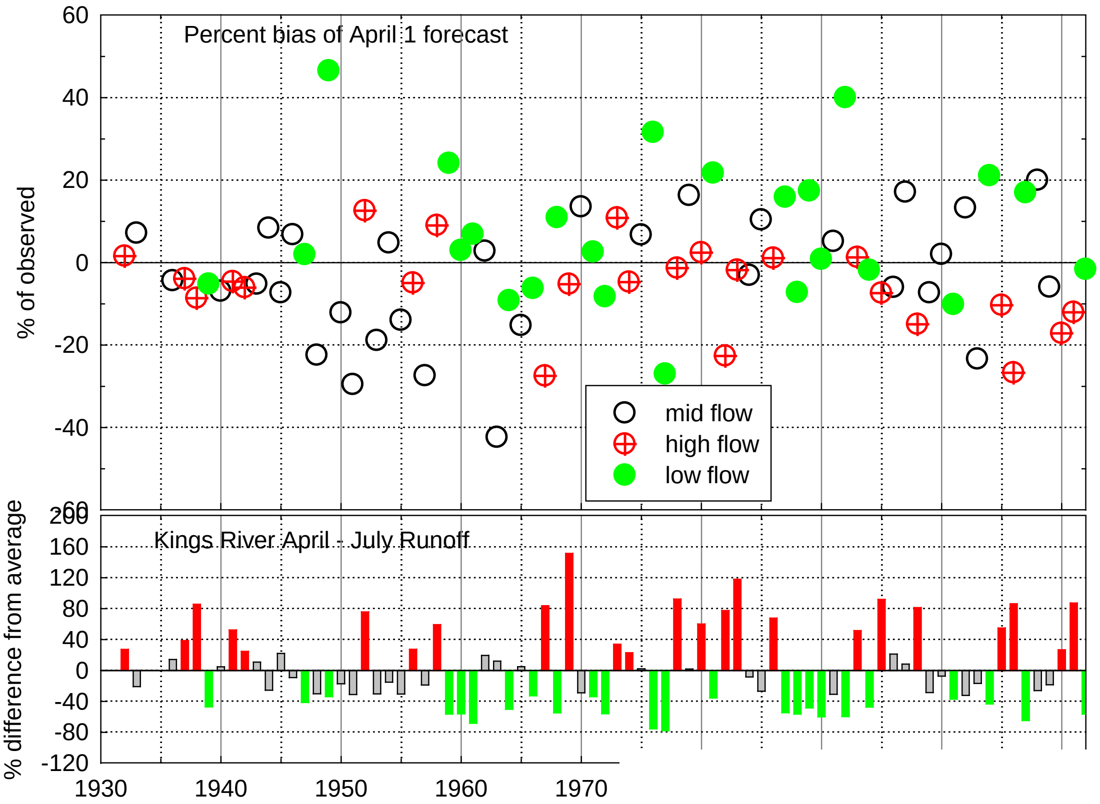
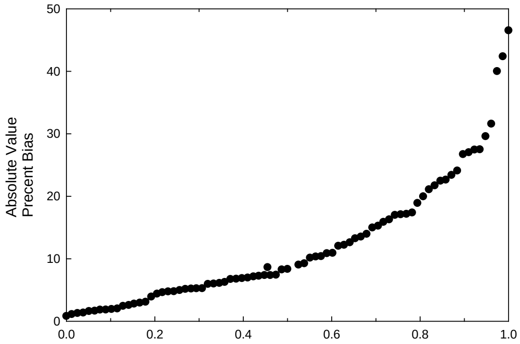
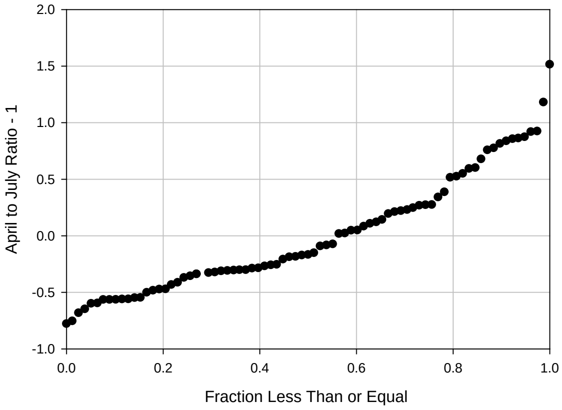


Figure A9: San Joaquin River. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.







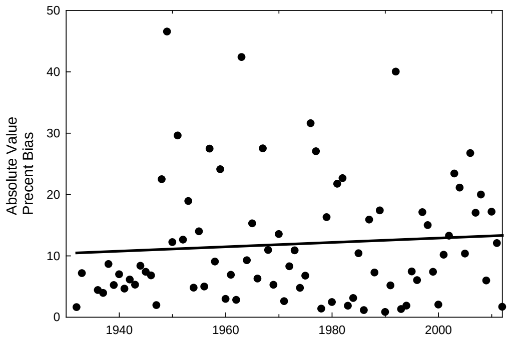
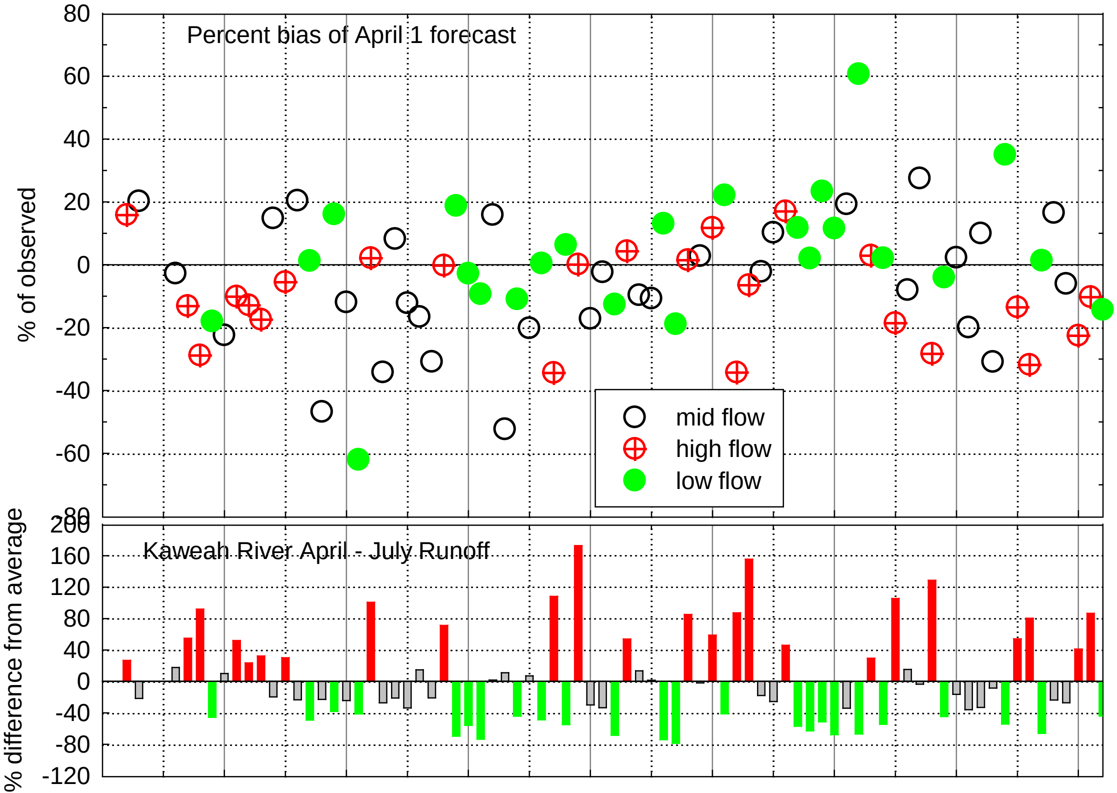
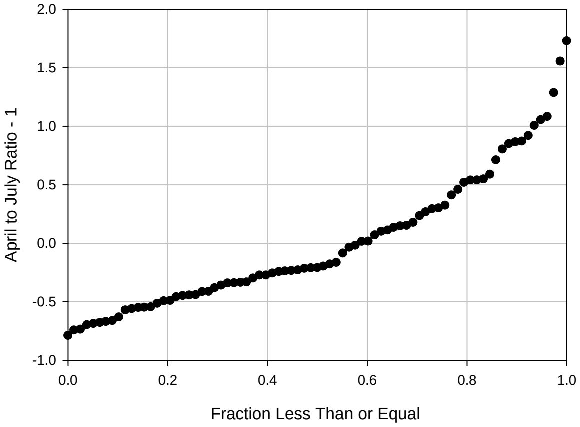
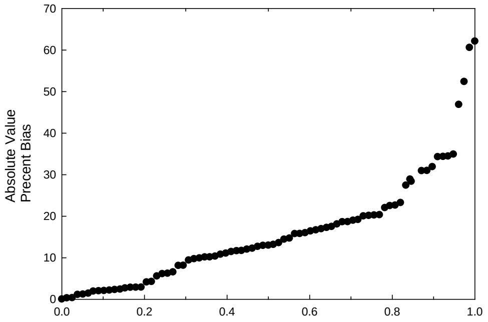


Figure A10: Kings River. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.







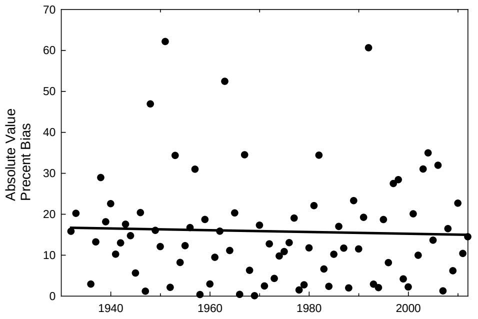
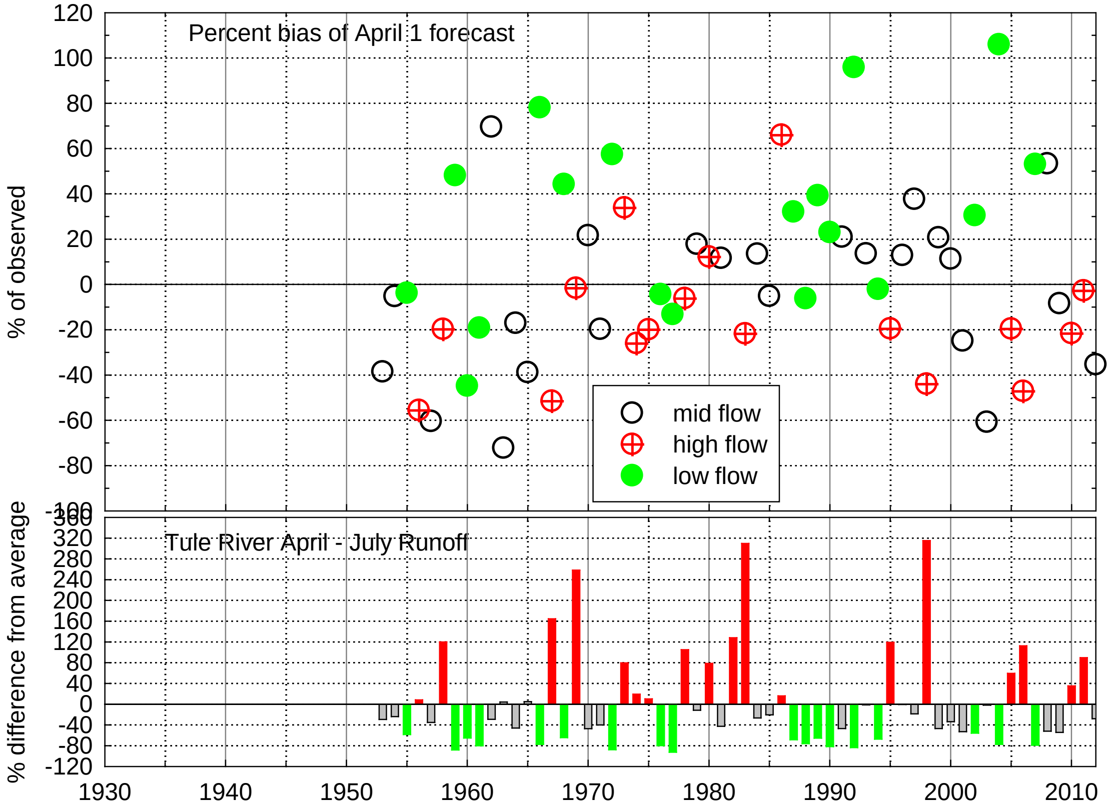
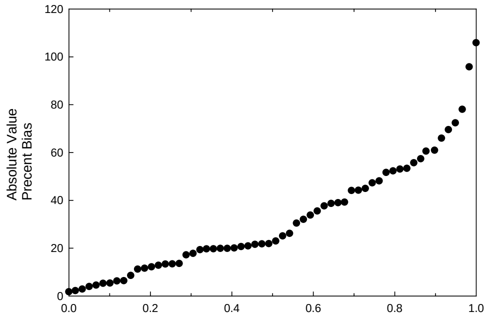
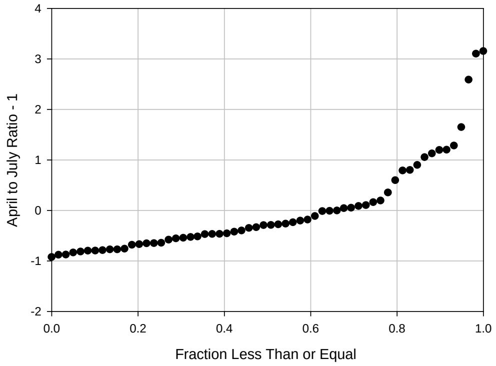


Figure A11: Kaweah River. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.







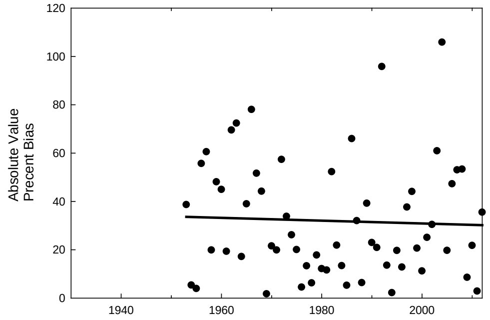
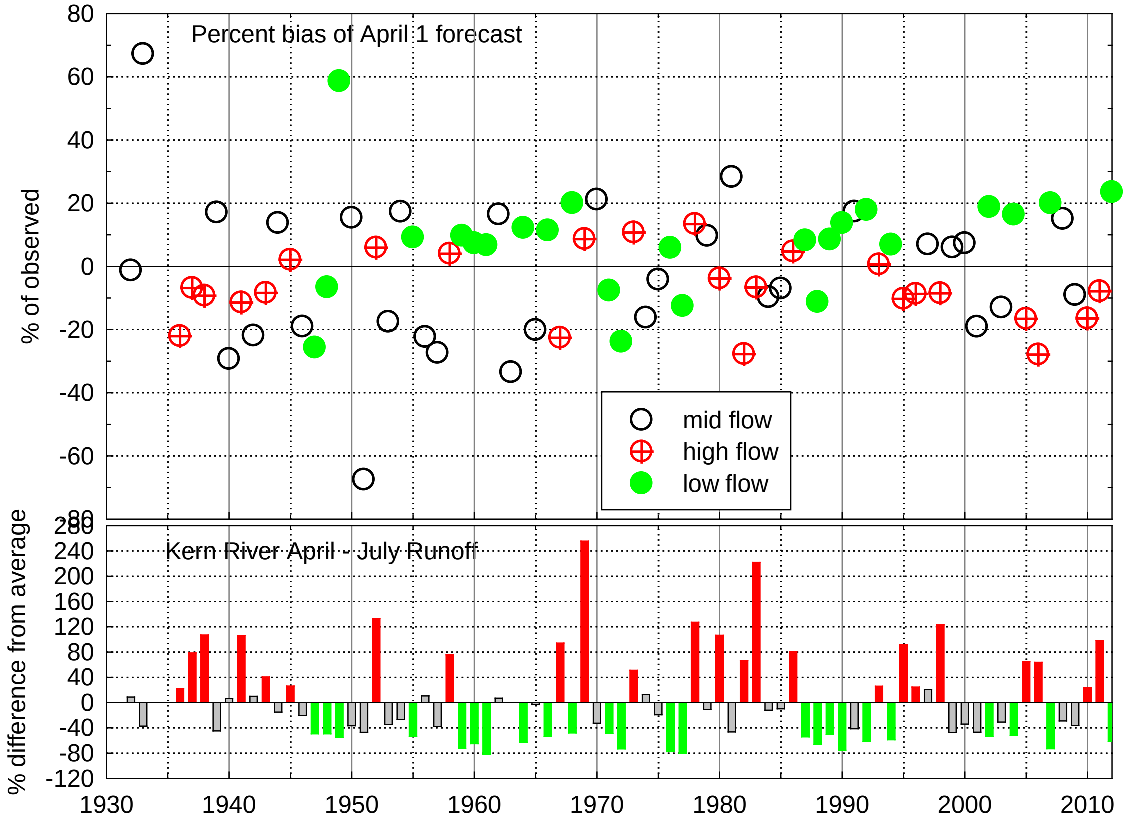
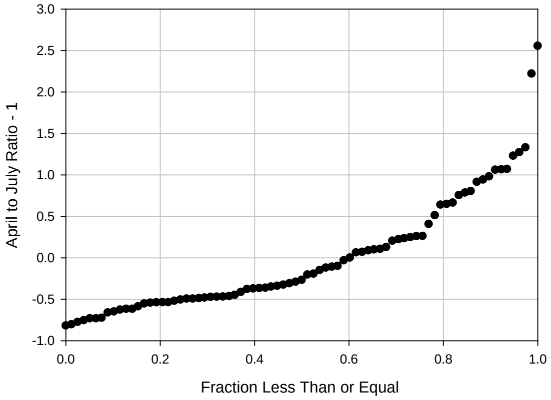
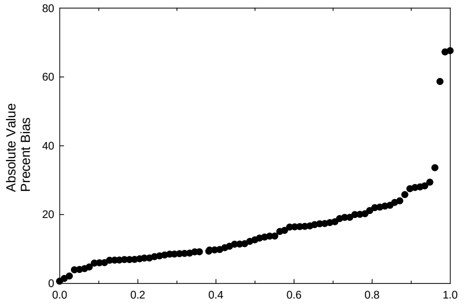


Figure A12: Tule River. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.







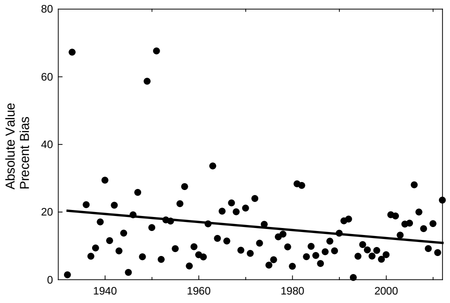


Figure A13: Kern River. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.

Appendix B

Western Sierra Nevada skill scores

Table 1: Skill Score Mean Absolute Error

Location	Name	Feb	Mar	Apr	May
1	Feather	0.284	0.279	0.539	0.752
2	Yuba	0.252	0.226	0.512	0.721
3	American	0.230	0.254	0.529	0.719
4	Cosumnes	0.210	0.224	0.466	0.747
5	Mokelumne	0.281	0.392	0.643	0.761
6	Stanislaus	0.285	0.418	0.641	0.752
7	Tuolumne	0.296	0.451	0.670	0.794
8	Merced	0.306	0.447	0.654	0.783
9	San Joaquin	0.333	0.520	0.708	0.812
10	Kings	0.320	0.532	0.746	0.832
11	Kaweah	0.319	0.474	0.671	0.790
12	Tule	0.284	0.390	0.570	0.775
13	Kern	0.318	0.563	0.753	0.840

Table 2: R^2 between forecasts and observations by month for April to July runoff

Location	Name	Feb	Mar	Apr	May
1	Feather	0.395	0.410	0.749	0.923
2	Yuba	0.374	0.361	0.721	0.921
3	American	0.358	0.389	0.751	0.916
4	Cosumnes	0.251	0.242	0.599	0.912
5	Mokelumne	0.457	0.533	0.838	0.935
6	Stanislaus	0.480	0.588	0.840	0.928
7	Tuolumne	0.505	0.625	0.866	0.950
8	Merced	0.524	0.604	0.846	0.944
9	San Joaquin	0.557	0.674	0.887	0.952
10	Kings	0.551	0.727	0.917	0.968
11	Kaweah	0.557	0.683	0.867	0.952
12	Tule	0.454	0.614	0.780	0.943
13	Kern	0.540	0.785	0.939	0.973

Table 3: Nash Sutcliffe score for April - July forecasts

Location	Name	Feb	Mar	Apr	May
1	Feather	0.379	0.395	0.745	0.922
2	Yuba	0.352	0.334	0.717	0.920
3	American	0.337	0.373	0.744	0.914
4	Cosumnes	0.216	0.211	0.560	0.907
5	Mokelumne	0.437	0.518	0.829	0.930
6	Stanislaus	0.456	0.573	0.835	0.927
7	Tuolumne	0.471	0.602	0.858	0.948
8	Merced	0.470	0.573	0.832	0.940
9	San Joaquin	0.520	0.652	0.884	0.950
10	Kings	0.511	0.694	0.912	0.966
11	Kaweah	0.477	0.631	0.848	0.939
12	Tule	0.313	0.534	0.753	0.922
13	Kern	0.444	0.764	0.936	0.971

Table 4: Probability of detection for low flow years

Location	Name	Feb	Mar	Apr	May
1	Feather	0.450	0.550	0.591	0.818
2	Yuba	0.524	0.524	0.652	0.783
3	American	0.550	0.550	0.682	0.864
4	Cosumnes	0.412	0.412	0.529	0.882
5	Mokelumne	0.571	0.619	0.739	0.957
6	Stanislaus	0.524	0.524	0.696	0.783
7	Tuolumne	0.524	0.571	0.826	0.826
8	Merced	0.600	0.700	0.864	0.864
9	San Joaquin	0.650	0.750	0.864	0.864
10	Kings	0.650	0.800	0.826	0.870
11	Kaweah	0.579	0.684	0.909	0.955
12	Tule	0.526	0.500	0.850	0.950
13	Kern	0.579	0.579	0.773	0.909

Table 5: Probability of detection for mid flow years

Location	Name	Feb	Mar	Apr	May
1	Feather	0.762	0.714	0.793	0.828
2	Yuba	0.750	0.750	0.690	0.862
3	American	0.682	0.636	0.636	0.774
4	Cosumnes	0.706	0.588	0.588	0.824
5	Mokelumne	0.773	0.818	0.645	0.839
6	Stanislaus	0.857	0.857	0.688	0.806
7	Tuolumne	0.857	0.810	0.750	0.839
8	Merced	0.810	0.810	0.727	0.833
9	San Joaquin	0.818	0.909	0.727	0.806
10	Kings	0.818	0.818	0.677	0.793
11	Kaweah	0.680	0.800	0.719	0.839
12	Tule	0.684	0.667	0.565	0.870
13	Kern	0.739	0.957	0.844	0.900

Table 6: Probability of detection for high flow years

Location	Name	Feb	Mar	Apr	May
1	Feather	0.421	0.316	0.652	0.739
2	Yuba	0.421	0.368	0.625	0.708
3	American	0.444	0.333	0.667	0.739
4	Cosumnes	0.438	0.375	0.750	0.875
5	Mokelumne	0.529	0.471	0.826	0.864
6	Stanislaus	0.500	0.500	0.833	0.955
7	Tuolumne	0.611	0.611	0.792	0.955
8	Merced	0.526	0.632	0.792	0.917
9	San Joaquin	0.444	0.611	0.875	0.957
10	Kings	0.500	0.611	0.800	0.917
11	Kaweah	0.375	0.625	0.840	0.913
12	Tule	0.563	0.588	0.765	0.882
13	Kern	0.389	0.667	0.880	0.917

Table 7: False alarm rate for low flow years

Location	Name	Feb	Mar	Apr	May
1	Feather	0.400	0.267	0.278	0.182
2	Yuba	0.353	0.267	0.318	0.100
3	American	0.353	0.267	0.318	0.136
4	Cosumnes	0.300	0.300	0.250	0.118
5	Mokelumne	0.200	0.071	0.261	0.083
6	Stanislaus	0.154	0.083	0.200	0.100
7	Tuolumne	0.267	0.200	0.174	0.136
8	Merced	0.200	0.176	0.269	0.174
9	San Joaquin	0.133	0.063	0.269	0.174
10	Kings	0.188	0.158	0.296	0.200
11	Kaweah	0.313	0.188	0.259	0.192
12	Tule	0.333	0.333	0.261	0.136
13	Kern	0.267	0.083	0.190	0.130

Table 8: False alarm rate for mid flow years

Location	Name	Feb	Mar	Apr	May
1	Feather	0.556	0.583	0.410	0.294
2	Yuba	0.545	0.583	0.429	0.324
3	American	0.531	0.588	0.382	0.273
4	Cosumnes	0.600	0.655	0.545	0.222
5	Mokelumne	0.485	0.486	0.333	0.133
6	Stanislaus	0.500	0.500	0.333	0.194
7	Tuolumne	0.455	0.469	0.273	0.161
8	Merced	0.500	0.433	0.250	0.167
9	San Joaquin	0.486	0.375	0.200	0.138
10	Kings	0.471	0.379	0.300	0.179
11	Kaweah	0.514	0.375	0.207	0.103
12	Tule	0.536	0.548	0.350	0.130
13	Kern	0.528	0.389	0.229	0.129

Table 9: False alarm rate for high flow years

Location	Name	Feb	Mar	Apr	May
1	Feather	0.111	0.333	0.118	0.056
2	Yuba	0.200	0.222	0.211	0.105
3	American	0.273	0.455	0.304	0.190
4	Cosumnes	0.300	0.455	0.250	0.067
5	Mokelumne	0.250	0.273	0.208	0.136
6	Stanislaus	0.182	0.250	0.231	0.160
7	Tuolumne	0.083	0.154	0.174	0.087
8	Merced	0.091	0.077	0.095	0.043
9	San Joaquin	0.200	0.083	0.087	0.083
10	Kings	0.100	0.083	0.091	0.043
11	Kaweah	0.333	0.167	0.087	0.000
12	Tule	0.182	0.167	0.235	0.000
13	Kern	0.222	0.000	0.043	0.000

Table 10: Bias for low flow years

Location	Name	Feb	Mar	Apr	May
1	Feather	0.750	0.750	0.818	1.000
2	Yuba	0.810	0.714	0.957	0.870
3	American	0.850	0.750	1.000	1.000
4	Cosumnes	0.588	0.588	0.706	1.000
5	Mokelumne	0.714	0.667	1.000	1.043
6	Stanislaus	0.619	0.571	0.870	0.870
7	Tuolumne	0.714	0.714	1.000	0.957
8	Merced	0.750	0.850	1.182	1.045
9	San Joaquin	0.750	0.800	1.182	1.045
10	Kings	0.800	0.950	1.174	1.087
11	Kaweah	0.842	0.842	1.227	1.182
12	Tule	0.789	0.750	1.150	1.100
13	Kern	0.789	0.632	0.955	1.045

Table 11: Bias for mid flow years

Location	Name	Feb	Mar	Apr	May
1	Feather	1.714	1.714	1.345	1.172
2	Yuba	1.650	1.800	1.207	1.276
3	American	1.455	1.545	1.030	1.065
4	Cosumnes	1.765	1.706	1.294	1.059
5	Mokelumne	1.500	1.591	0.968	0.968
6	Stanislaus	1.714	1.714	1.031	1.000
7	Tuolumne	1.571	1.524	1.031	1.000
8	Merced	1.619	1.429	0.970	1.000
9	San Joaquin	1.591	1.455	0.909	0.935
10	Kings	1.545	1.318	0.968	0.966
11	Kaweah	1.400	1.280	0.906	0.935
12	Tule	1.474	1.476	0.870	1.000
13	Kern	1.565	1.565	1.094	1.033

Table 12: Bias for high flow years

Location	Name	Feb	Mar	Apr	May
1	Feather	0.474	0.474	0.739	0.783
2	Yuba	0.526	0.474	0.792	0.792
3	American	0.611	0.611	0.958	0.913
4	Cosumnes	0.625	0.688	1.000	0.938
5	Mokelumne	0.706	0.647	1.043	1.000
6	Stanislaus	0.611	0.667	1.083	1.136
7	Tuolumne	0.667	0.722	0.958	1.045
8	Merced	0.579	0.684	0.875	0.958
9	San Joaquin	0.556	0.667	0.958	1.043
10	Kings	0.556	0.667	0.880	0.958
11	Kaweah	0.563	0.750	0.920	0.913
12	Tule	0.688	0.706	1.000	0.882
13	Kern	0.500	0.667	0.920	0.917

Table 13: Threat score for low flow years

Location	Name	Feb	Mar	Apr	May
1	Feather	0.346	0.458	0.481	0.692
2	Yuba	0.407	0.440	0.500	0.720
3	American	0.423	0.458	0.517	0.760
4	Cosumnes	0.350	0.350	0.450	0.789
5	Mokelumne	0.500	0.591	0.586	0.880
6	Stanislaus	0.478	0.500	0.593	0.720
7	Tuolumne	0.440	0.500	0.704	0.731
8	Merced	0.522	0.609	0.655	0.731
9	San Joaquin	0.591	0.714	0.655	0.731
10	Kings	0.565	0.696	0.613	0.714
11	Kaweah	0.458	0.591	0.690	0.778
12	Tule	0.417	0.400	0.654	0.826
13	Kern	0.478	0.550	0.654	0.800

Table 14: Threat score for mid flow years

Location	Name	Feb	Mar	Apr	May
1	Feather	0.390	0.357	0.511	0.615
2	Yuba	0.395	0.366	0.455	0.610
3	American	0.385	0.333	0.457	0.600
4	Cosumnes	0.343	0.278	0.345	0.667
5	Mokelumne	0.447	0.462	0.488	0.743
6	Stanislaus	0.462	0.462	0.512	0.676
7	Tuolumne	0.500	0.472	0.585	0.722
8	Merced	0.447	0.500	0.585	0.714
9	San Joaquin	0.462	0.588	0.615	0.714
10	Kings	0.474	0.545	0.525	0.676
11	Kaweah	0.395	0.541	0.605	0.765
12	Tule	0.382	0.368	0.433	0.769
13	Kern	0.405	0.595	0.675	0.794

Table 15: Threat score for high flow years

Location	Name	Feb	Mar	Apr	May
1	Feather	0.400	0.273	0.600	0.708
2	Yuba	0.381	0.333	0.536	0.654
3	American	0.381	0.261	0.516	0.630
4	Cosumnes	0.368	0.286	0.600	0.824
5	Mokelumne	0.450	0.400	0.679	0.760
6	Stanislaus	0.450	0.429	0.667	0.808
7	Tuolumne	0.579	0.550	0.679	0.875
8	Merced	0.500	0.600	0.731	0.880
9	San Joaquin	0.400	0.579	0.808	0.880
10	Kings	0.474	0.579	0.741	0.880
11	Kaweah	0.316	0.556	0.778	0.913
12	Tule	0.500	0.526	0.619	0.882
13	Kern	0.350	0.667	0.846	0.917

Table 16: Hit rate for low flow years

Location	Name	Feb	Mar	Apr	May
1	Feather	0.717	0.783	0.811	0.892
2	Yuba	0.733	0.767	0.803	0.908
3	American	0.750	0.783	0.823	0.921
4	Cosumnes	0.740	0.740	0.780	0.920
5	Mokelumne	0.800	0.850	0.844	0.961
6	Stanislaus	0.800	0.817	0.861	0.908
7	Tuolumne	0.767	0.800	0.899	0.908
8	Merced	0.817	0.850	0.873	0.908
9	San Joaquin	0.850	0.900	0.873	0.908
10	Kings	0.833	0.883	0.848	0.895
11	Kaweah	0.783	0.850	0.886	0.921
12	Tule	0.741	0.741	0.850	0.933
13	Kern	0.800	0.850	0.886	0.934

Table 17: Hit rate for mid flow years

Location	Name	Feb	Mar	Apr	May
1	Feather	0.583	0.550	0.703	0.797
2	Yuba	0.617	0.567	0.684	0.789
3	American	0.600	0.533	0.684	0.789
4	Cosumnes	0.540	0.480	0.620	0.860
5	Mokelumne	0.650	0.650	0.727	0.882
6	Stanislaus	0.650	0.650	0.734	0.842
7	Tuolumne	0.700	0.683	0.785	0.868
8	Merced	0.650	0.717	0.785	0.868
9	San Joaquin	0.650	0.767	0.810	0.868
10	Kings	0.667	0.750	0.759	0.855
11	Kaweah	0.567	0.717	0.810	0.895
12	Tule	0.611	0.586	0.717	0.900
13	Kern	0.583	0.750	0.835	0.908

Table 18: Hit rate for high flow years

Location	Name	Feb	Mar	Apr	May
1	Feather	0.800	0.733	0.865	0.905
2	Yuba	0.783	0.767	0.829	0.882
3	American	0.783	0.717	0.810	0.868
4	Cosumnes	0.760	0.700	0.840	0.940
5	Mokelumne	0.817	0.800	0.883	0.921
6	Stanislaus	0.817	0.800	0.873	0.934
7	Tuolumne	0.867	0.850	0.886	0.961
8	Merced	0.833	0.867	0.911	0.961
9	San Joaquin	0.800	0.867	0.937	0.961
10	Kings	0.833	0.867	0.911	0.961
11	Kaweah	0.783	0.867	0.924	0.974
12	Tule	0.833	0.845	0.867	0.967
13	Kern	0.783	0.900	0.949	0.974

Appendix C
Comparative Hydrology
Western Sierra Nevada

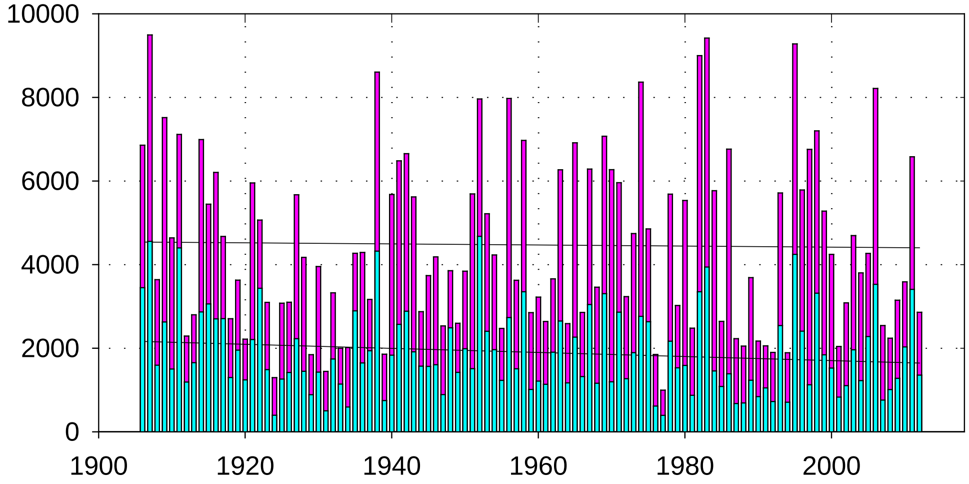


Figure C.1: Feather River runoff for historical record showing both April through July and water year runoff (1000 acre-ft.) with trend lines.

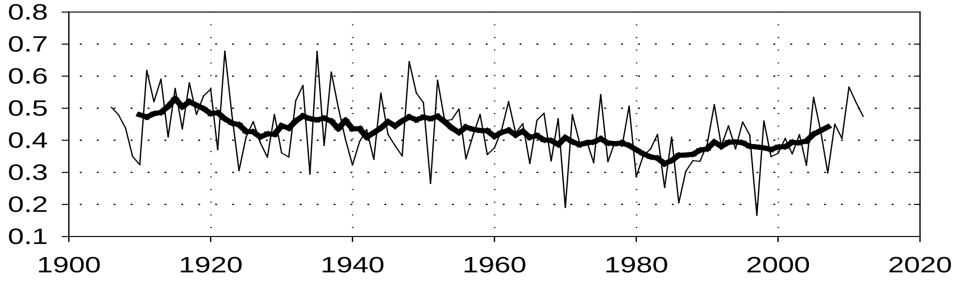


Figure C.2: Feather River April-July runoff ratio, along with 10 year moving average.

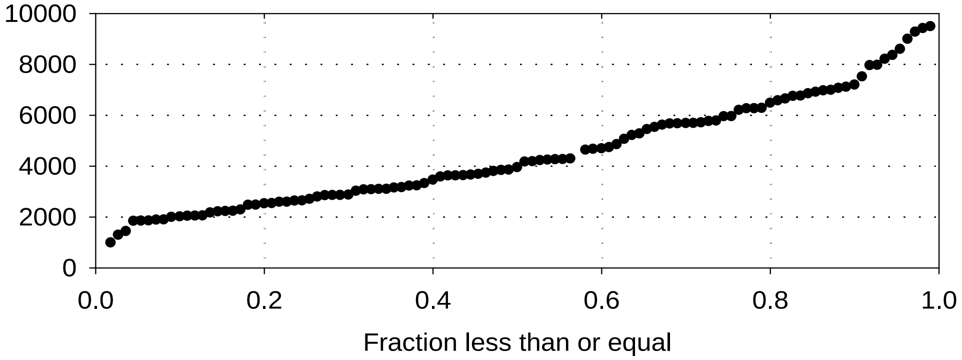


Figure C.3: Distribution of Feather River water year runoff (taf)

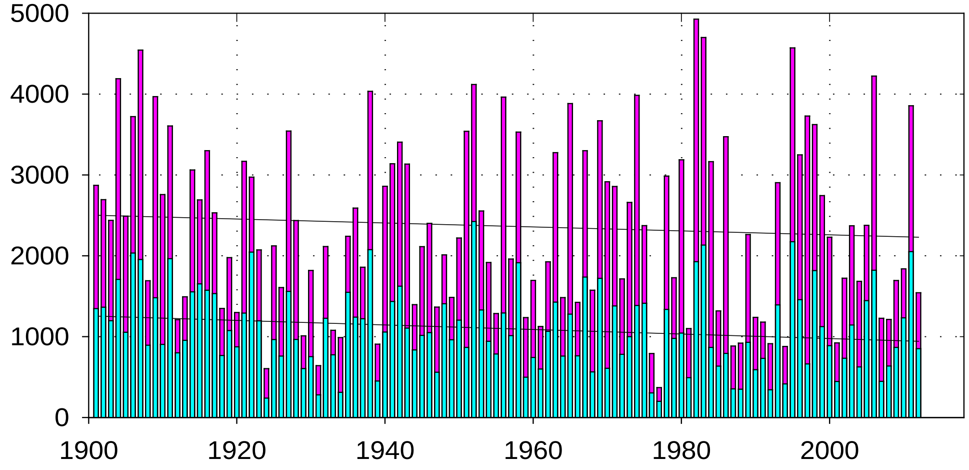


Figure C.4: Yuba River runoff for historical record showing both April through July and water year runoff (1000 acre-ft.) with trend lines.

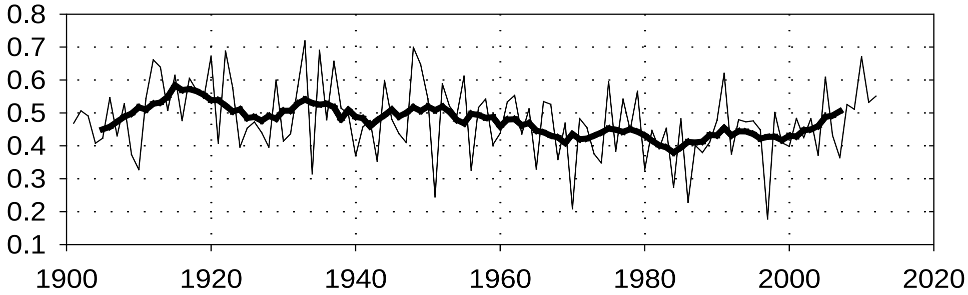


Figure C.5: Yuba River April-July runoff ratio, along with 10 year moving average.

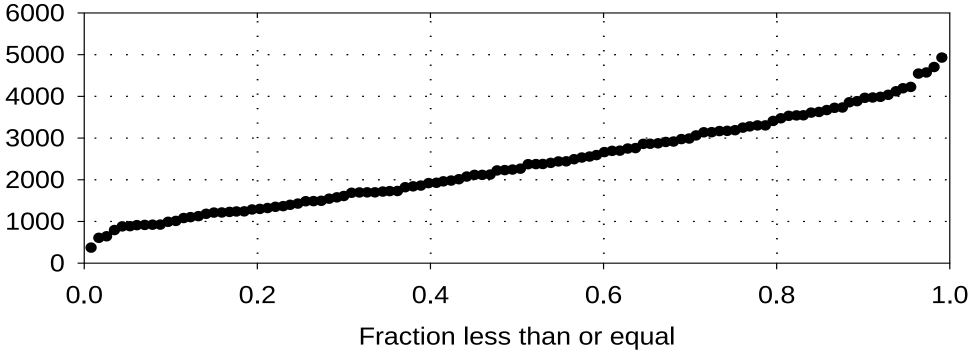


Figure C.6: Distribution of Yuba River water year runoff (taf)

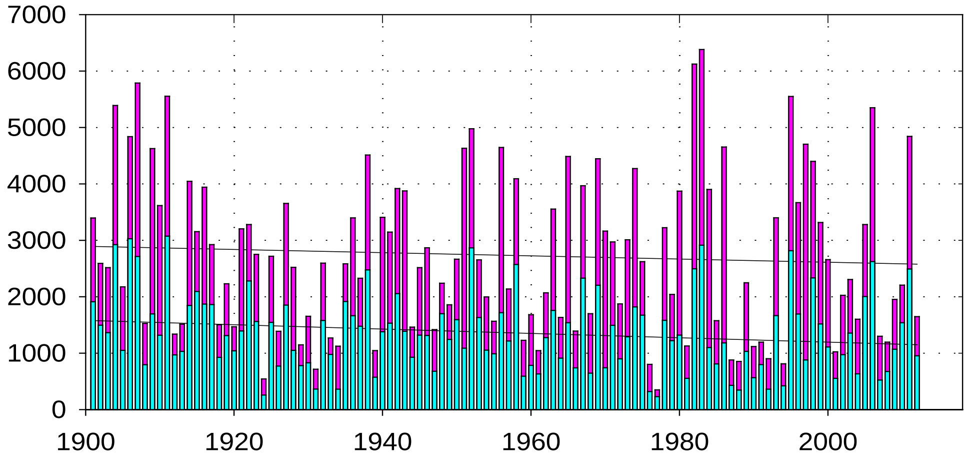


Figure C.7: American River runoff for historical record showing both April through July and water year runoff (1000 acre-ft.) with trend lines.

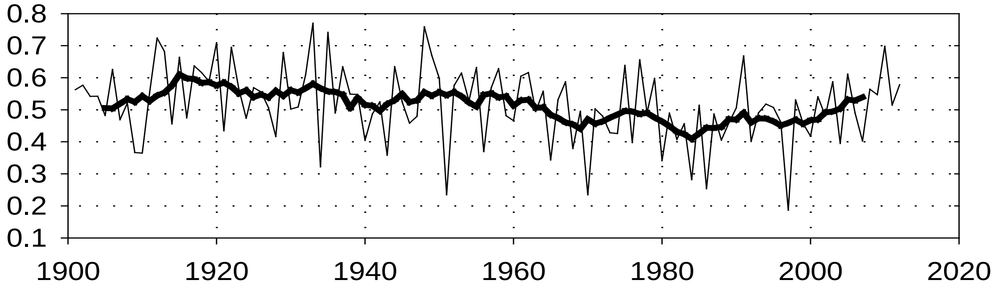


Figure C.8: American River April-July runoff ratio, along with 10 year moving average.

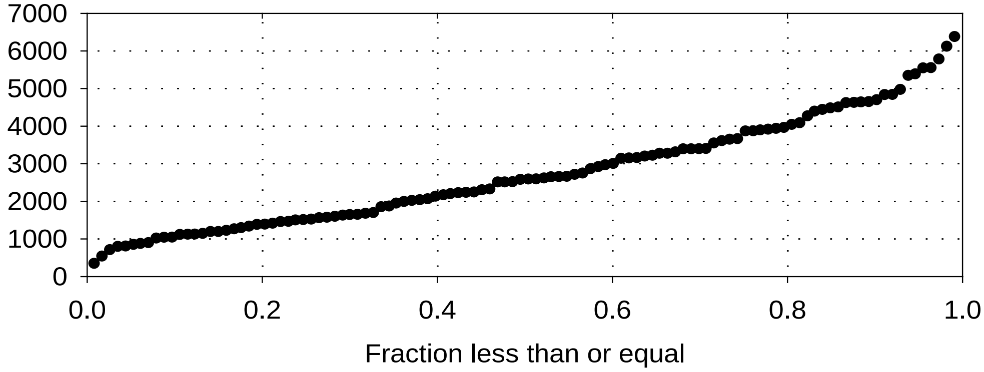


Figure C.9: Distribution of American River water year runoff (taf)

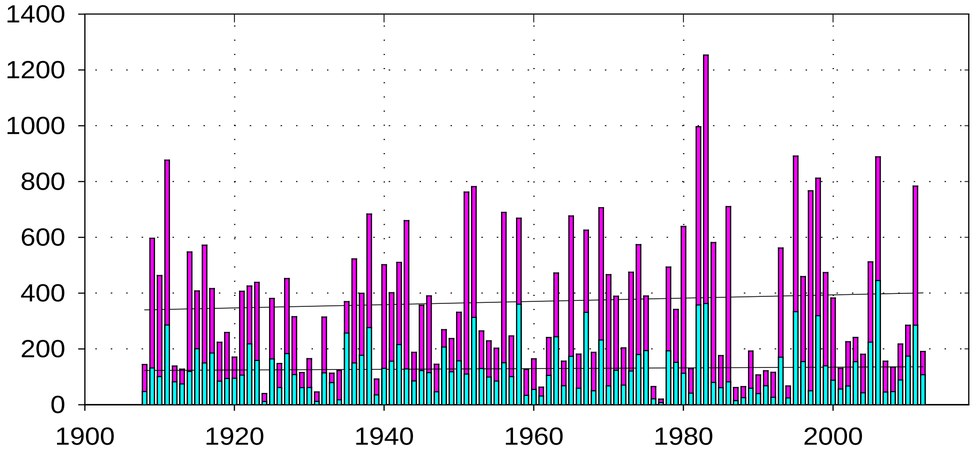


Figure C.10: Cosumnes River runoff for historical record showing both April through July and water year runoff (1000 acre-ft.) with trend lines.

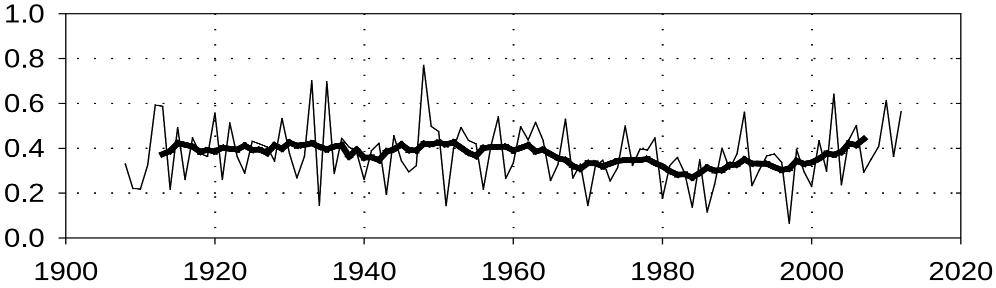


Figure C.11: Cosumnes River April-July runoff ratio, along with 10 year moving average.

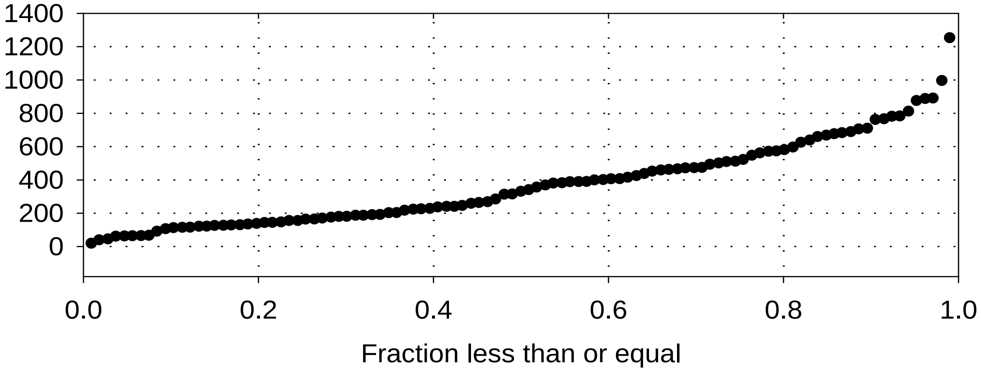


Figure C.12: Distribution of Cosumnes River water year runoff (taf)

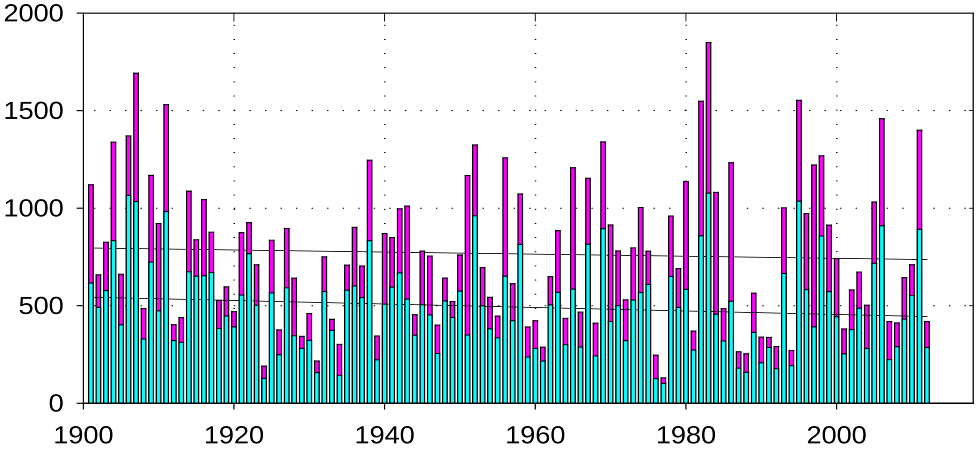


Figure C.13: Mokelumne River runoff for historical record showing both April through July and water year runoff (1000 acre-ft.) with trend lines.

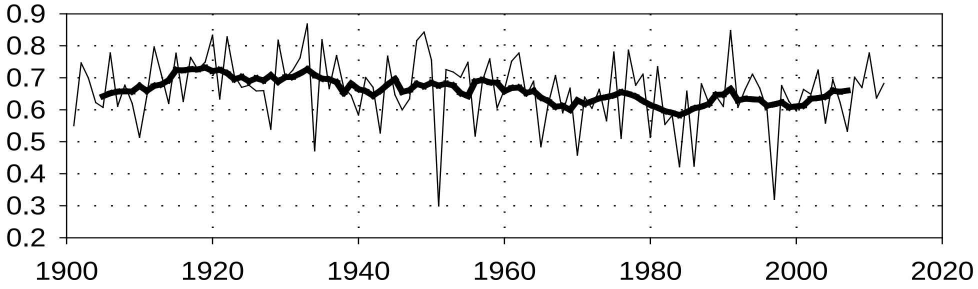


Figure C.14: Mokelumne River April-July/WY runoff ratio , along with 10 year moving average.

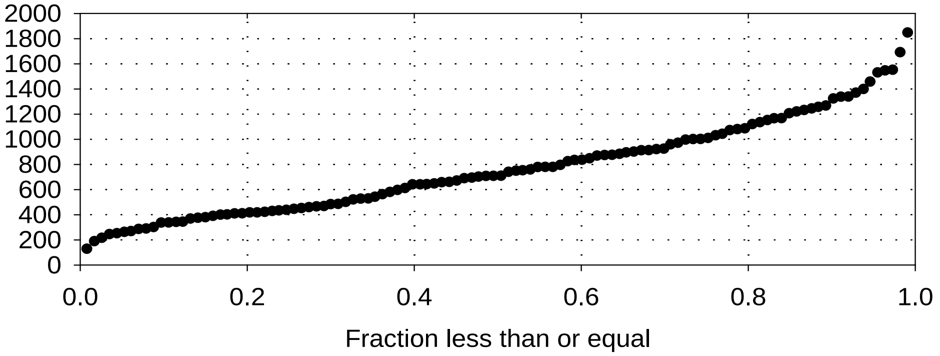


Figure C.15: Distribution of Mokelumne River water year runoff (taf)

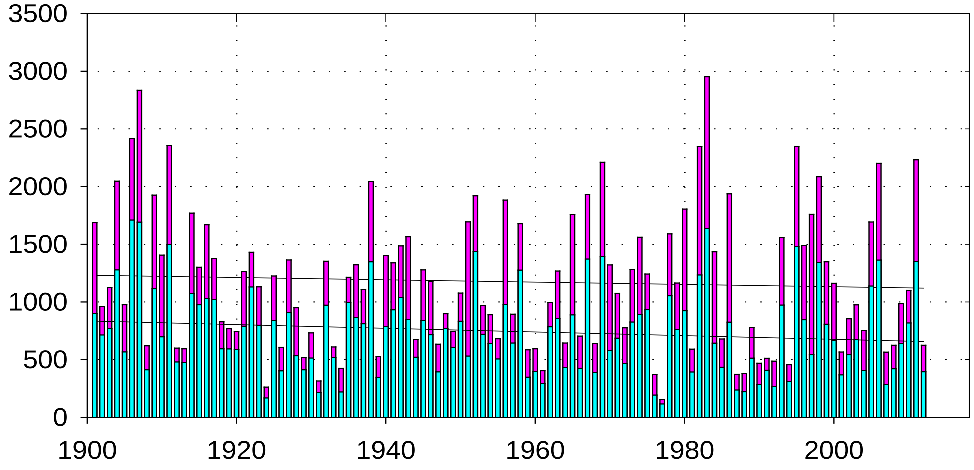


Figure C.16: Stanislaus River runoff for historical record showing both April through July and water year runoff (1000 acre-ft.) with trend lines.

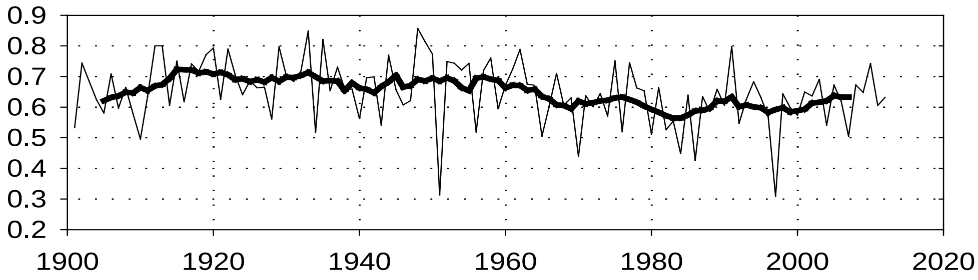


Figure C.17: Stanislaus River April-July/WY runoff ratio , along with 10 year moving average.

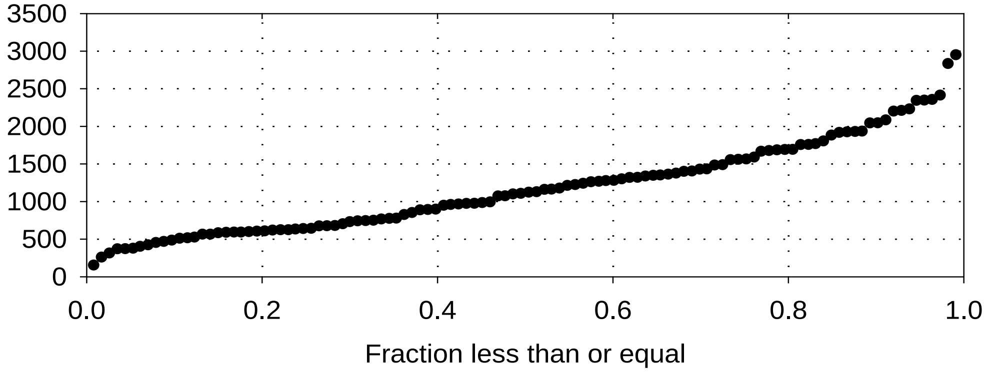


Figure C.18: Distribution of Stanislaus River water year runoff (taf)

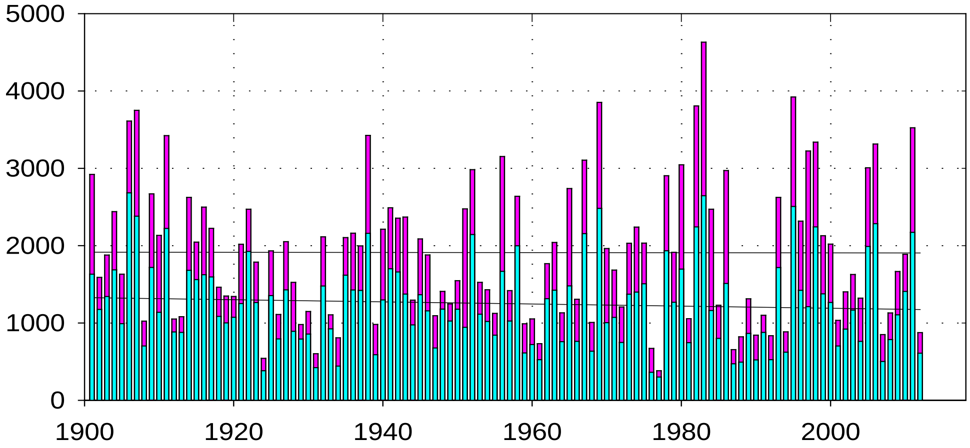


Figure C.19: Tuolumne River runoff for historical record showing both April through July and water year runoff (1000 acre-ft.) with trend lines.

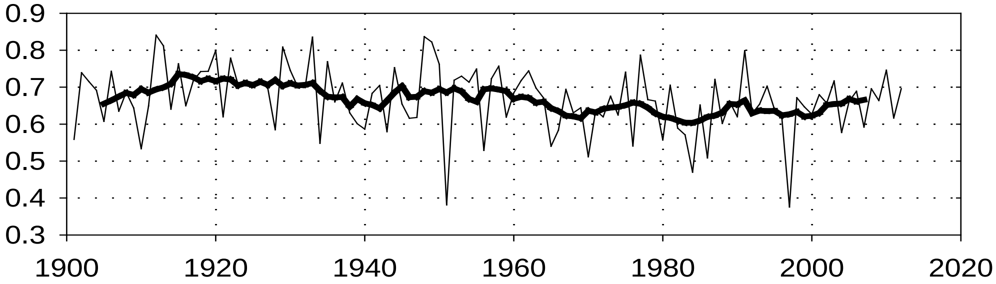


Figure C.20: Tuolumne River April-July/WY runoff ratio, along with 10 year moving average.

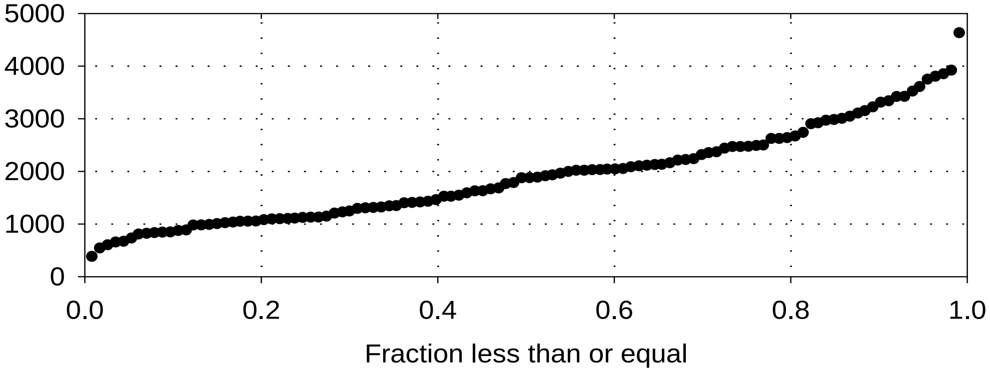


Figure C.21: Distribution of Tuolumne River water year runoff (taf)

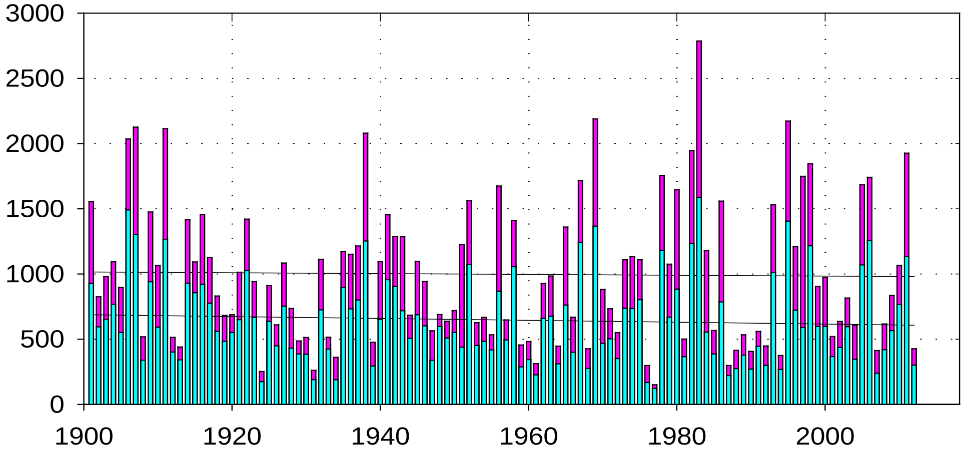


Figure C.22: Merced River runoff for historical record showing both April through July and water year runoff (1000 acre-ft.) with trend lines.

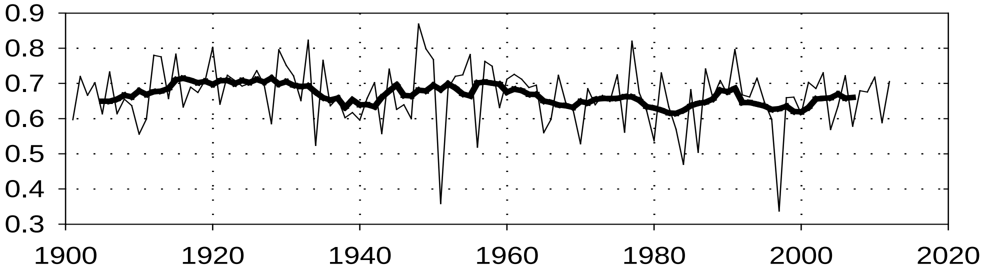


Figure C.23: Merced River April-July/WY runoff ratio, along with 10 year moving average.

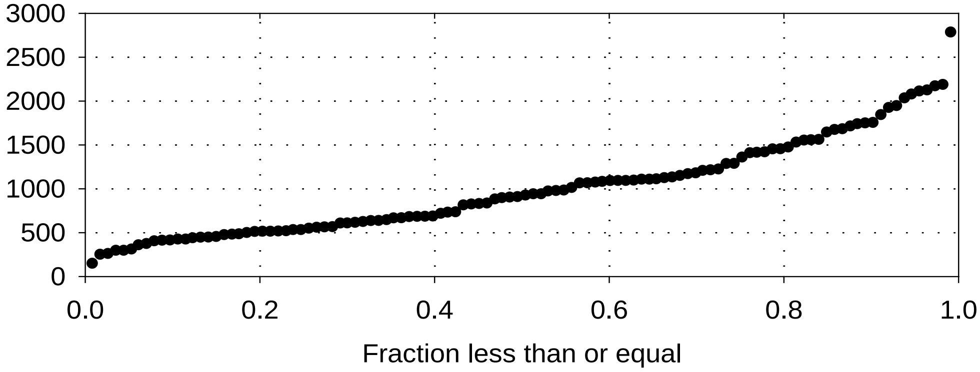


Figure C.24: Distribution of Merced River water year runoff (taf)

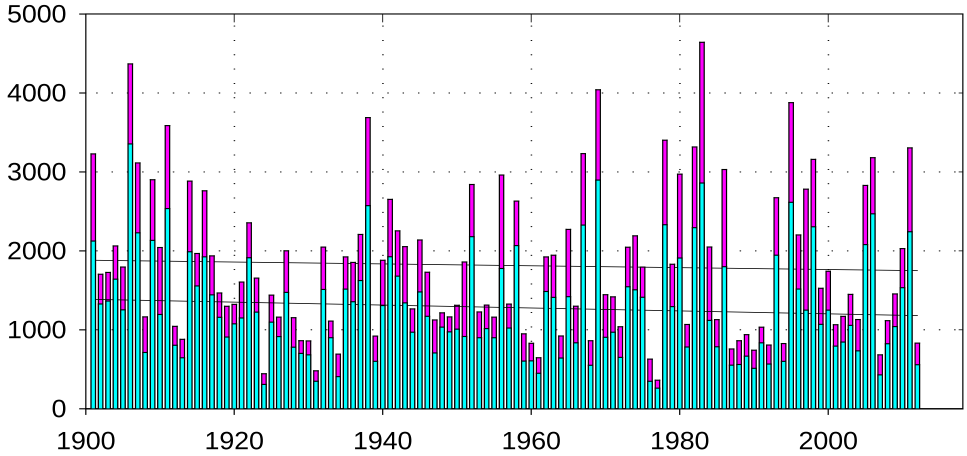


Figure C.25: San Joaquin River runoff for historical record showing both April through July and water year runoff (1000 acre-ft.) with trend lines.

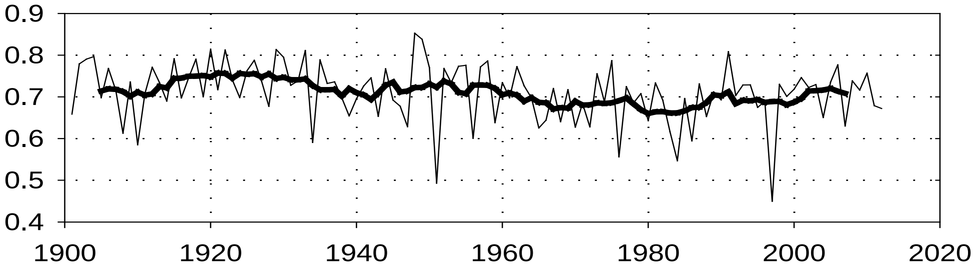


Figure C.26: San Joaquin River April-July/WY runoff ratio, along with 10 year moving average.

Figure C.27: Distribution of San Joaquin River water year runoff (taf)

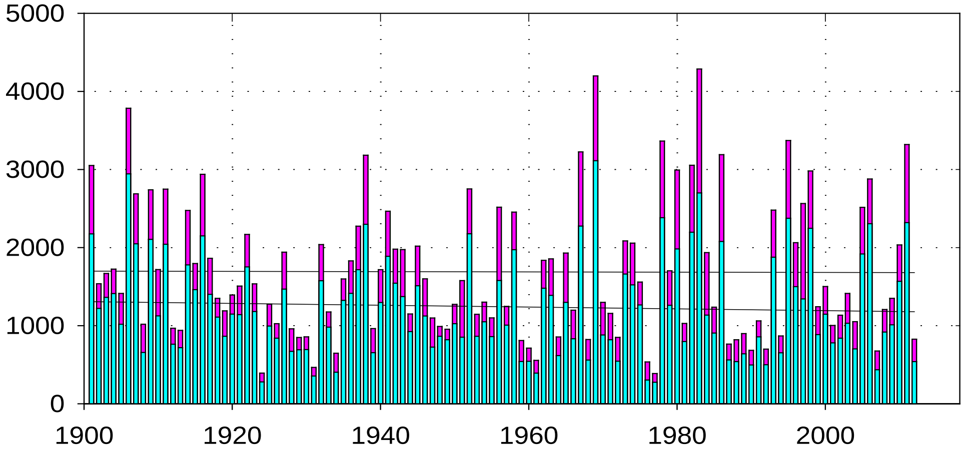


Figure C.28: Kings River runoff for historical record showing both April through July and water year runoff (1000 acre-ft.) with trend lines.

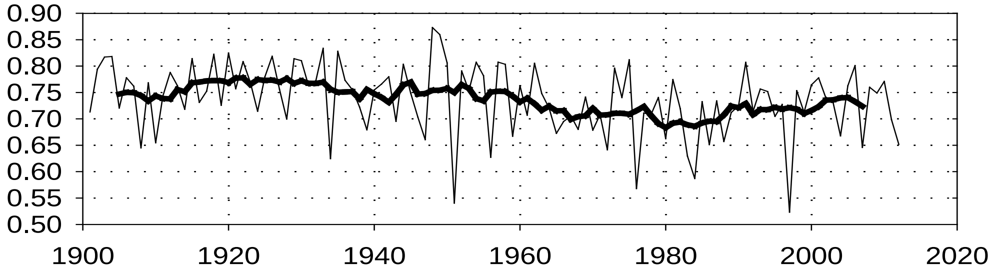


Figure C.29: Kings River April-July/WY runoff ratio, along with 10 year moving average.

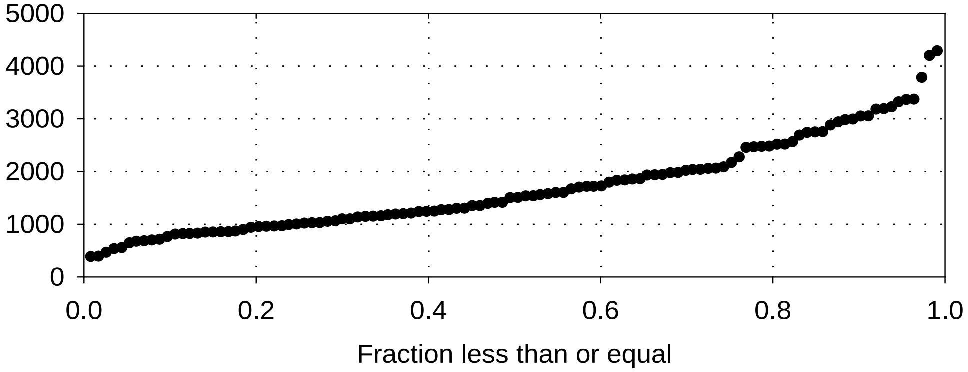


Figure C.30: Distribution of Kings River water year runoff (taf)

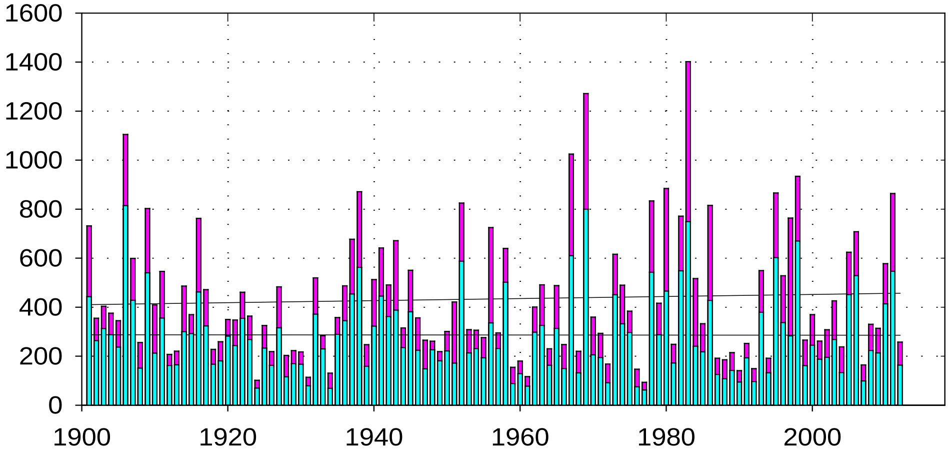


Figure C.31: Kaweah River runoff for historical record showing both April through July and water year runoff (1000 acre-ft.) with trend lines.

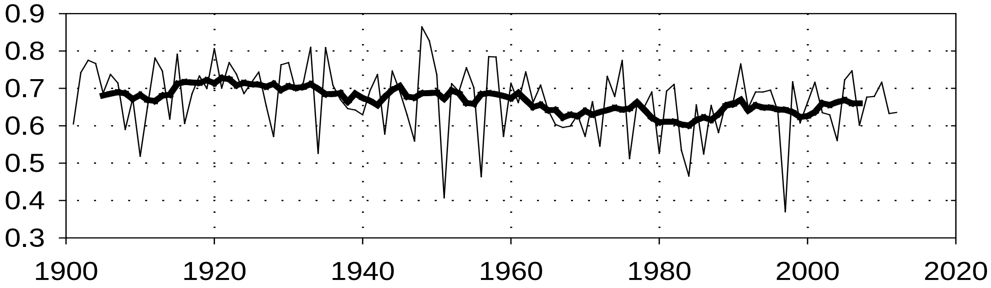


Figure C.32: Kaweah River April-July/WY runoff ratio, along with 10 year moving average.

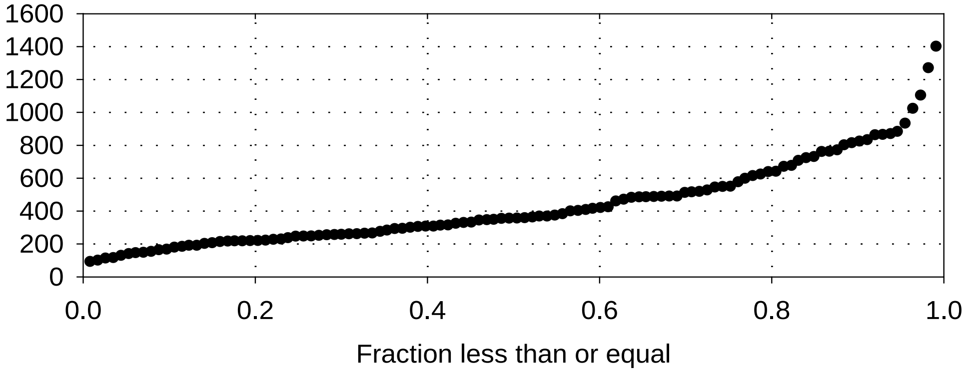


Figure C.33: Distribution of Kaweah River water year runoff (taf)

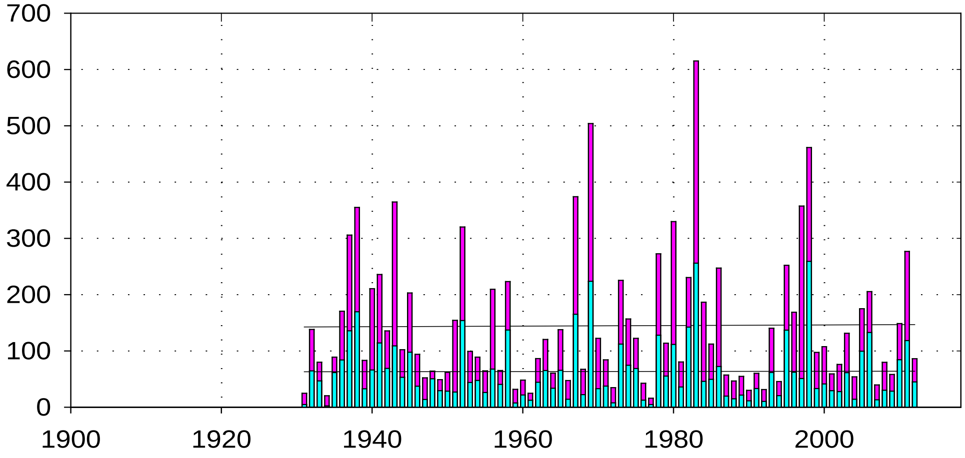


Figure C.34: Tule River runoff for historical record showing both April through July and water year runoff (1000 acre-ft.) with trend lines.

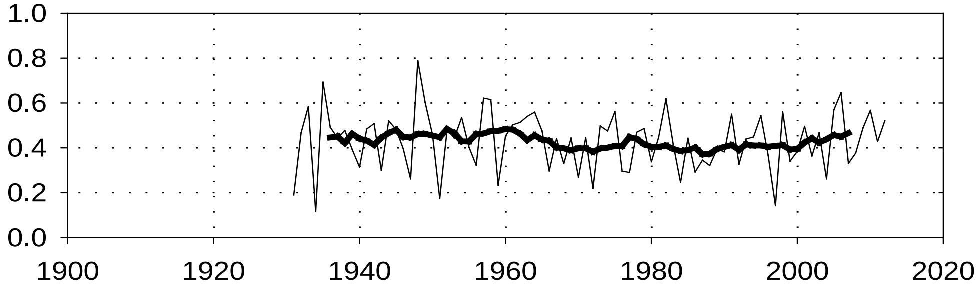


Figure C.35: Tule River April-July/WY runoff ratio, along with 10 year moving average.

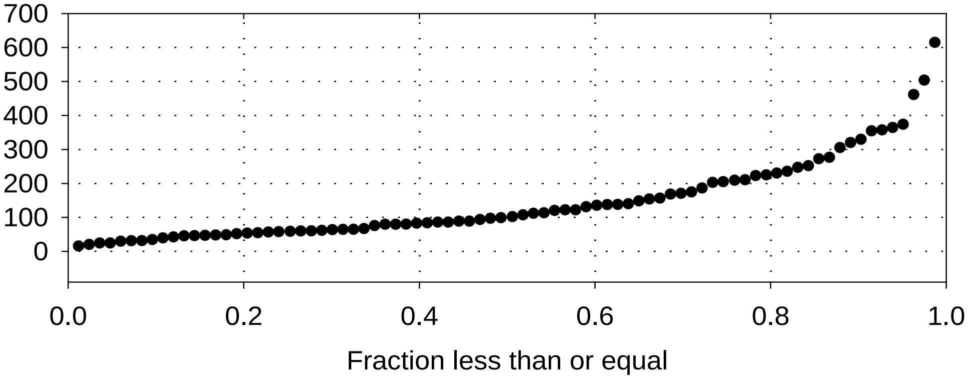


Figure C.36: Distribution of Tule River water year runoff (taf)

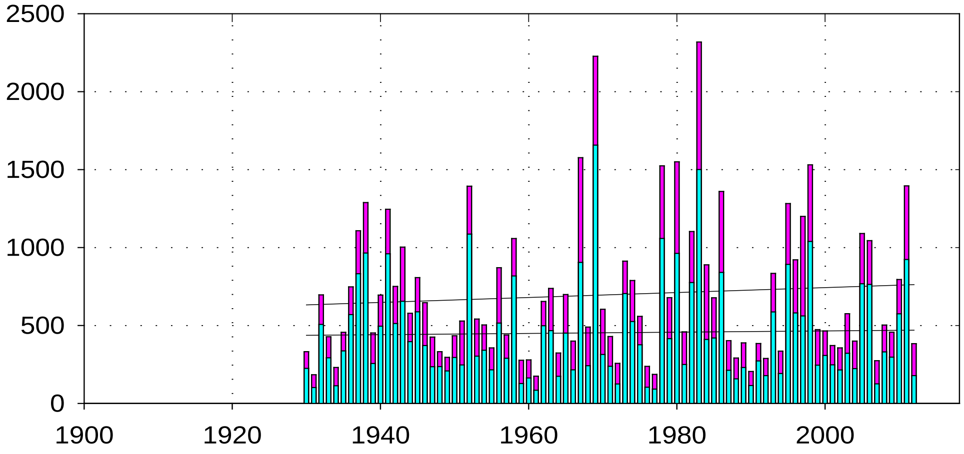


Figure C.37: Kern River runoff for historical record showing both April through July and water year runoff (1000 acre-ft.) with trend lines.

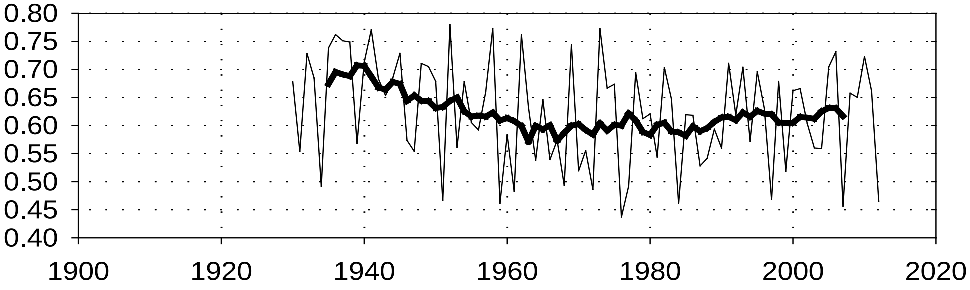


Figure C.38: Kern River April-July/WY runoff ratio, along with 10 year moving average.

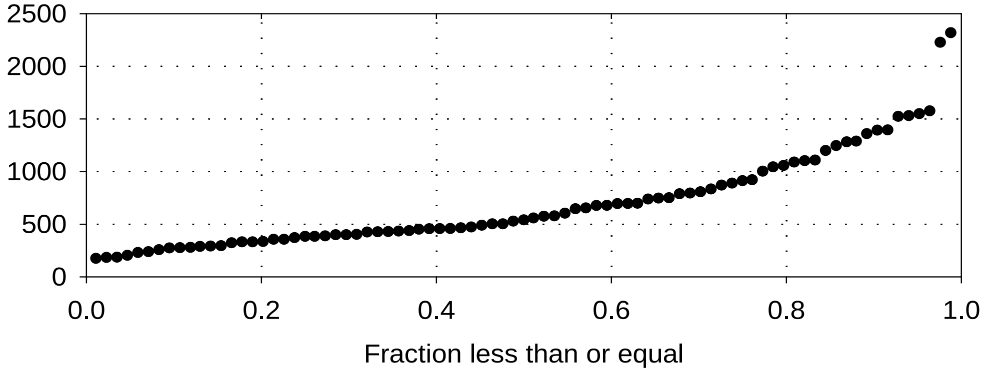
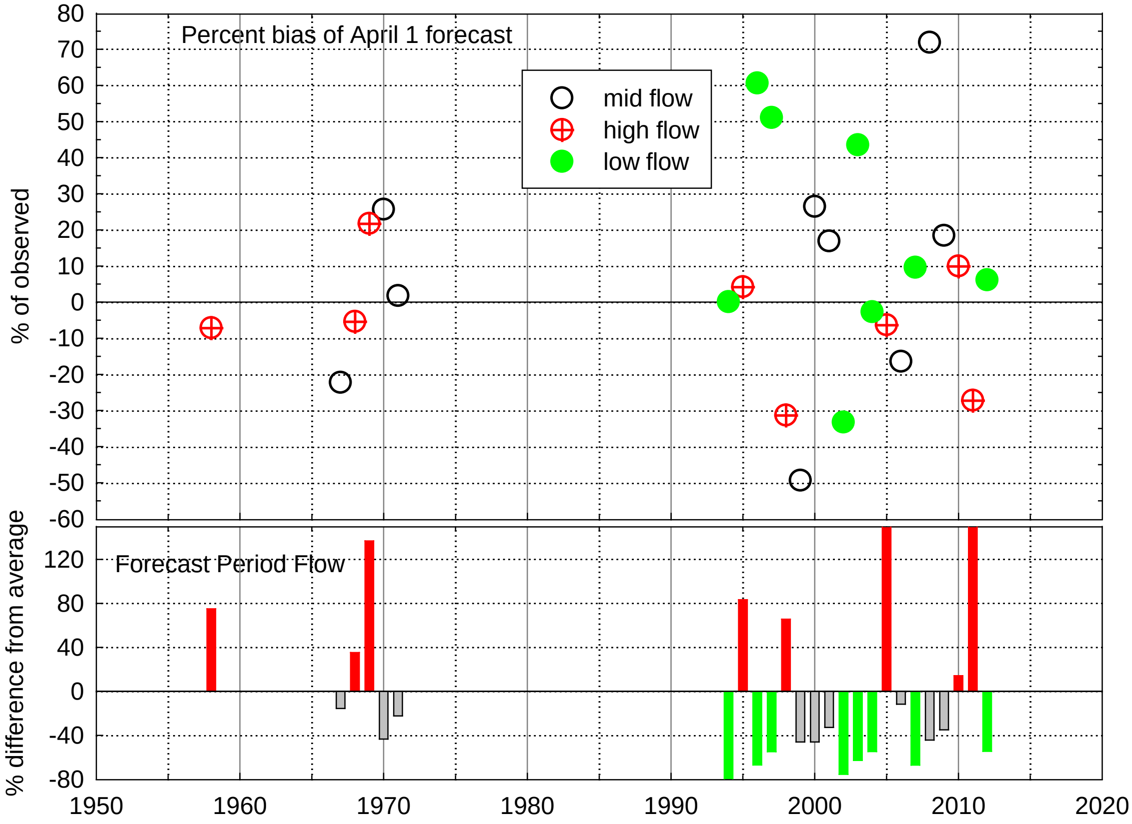
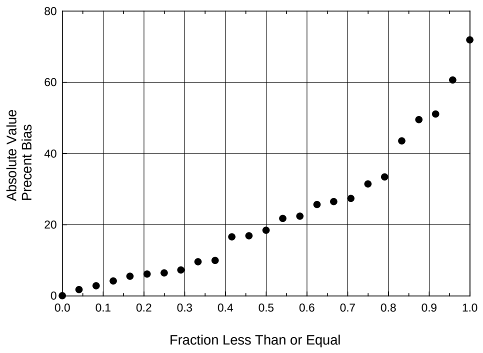


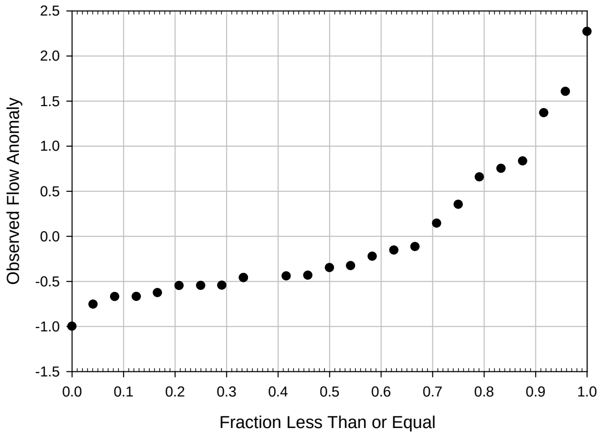
Figure C.39: Distribution of Kern River water year runoff (taf)

Appendix D

Percent bias information for Colorado River basin locations







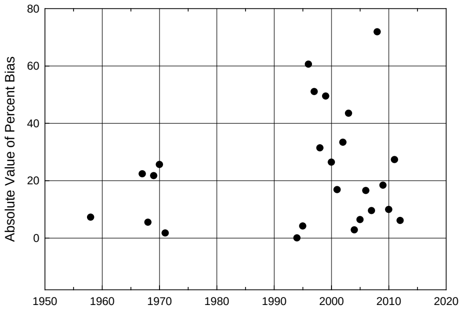
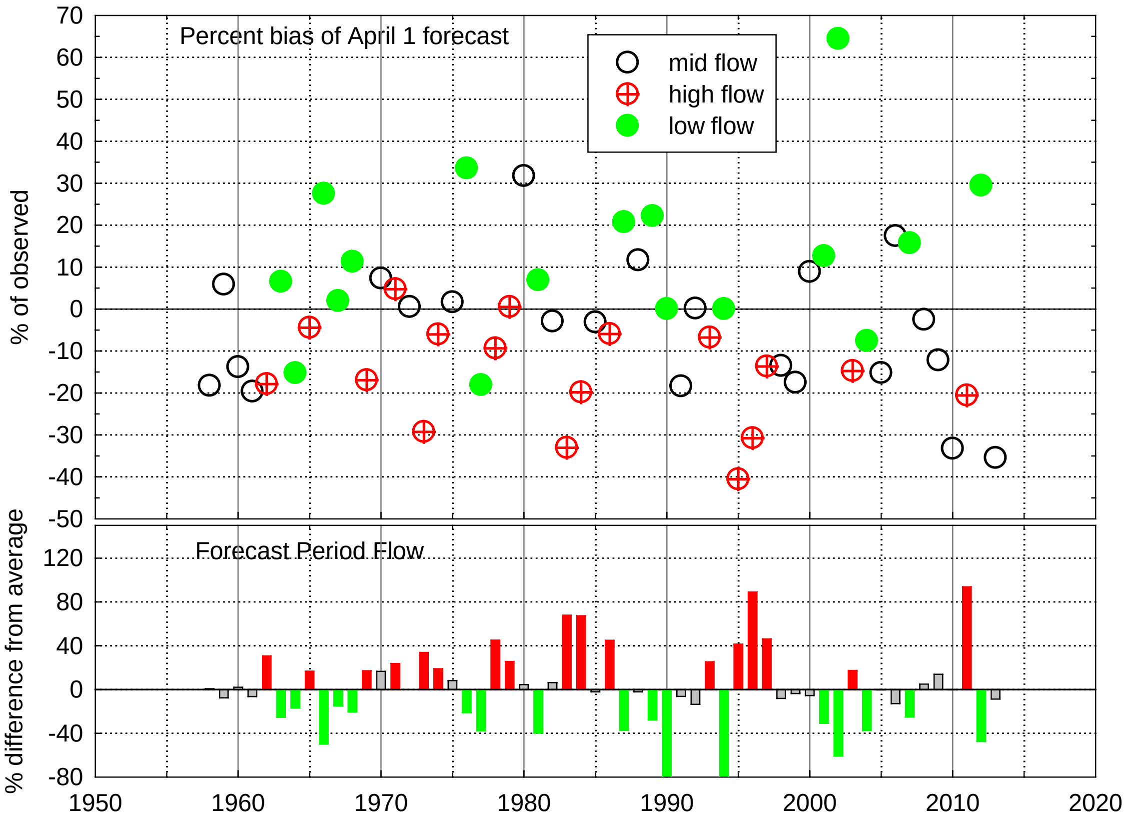
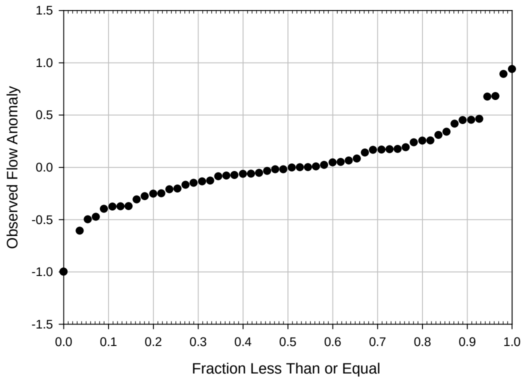
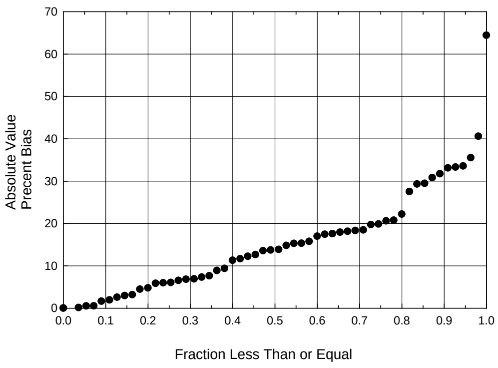


Figure D1: Virgin River at Virgin, UT. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.







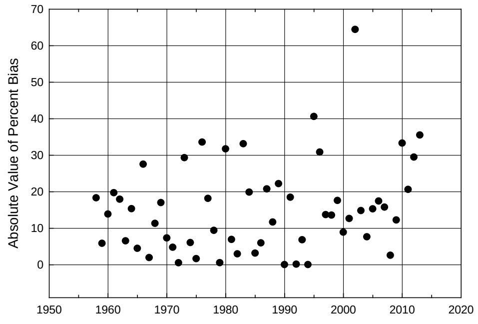
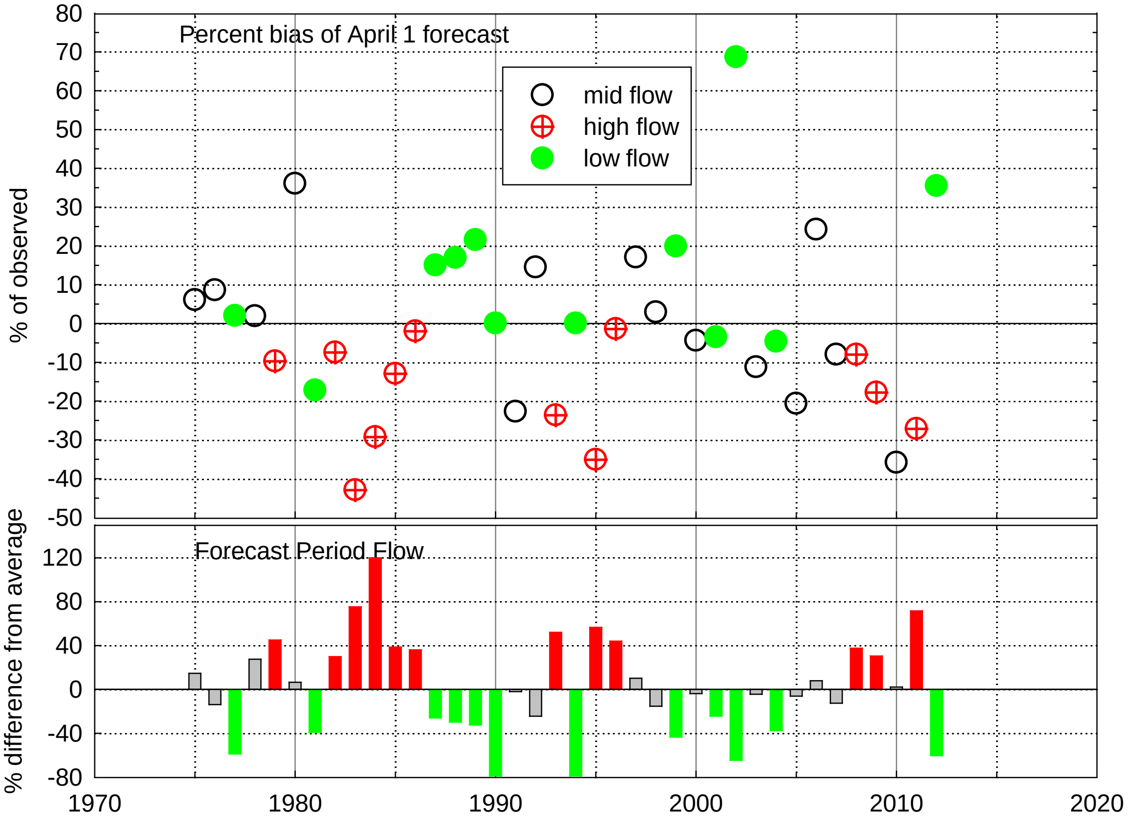
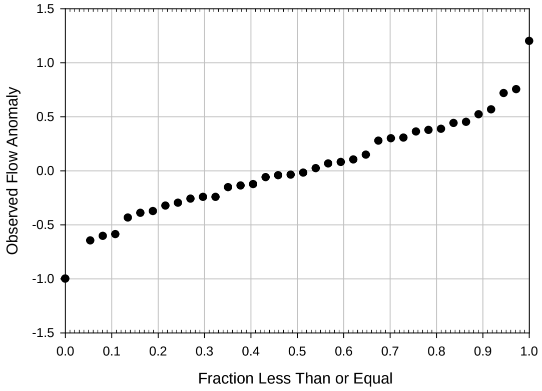
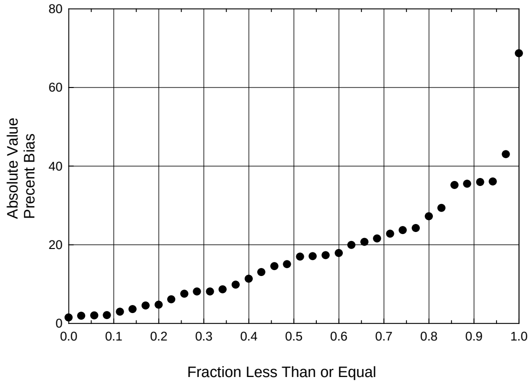


Figure D2: Colorado River below Lake Granby, CO. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.







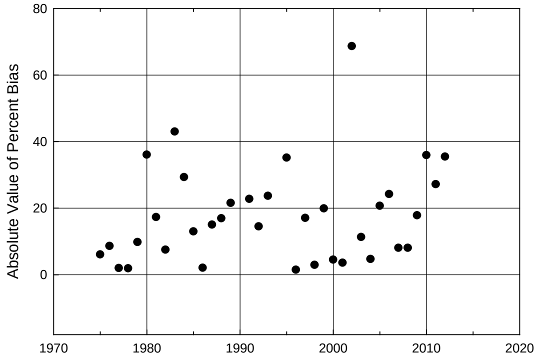
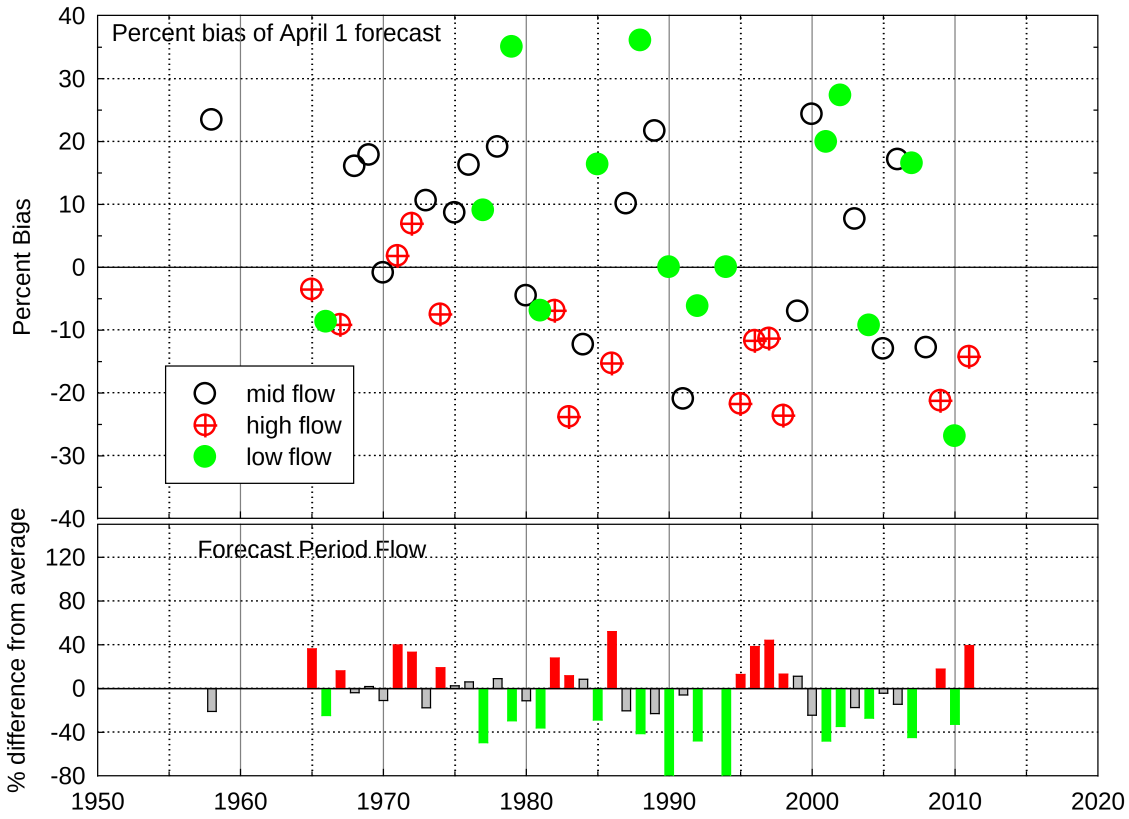
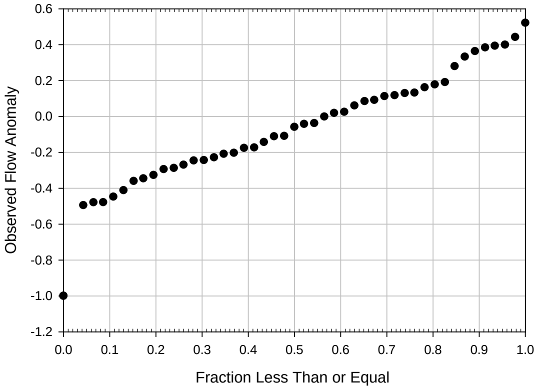
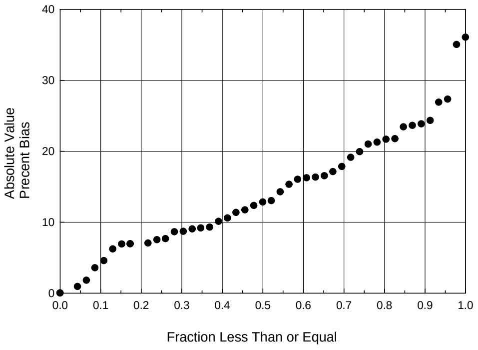


Figure D3: Eagle River below Gypsum, CO. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.







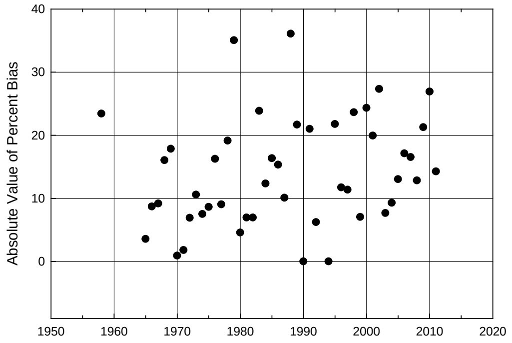
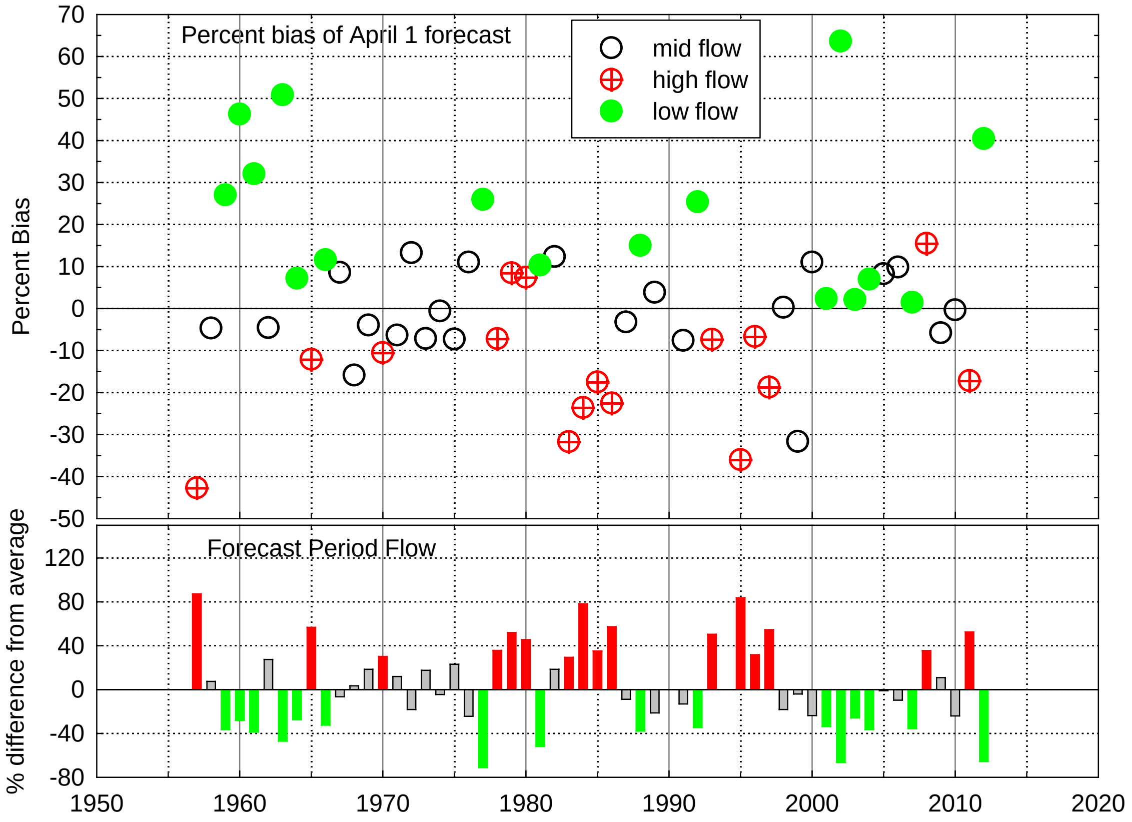
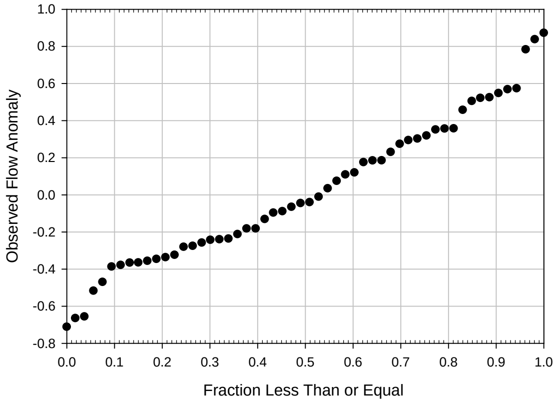
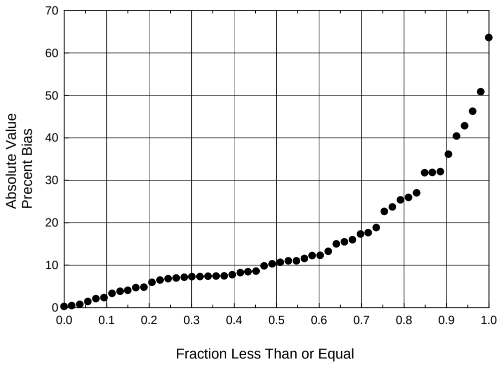


Figure D4: Green River at Warren Bridge, near Daniel, WY. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.







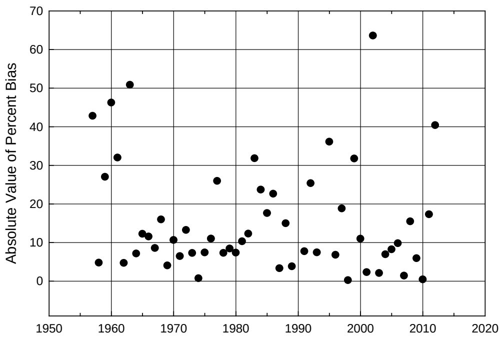
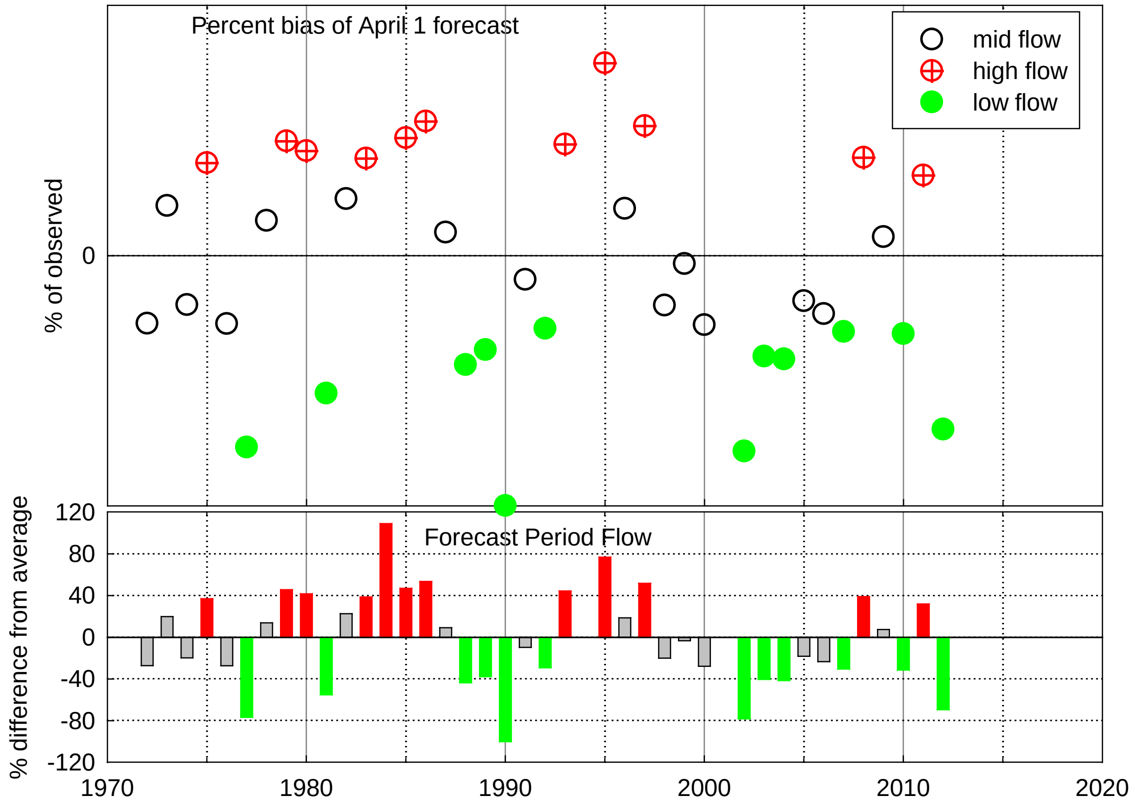
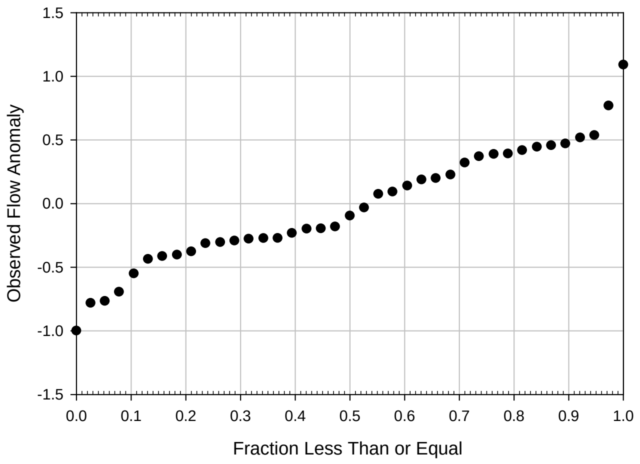


Figure D5: East River at Almont, CO. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.





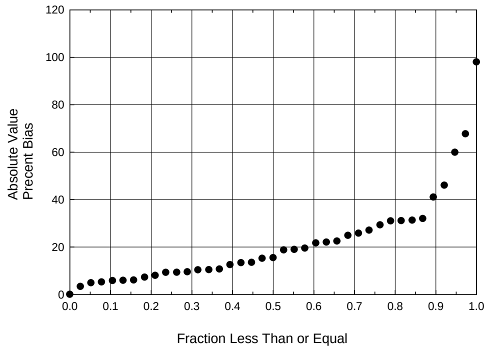
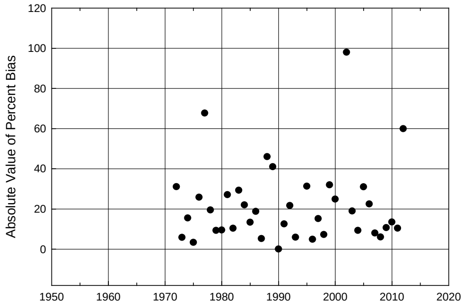
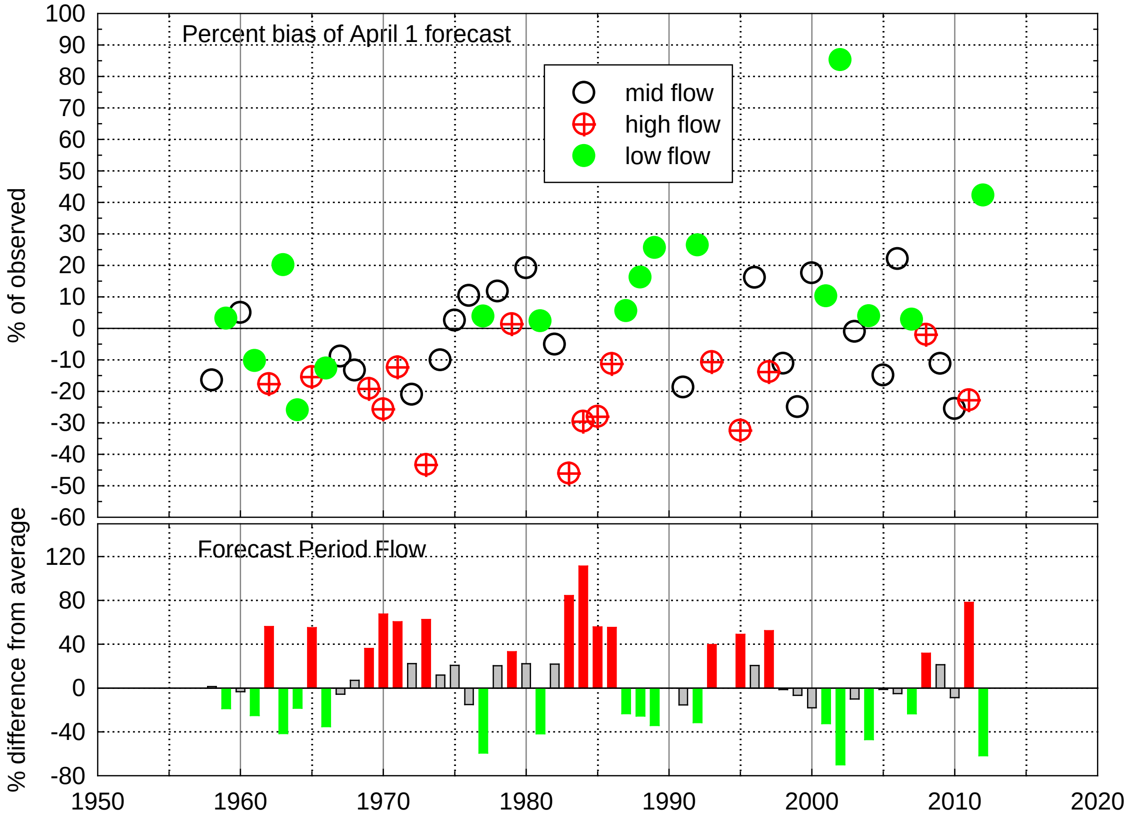
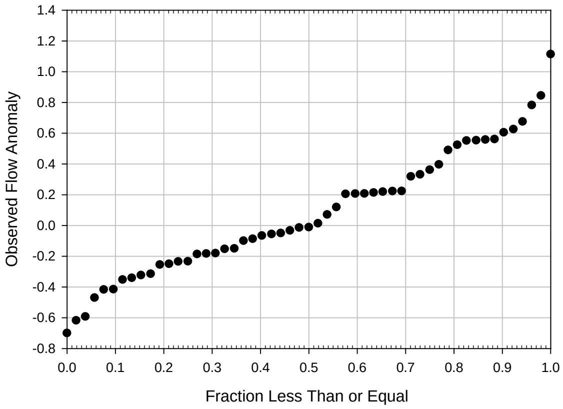
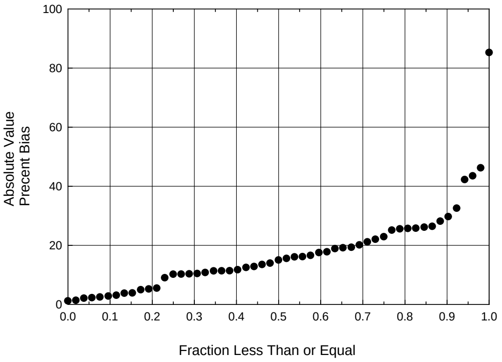


Figure D6: Gunnison River inflow to Blue Mesa Reservoir. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.









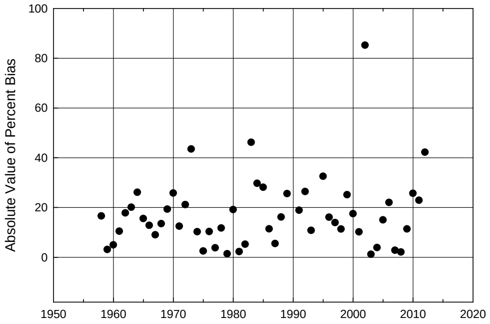
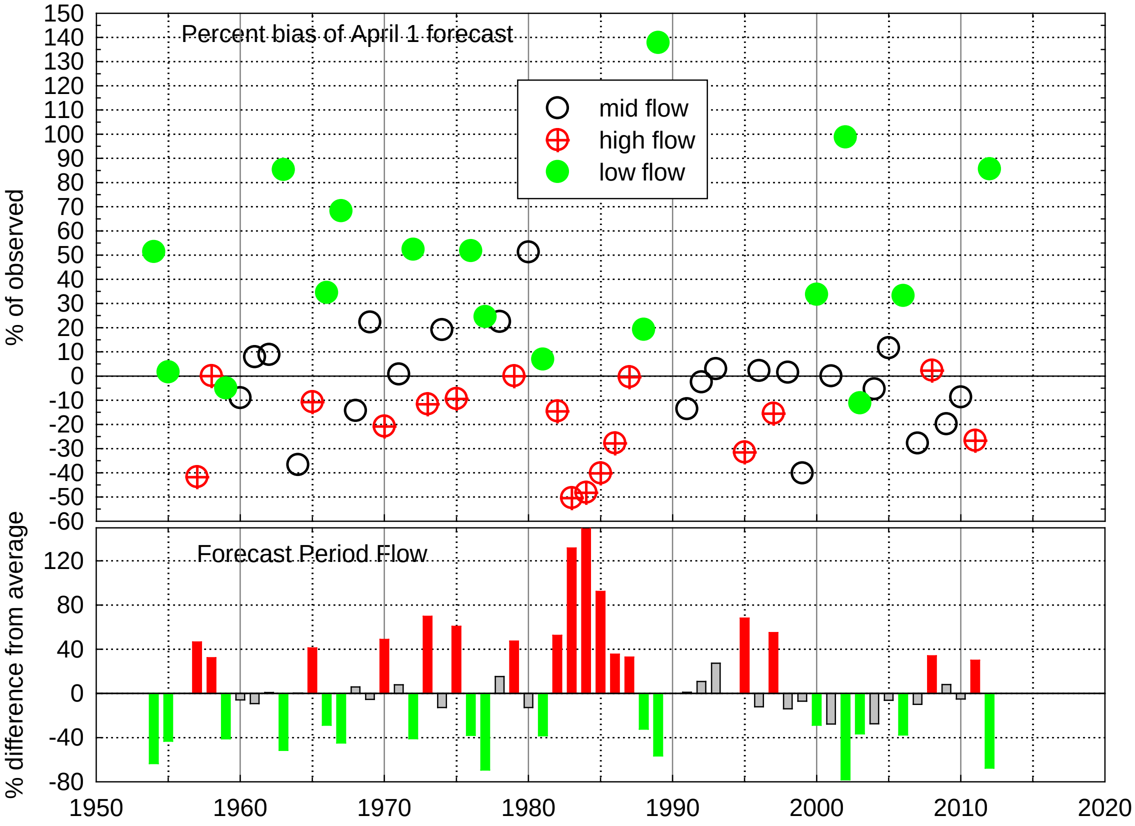
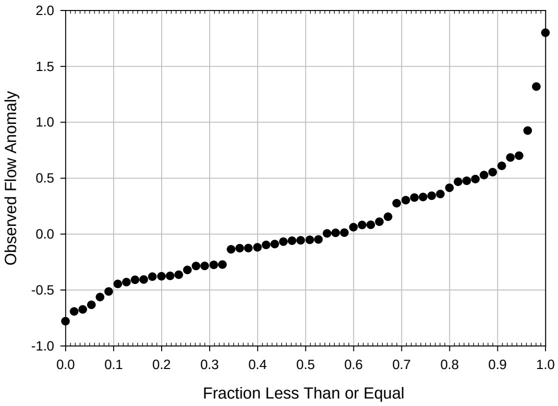


Figure D7: Colorado River near Cameo, CO. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.





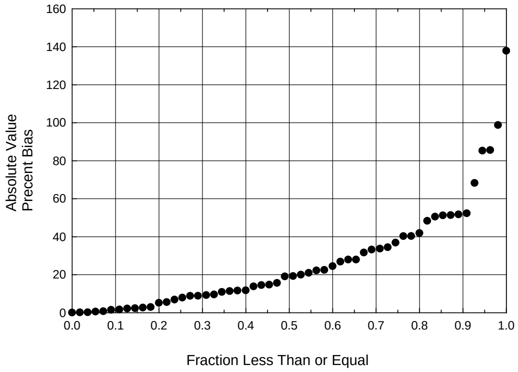
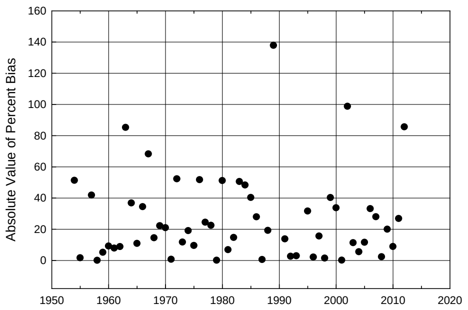
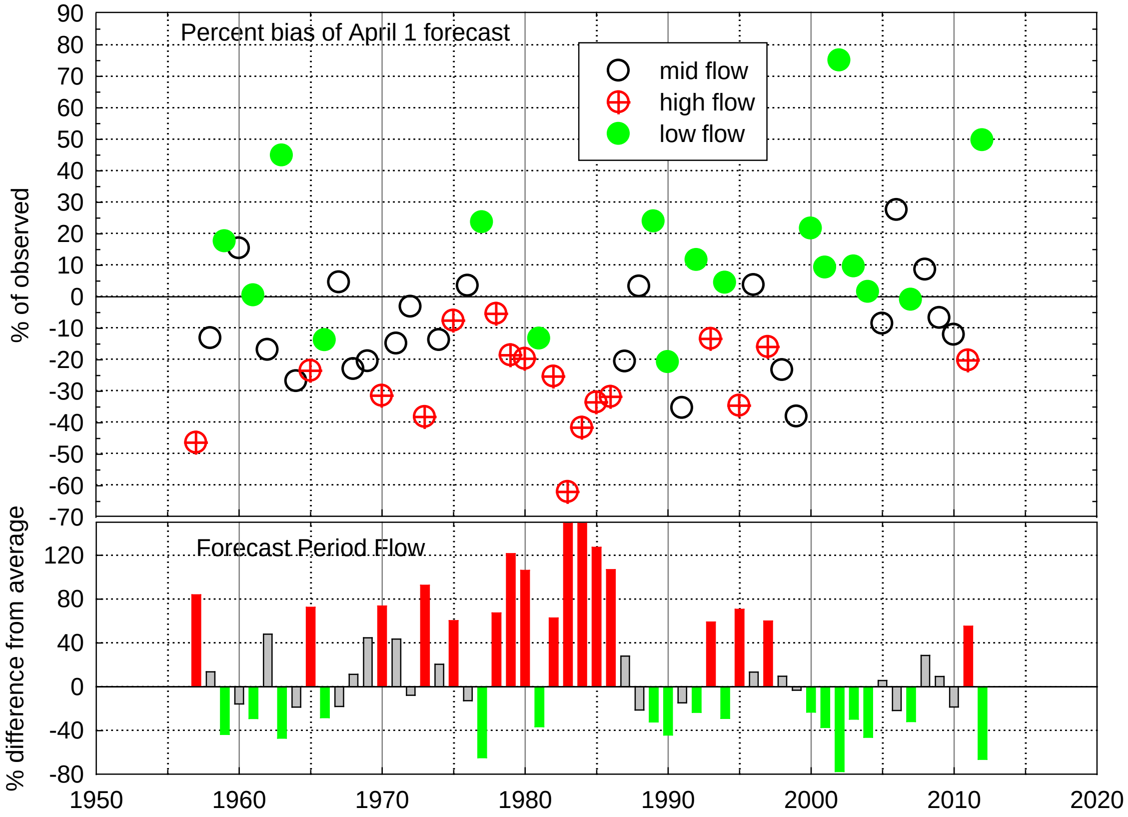
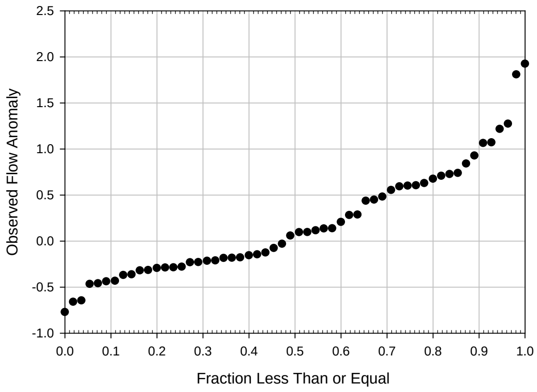


Figure D8: Uncompahgre River at Colona, CO. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.







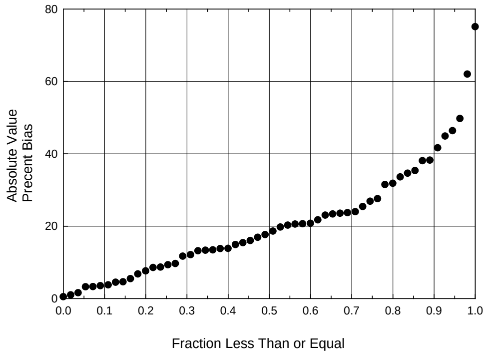
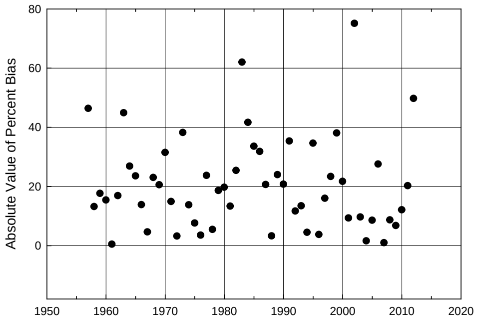
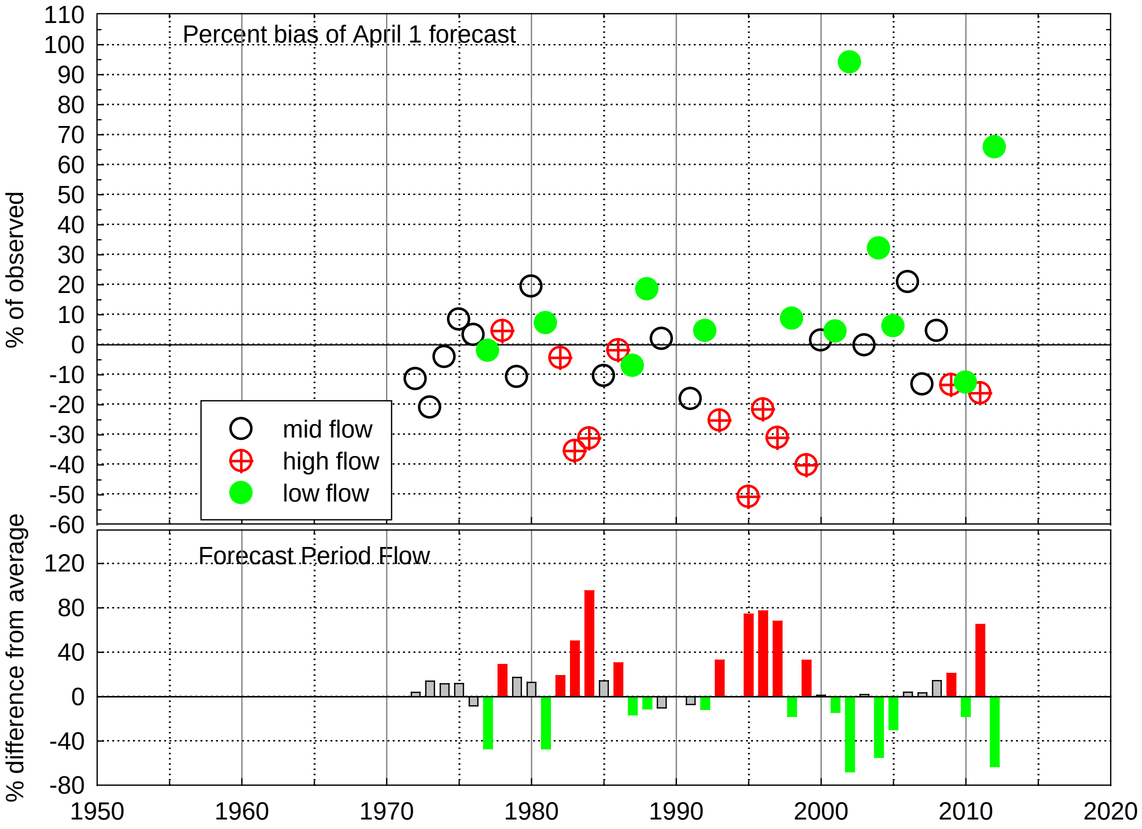
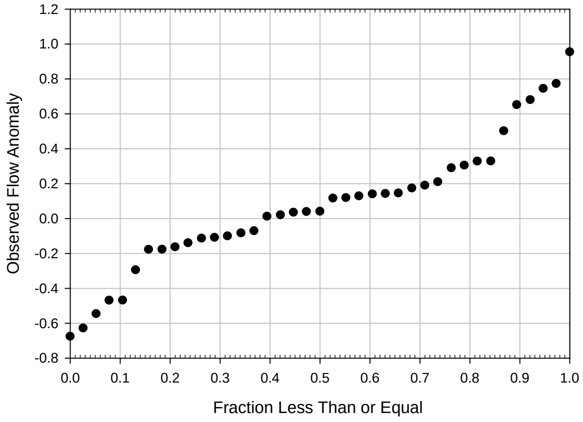


Figure D9: Colorado River near Cisco, UT. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.







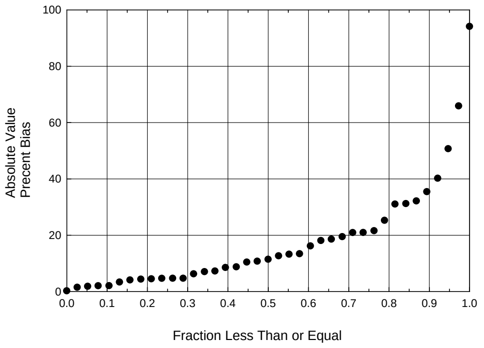
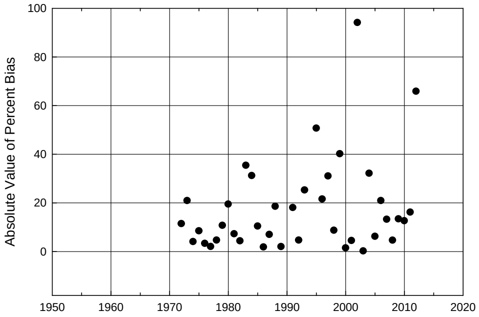
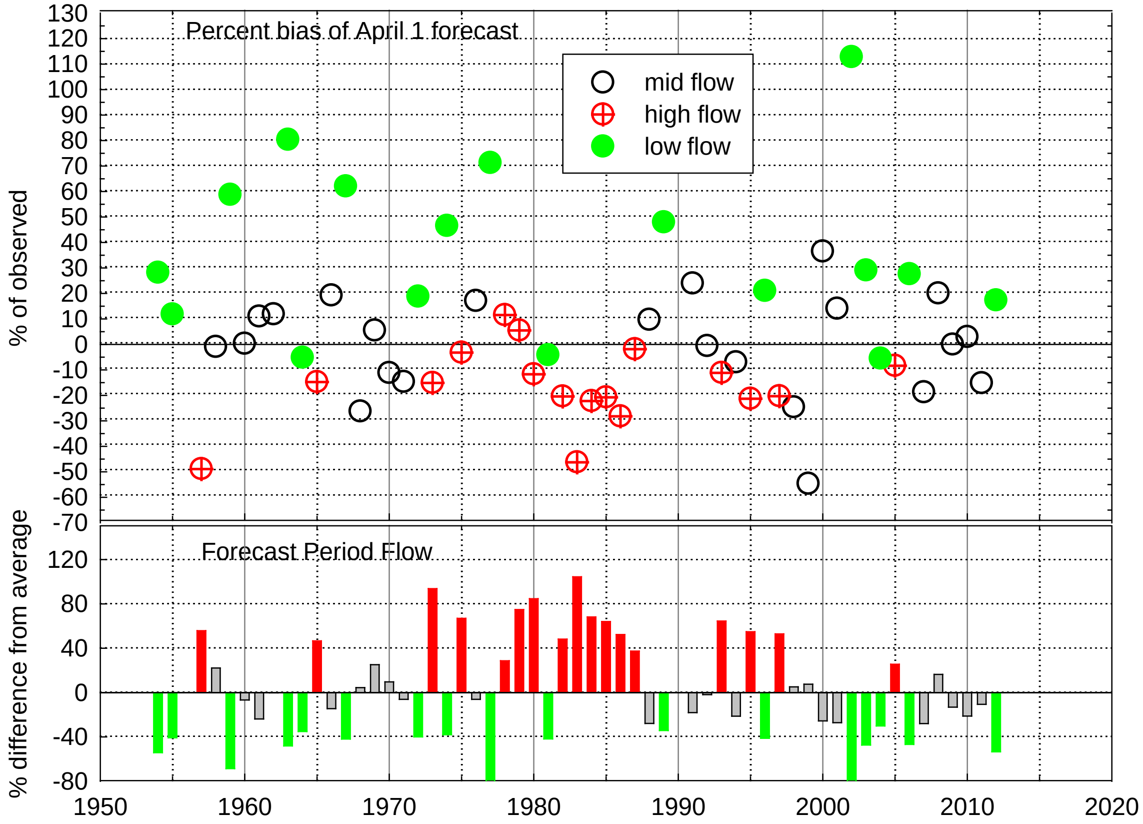
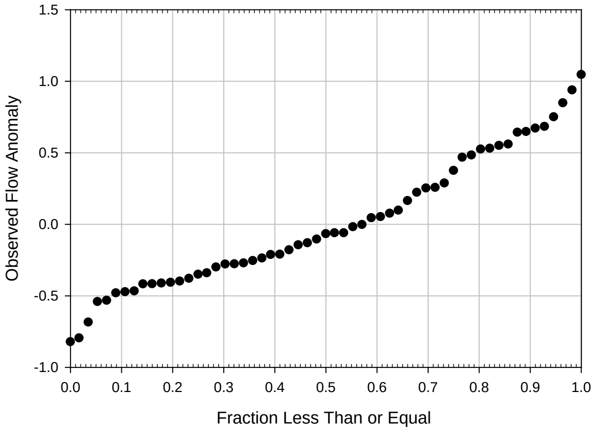
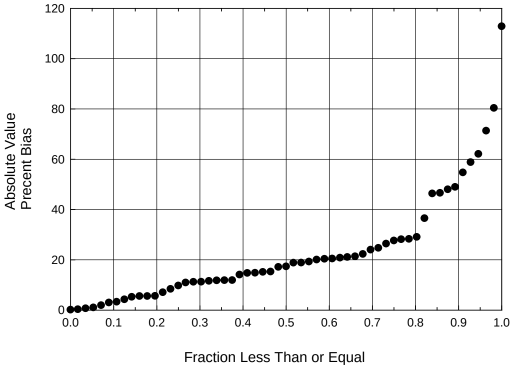


Figure D10: Blue River inflow to Dillon Reservoir, CO. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.









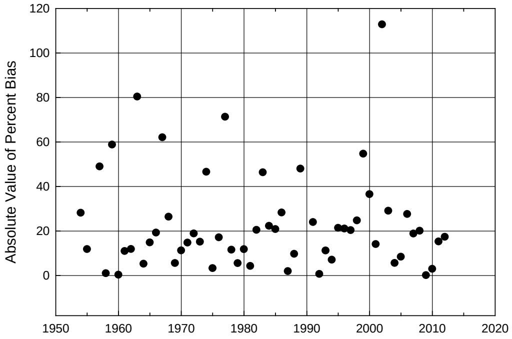
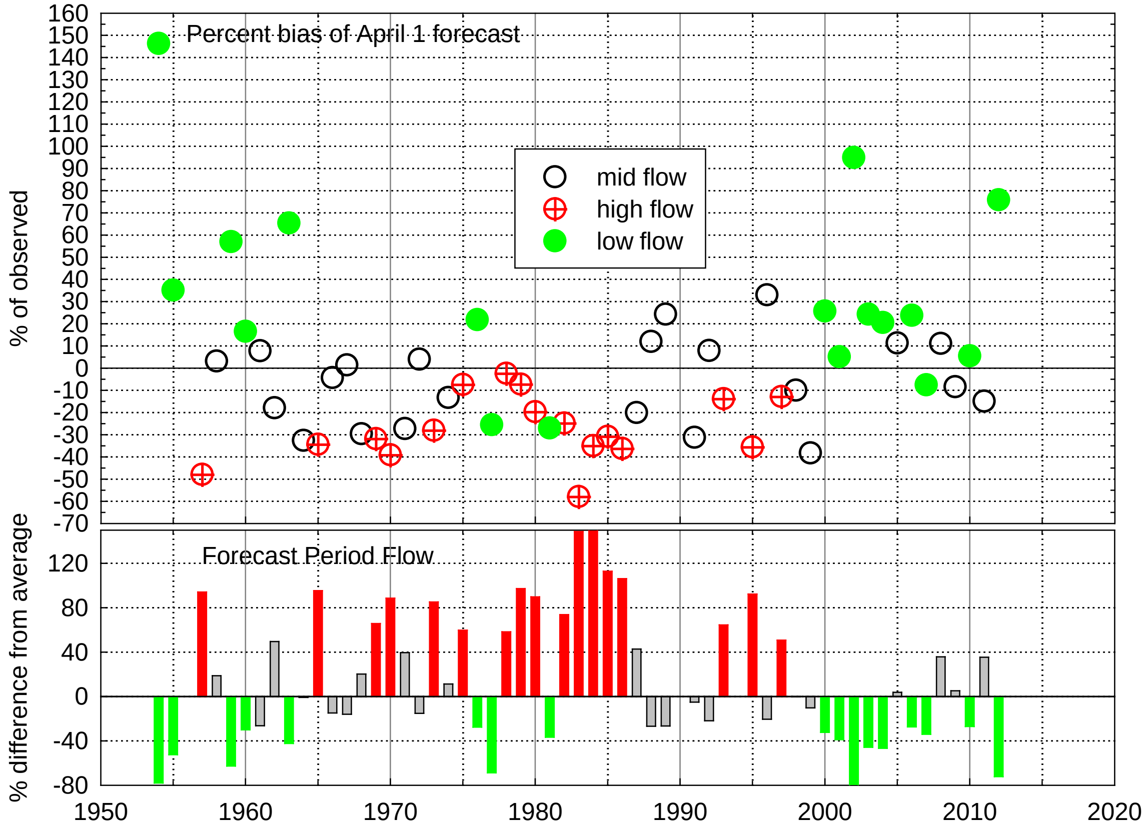
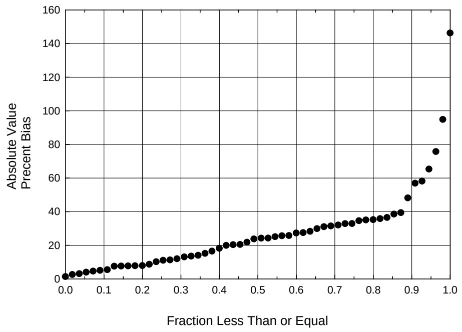
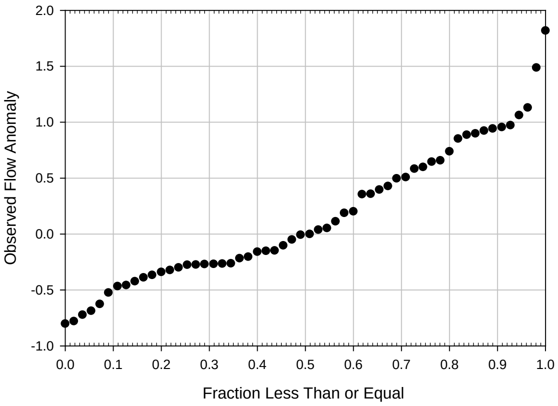


Figure D11: Dolores River at Dolores, CO. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.







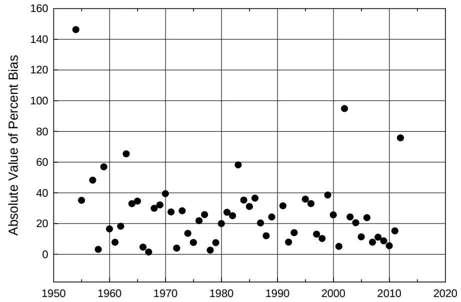
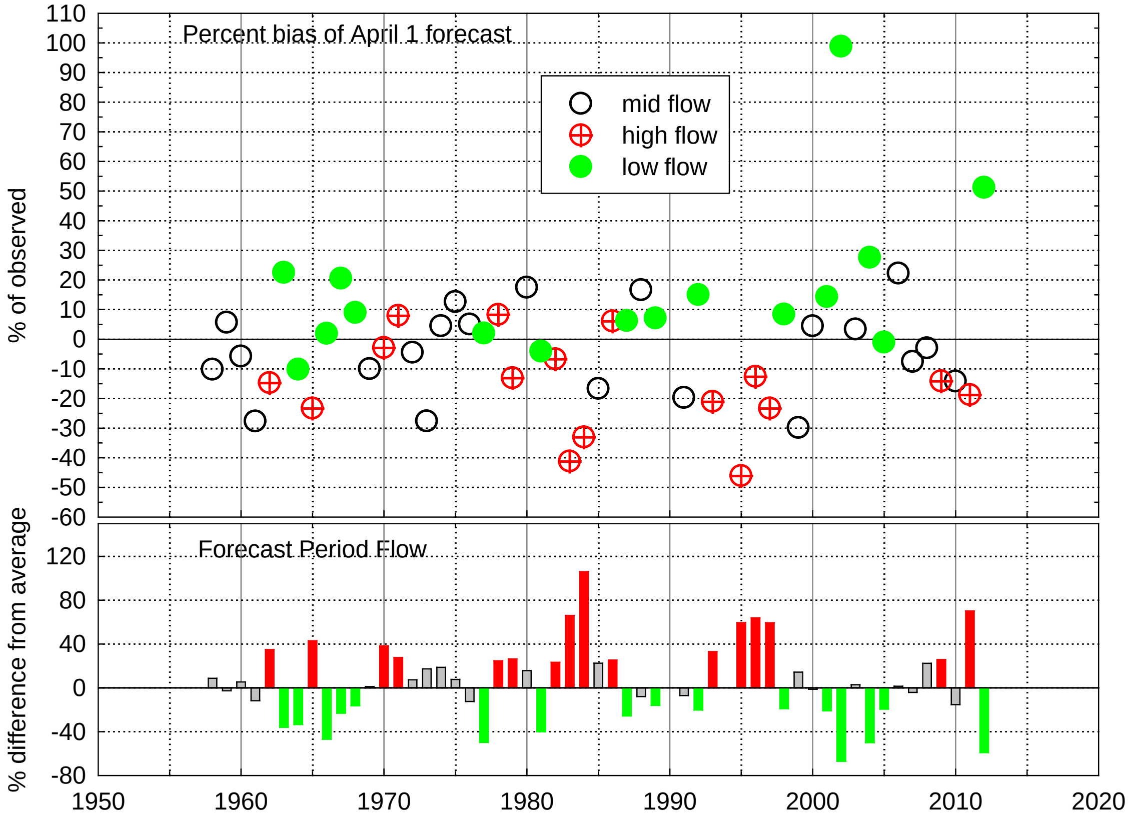
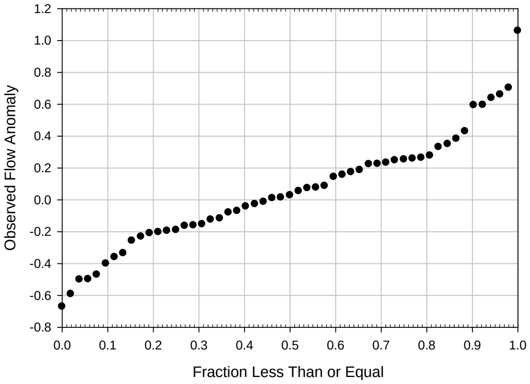


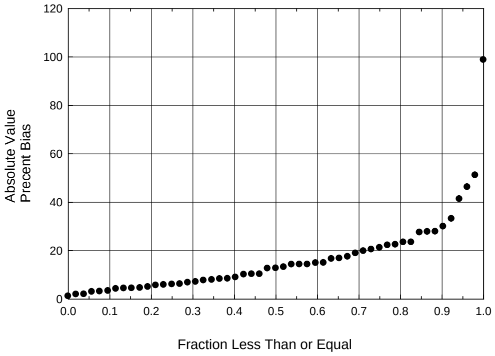
Figure D12: Gunnison River near Grand Junction, CO. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.



Frequency of Observed Flow Anomaly



Absolute Value of April 1 Percent Bias Frequency



Absolute Value of April 1 Percent Bias Time Series

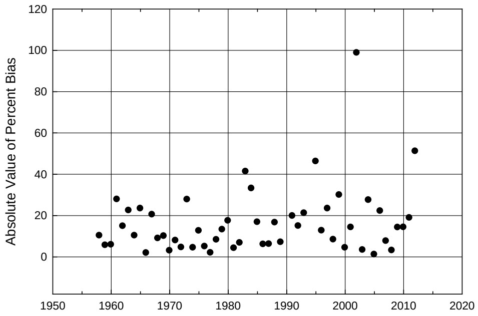
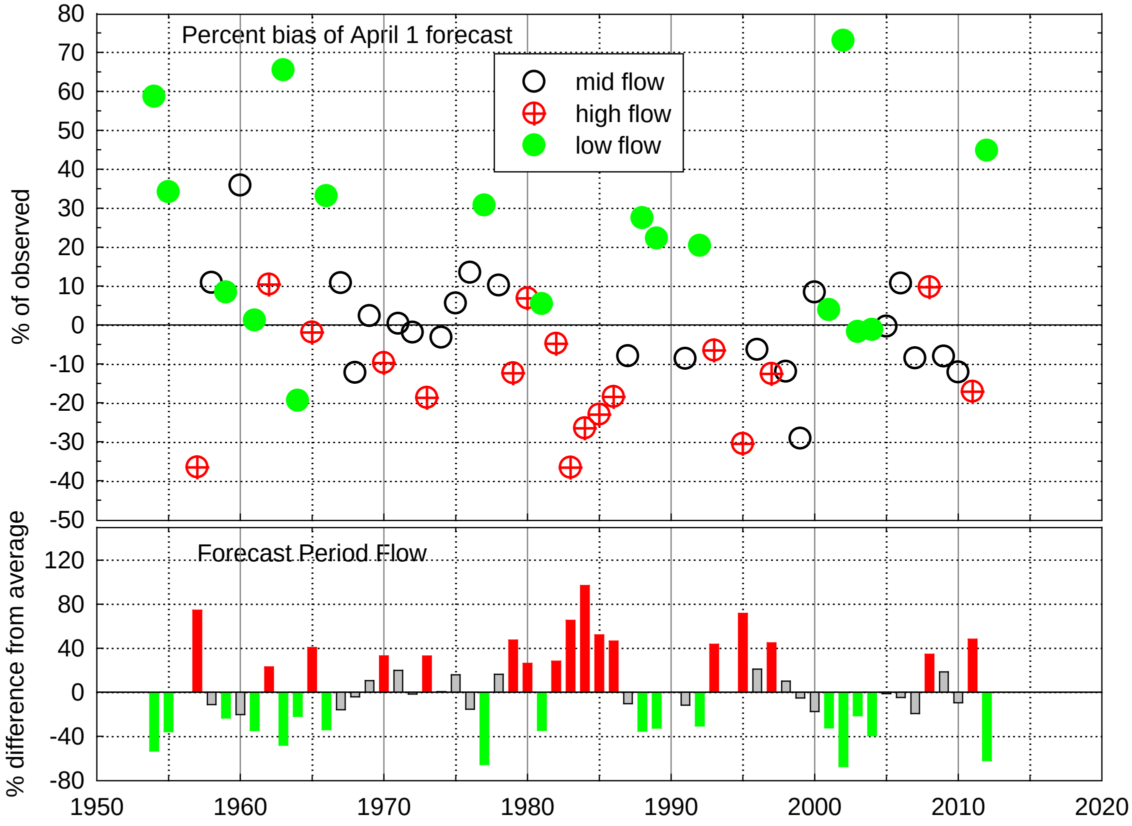
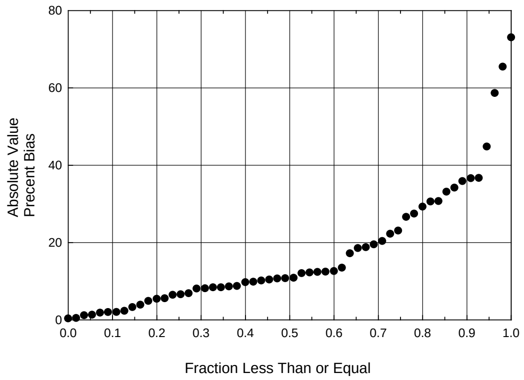


Figure D13: Blue River inflow to Green Mountain Reservoir, CO. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.





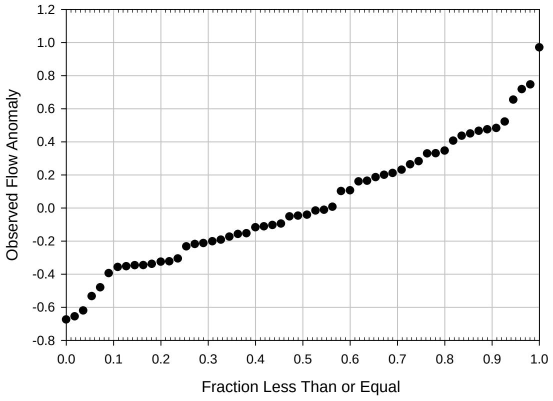
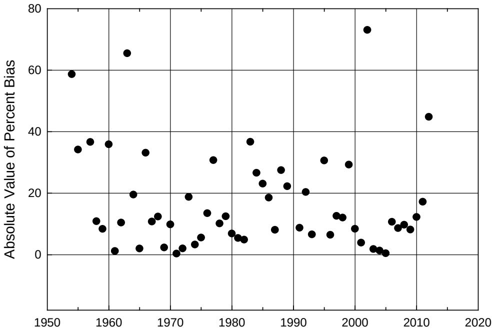
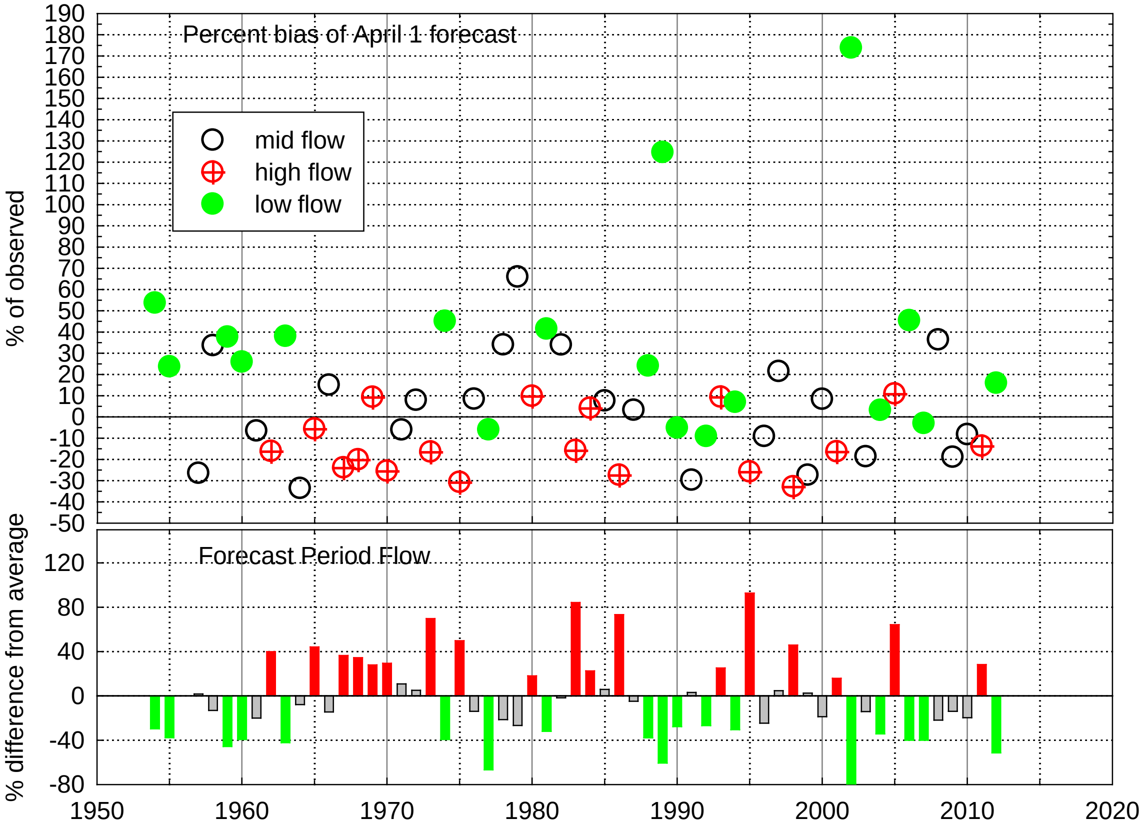
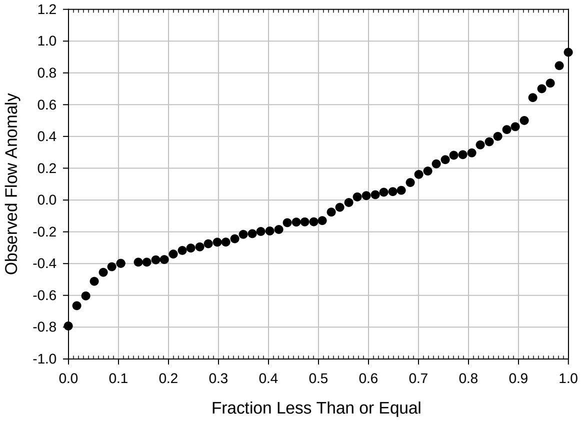
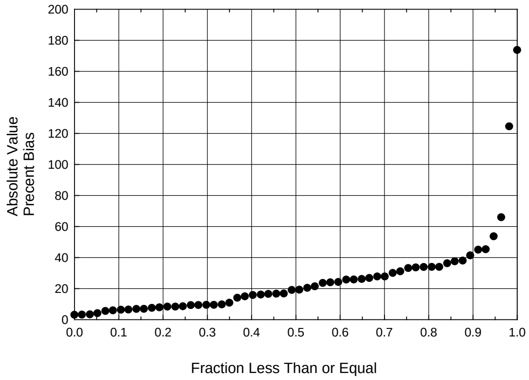


Figure D14: Roaring Fork at Glenwood Springs, CO. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.









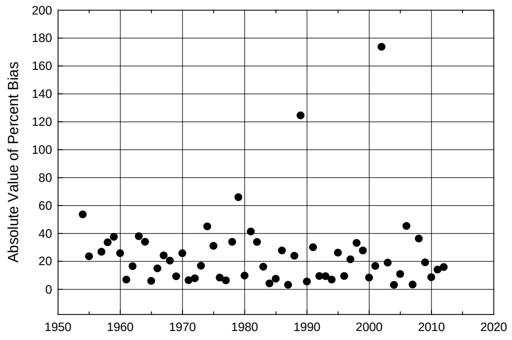
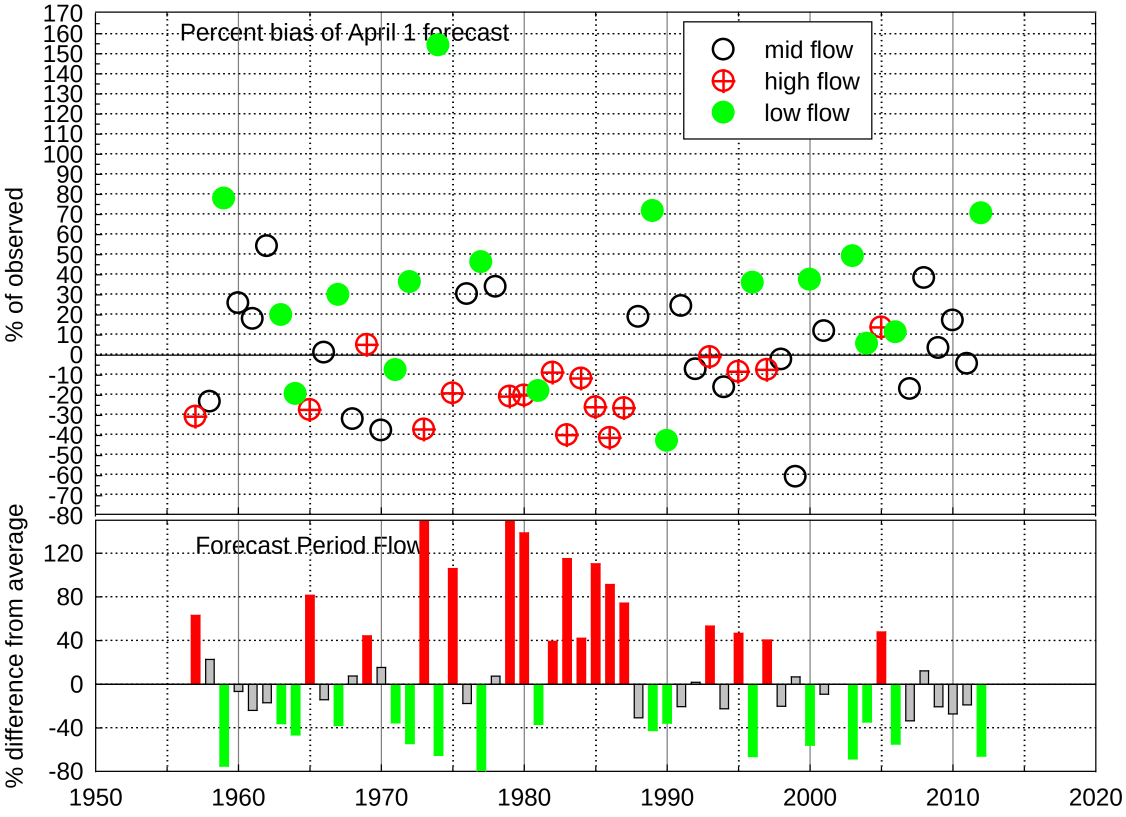
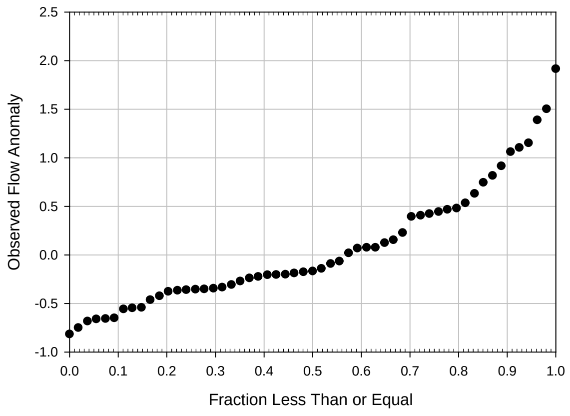
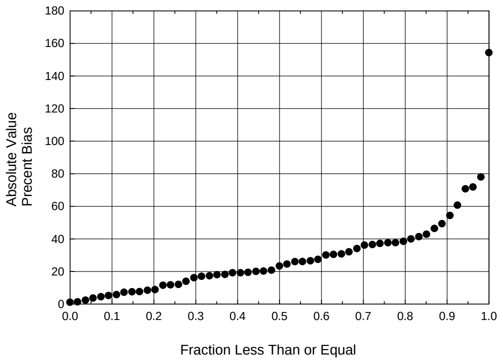


Figure D15: Ashley Creek near Vernal, UT. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.







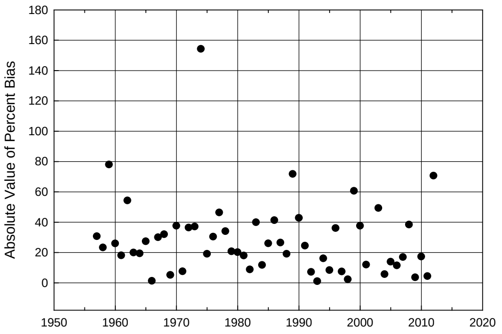
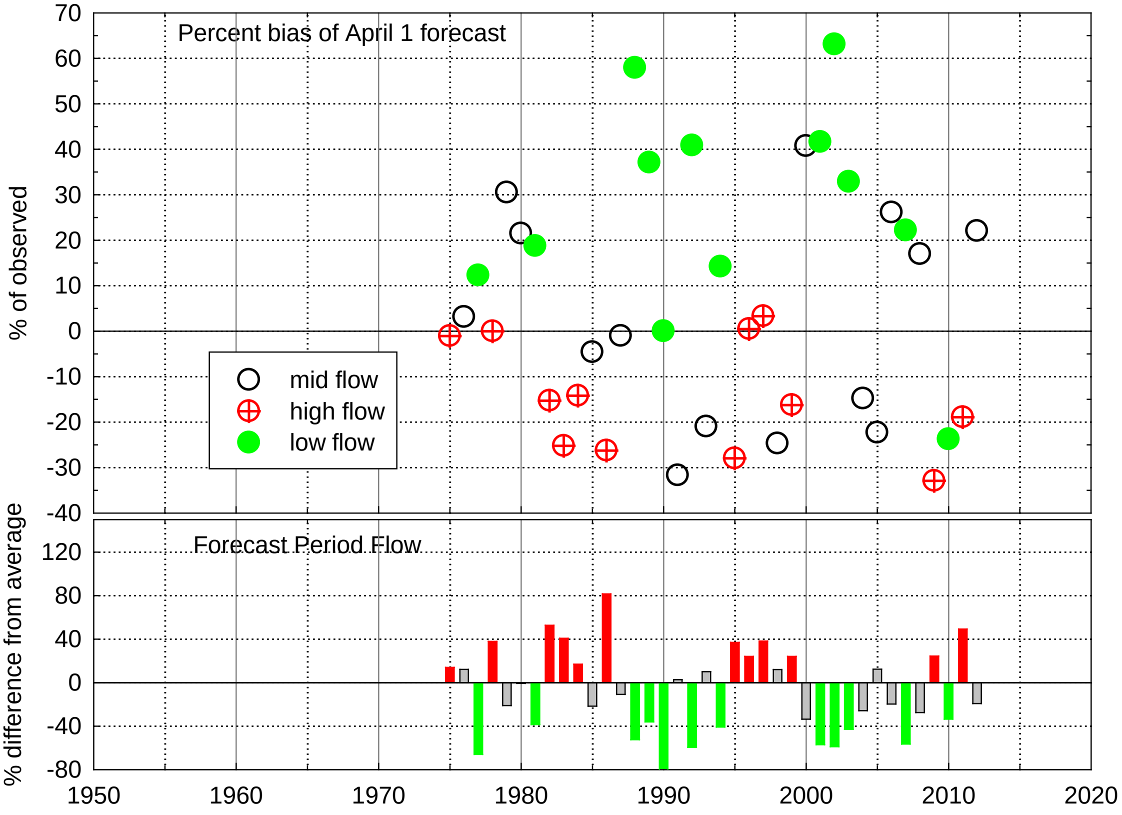
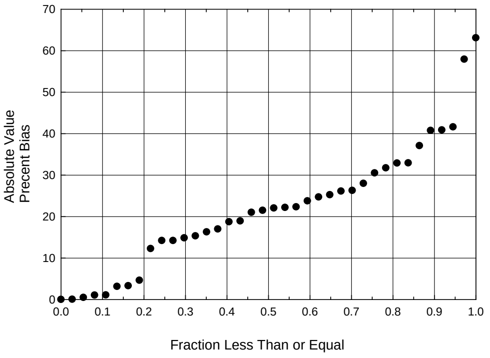
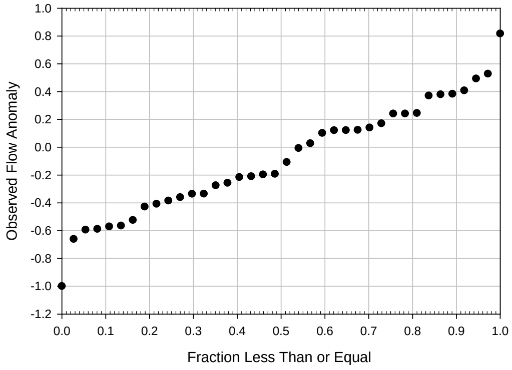


Figure D16: San Juan River near Bluff, UT. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.







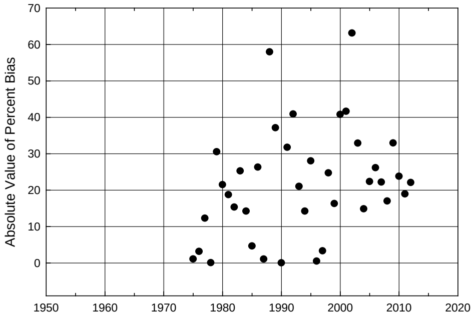
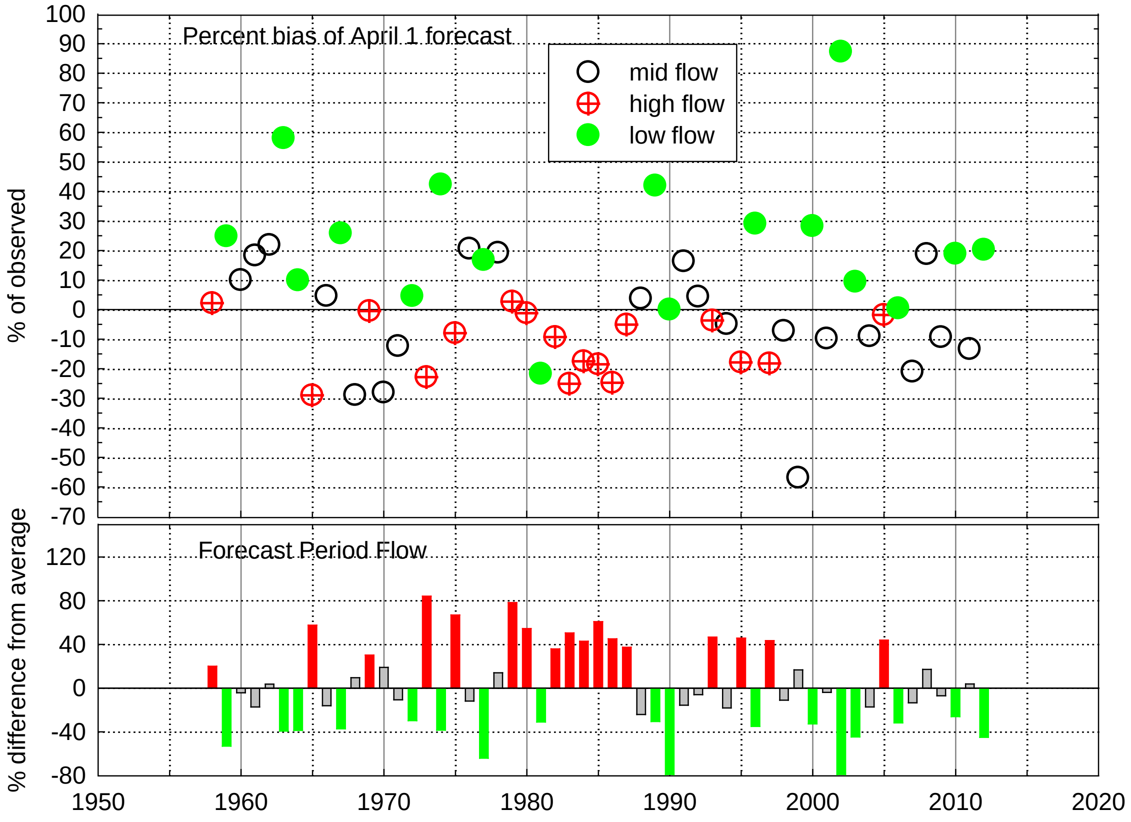
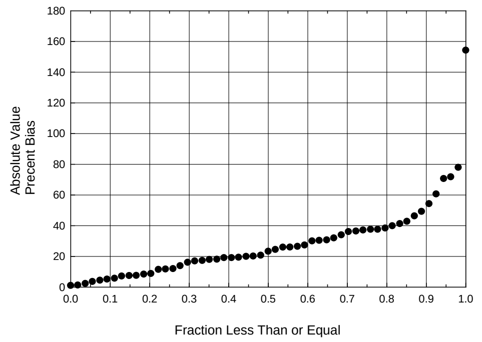
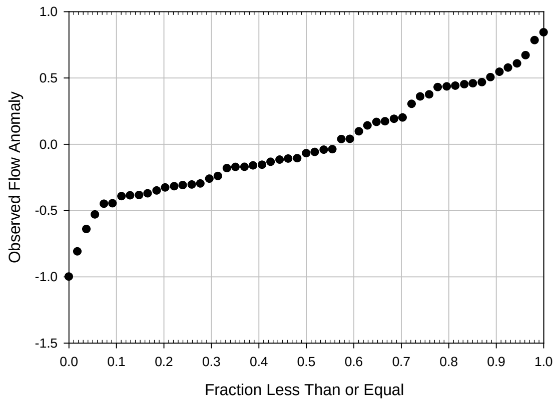


Figure D17:New Fork River near Big Piney, WY. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.







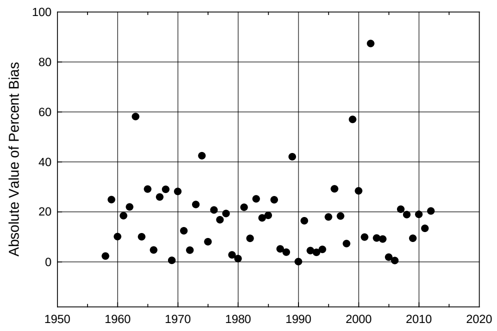
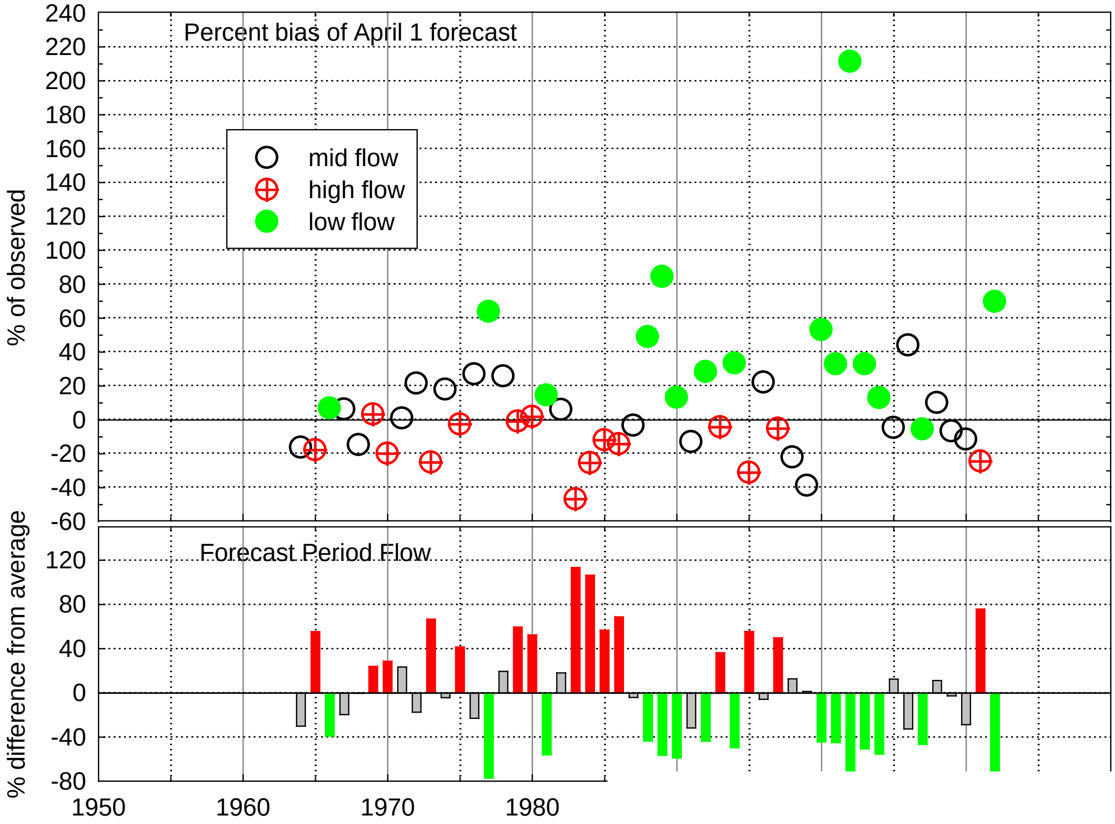
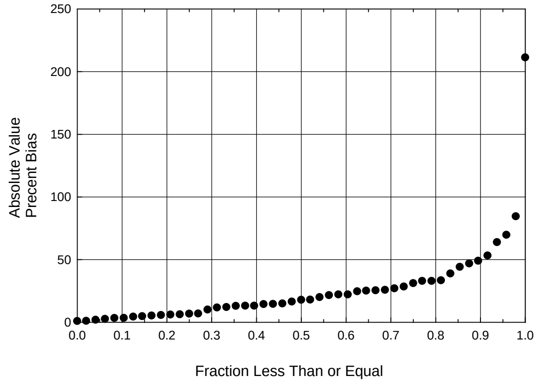
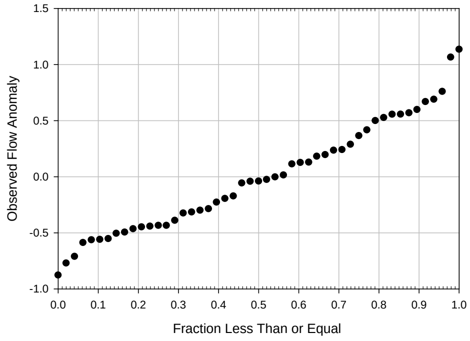


Figure D18: Animas River at Durango, CO. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.







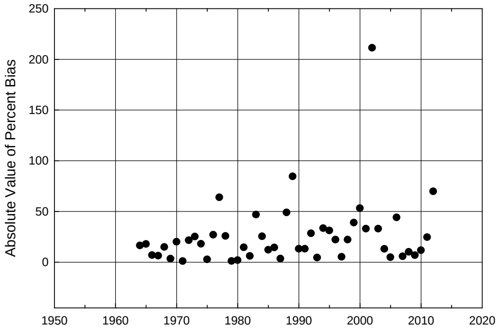
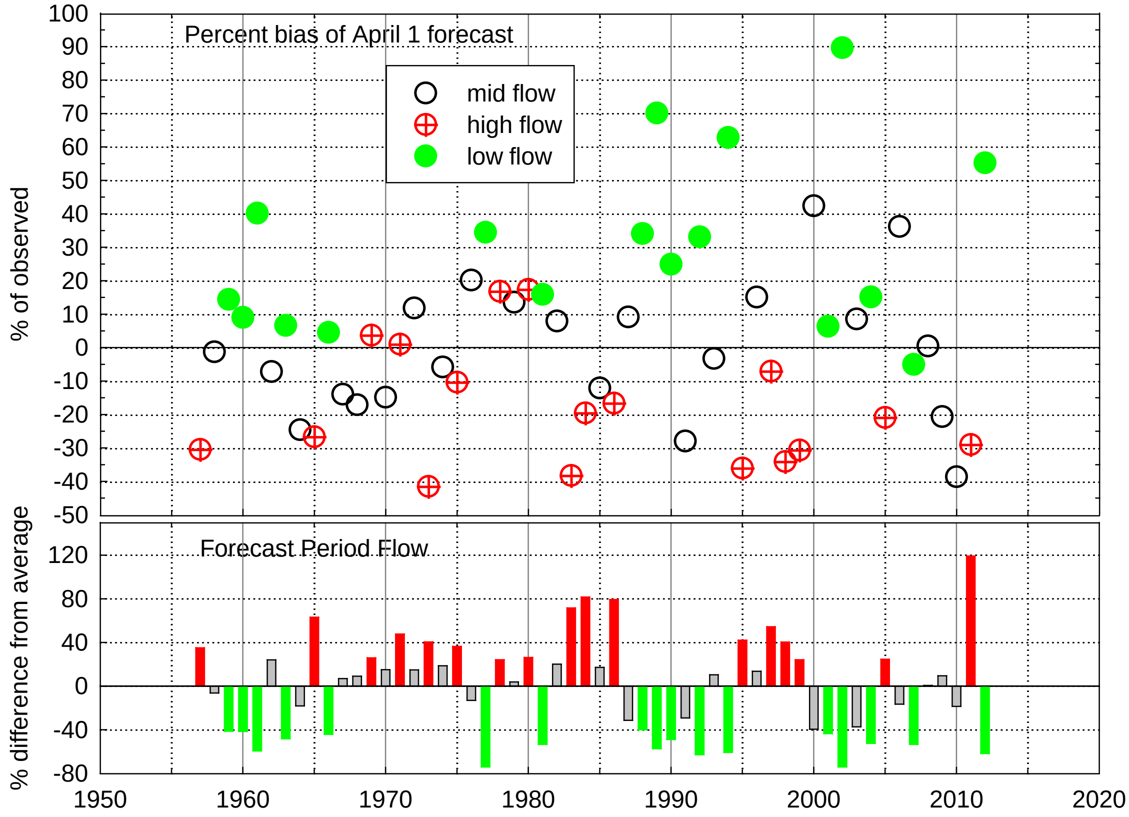
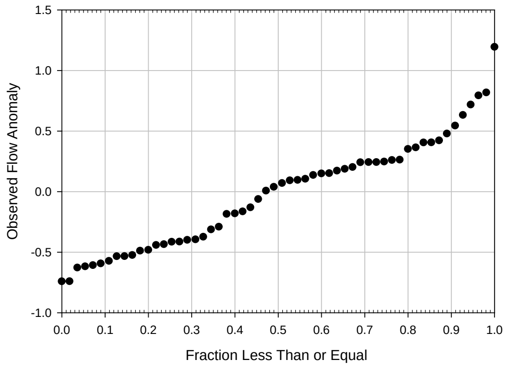
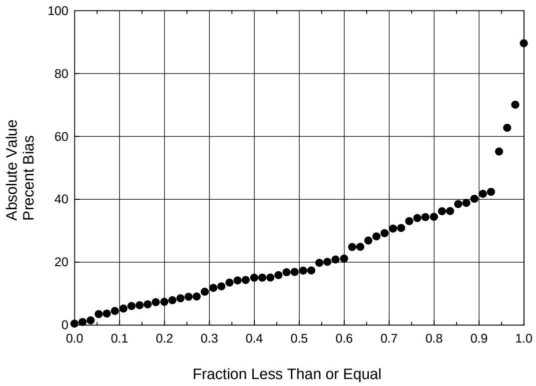


Figure D19:Lake Powell at Glen Canyon Dam, AZ. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.







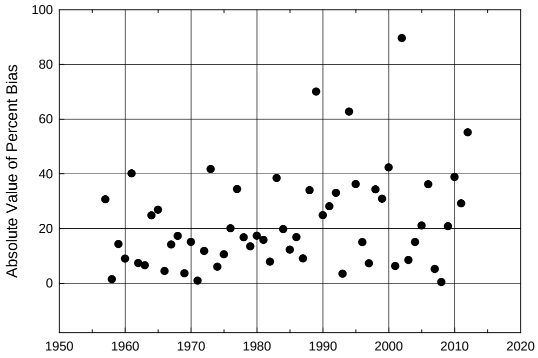
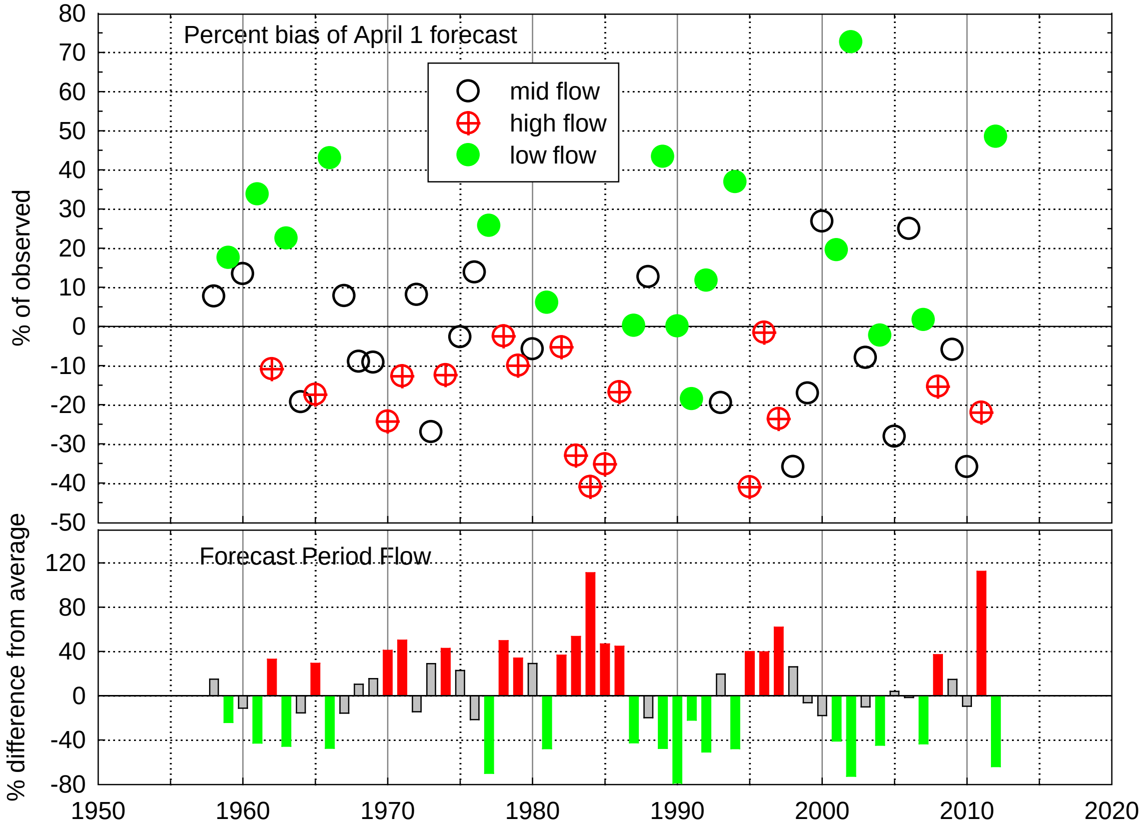
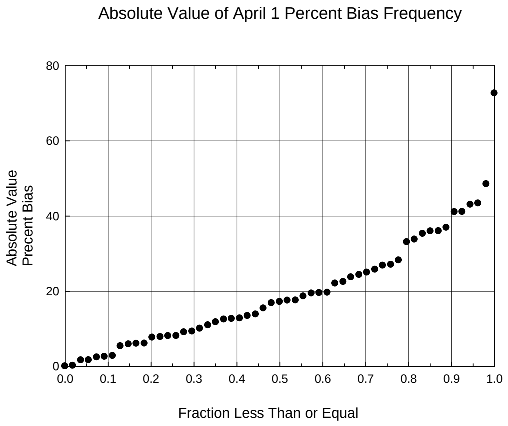
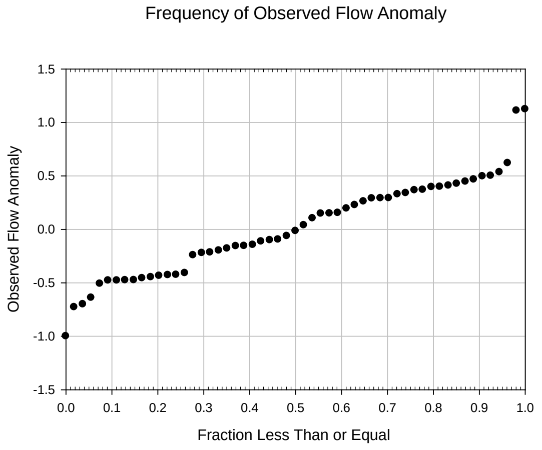


Figure D20: Green River at Green River, UT. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.







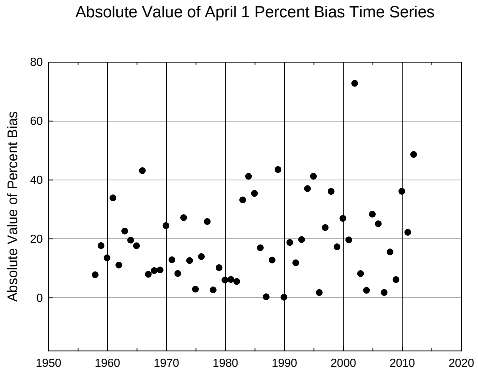
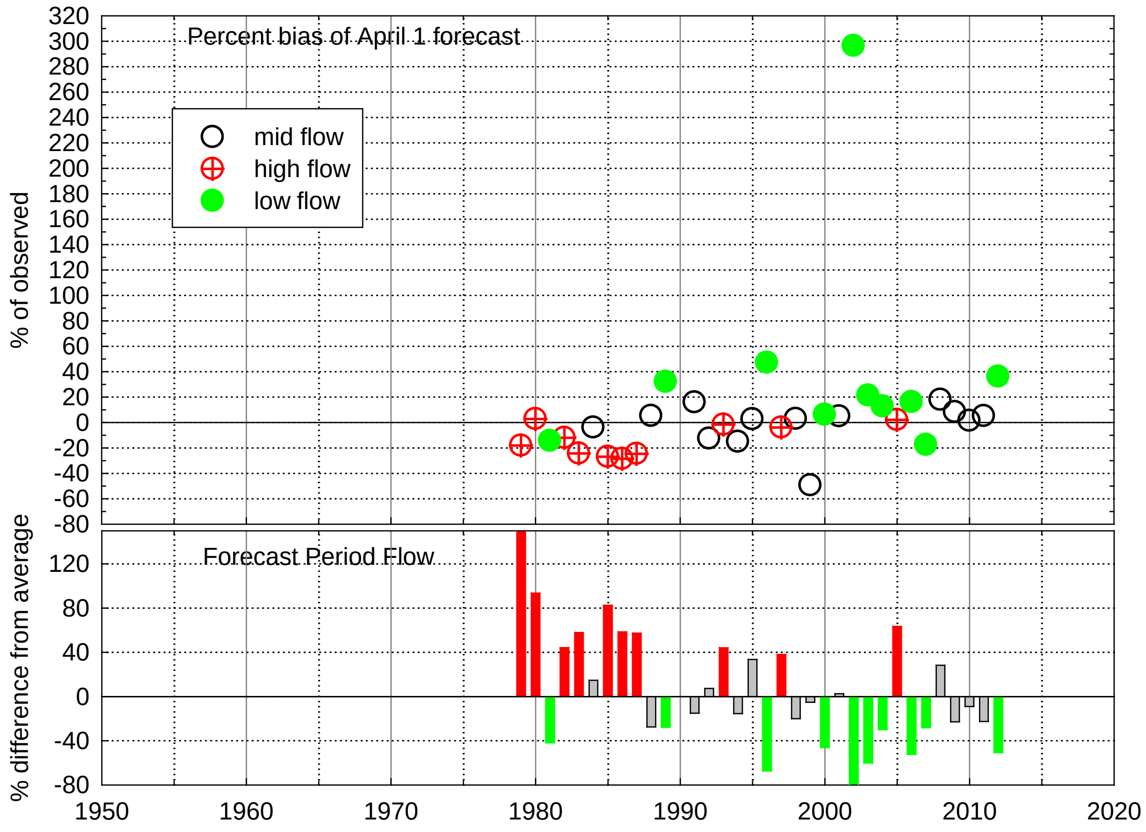
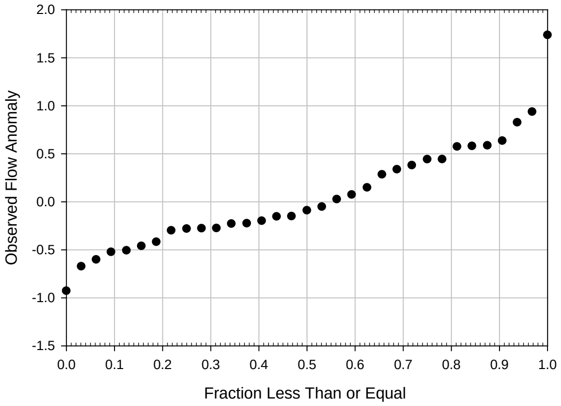


Figure D21: Yampa River near Maybell, CO. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.





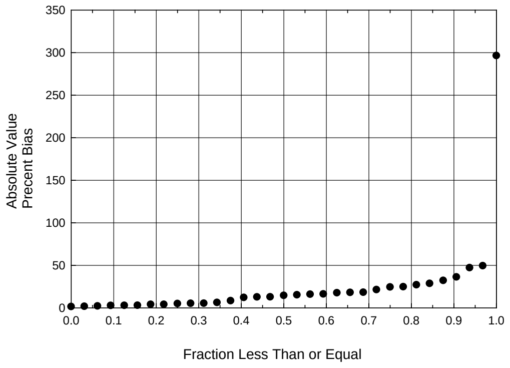
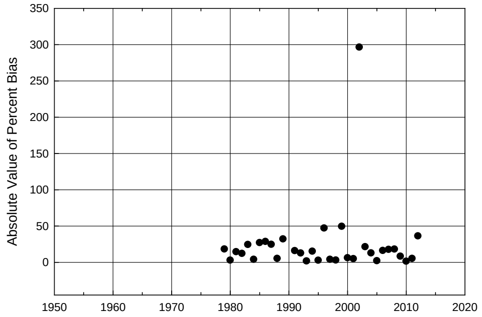
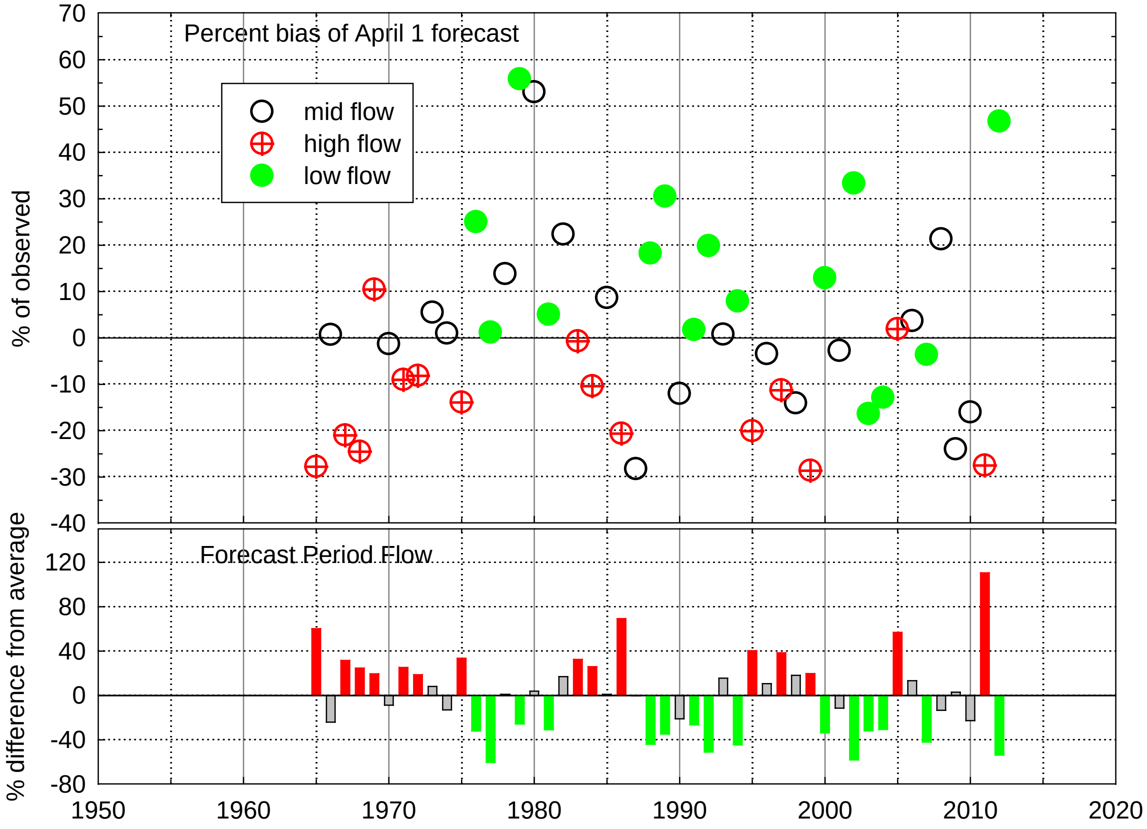
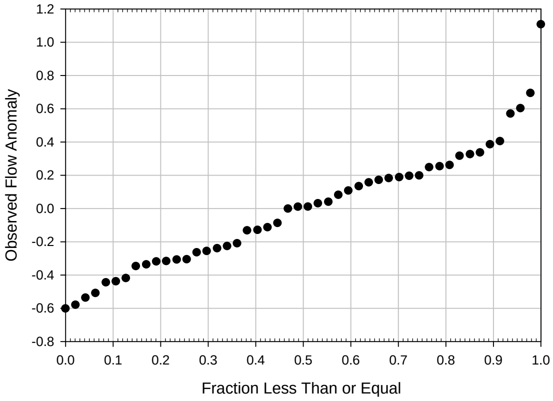
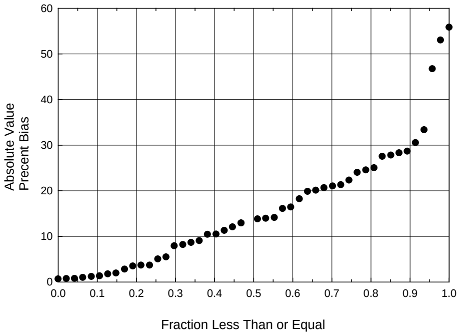


Figure D22: Piedra River near Arboles, CO. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.









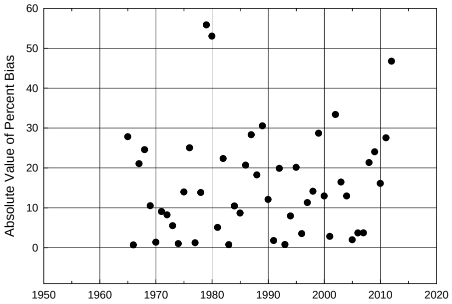
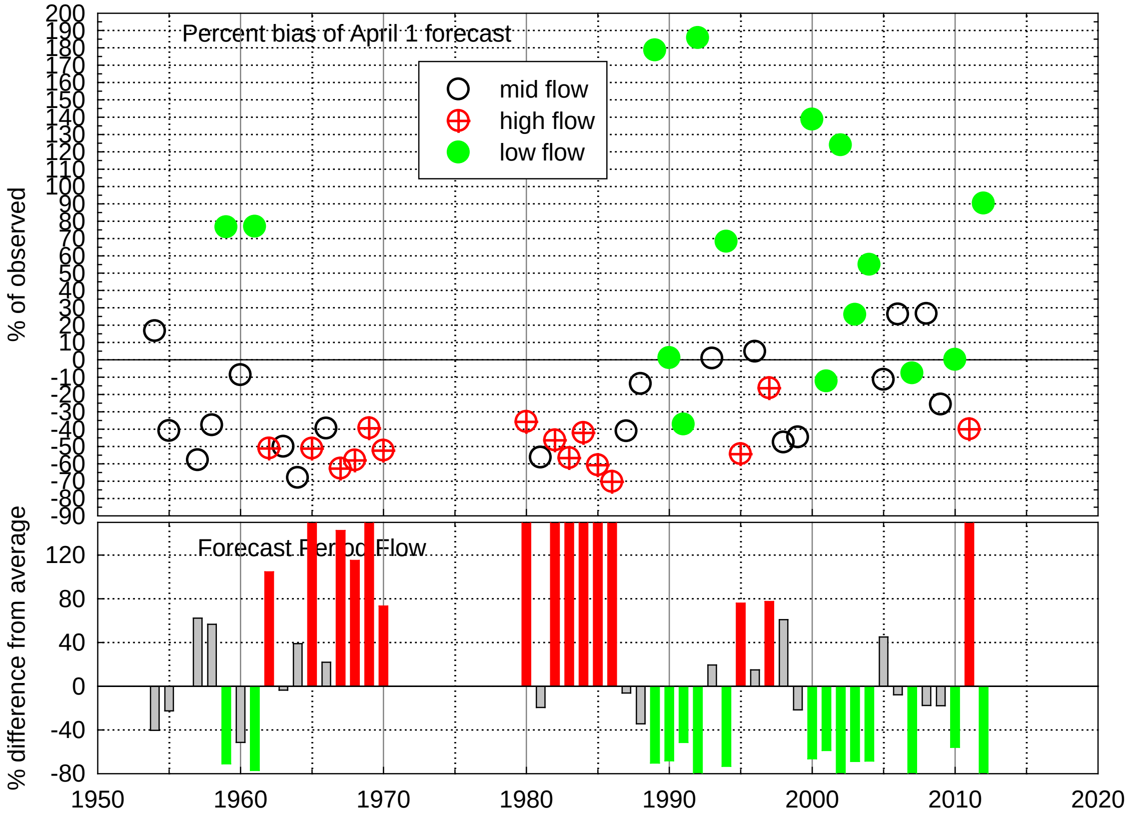
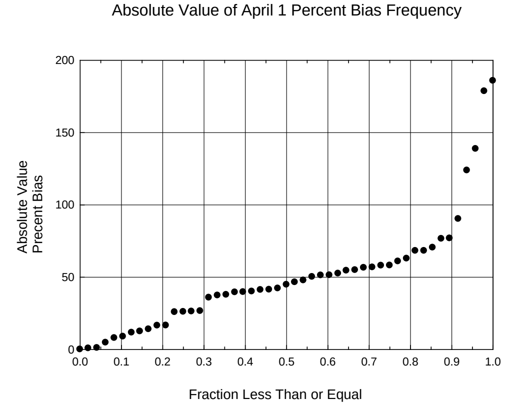
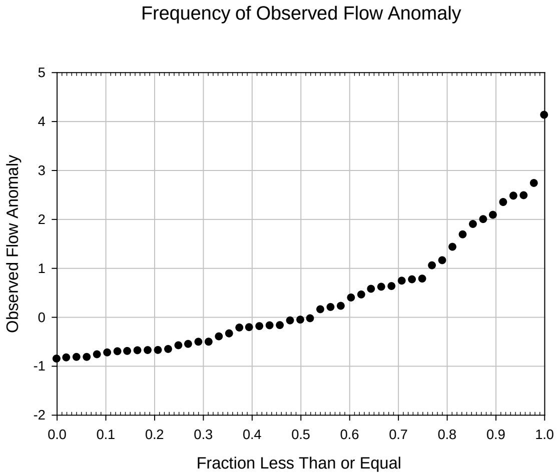


Figure D23: Rock Creek near Mtn Home, UT. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.







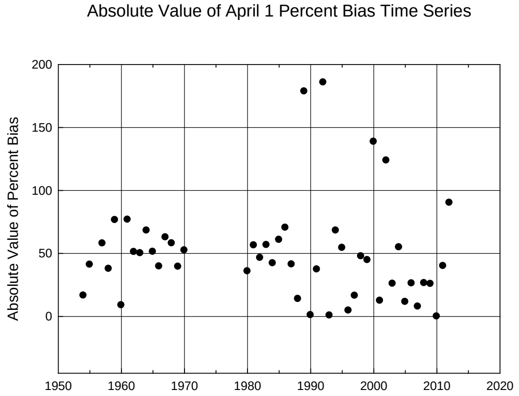
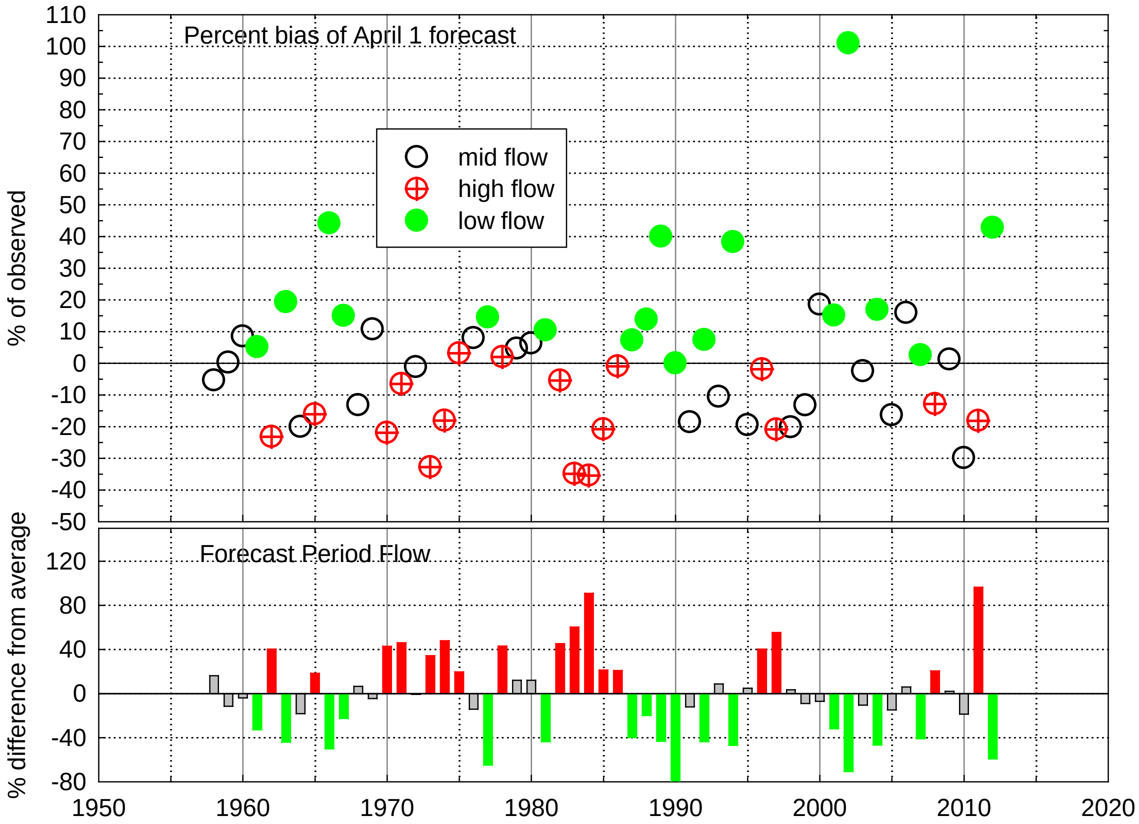
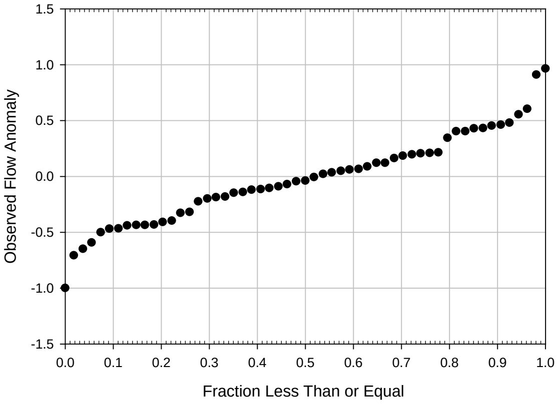


Figure D24: Strawberry River near Duchesne, UT. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.





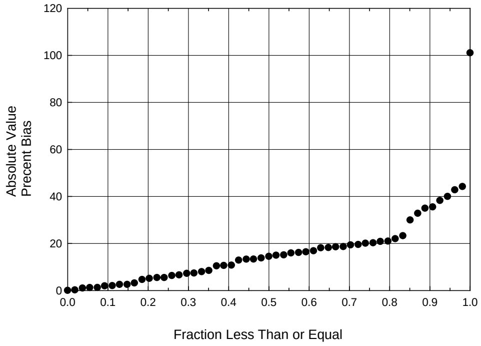
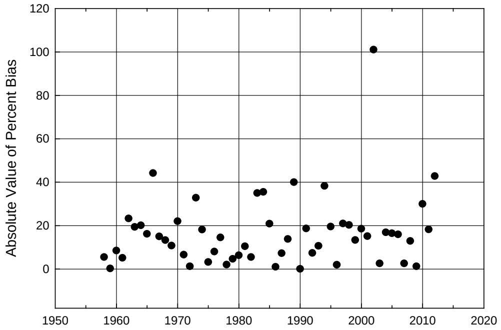
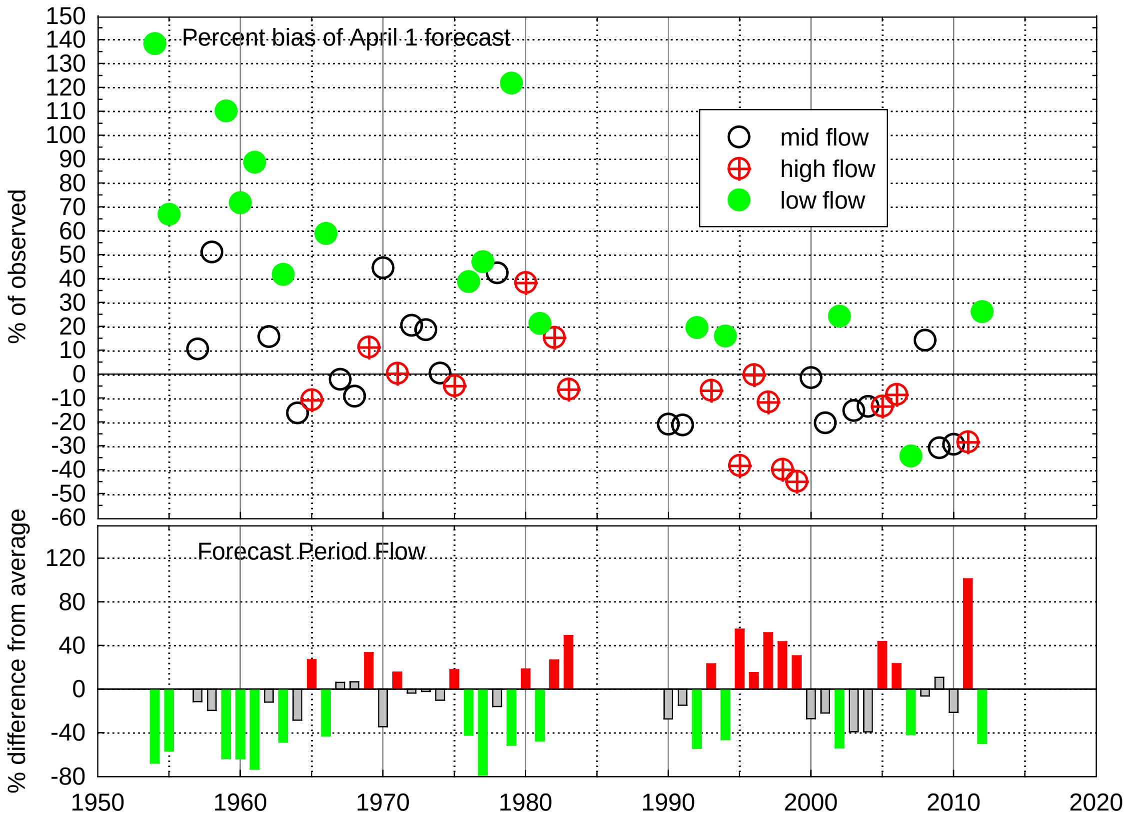
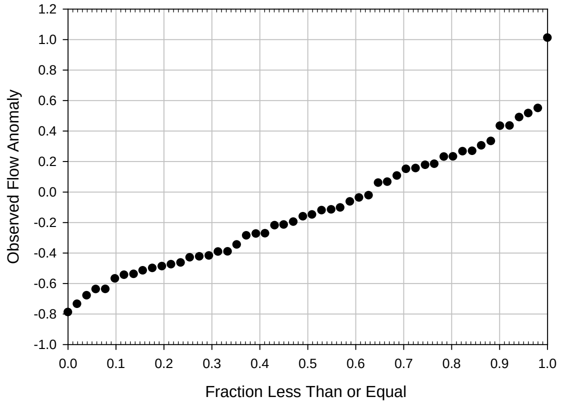


Figure D25: Yampa River at Steamboat Springs, CO. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.







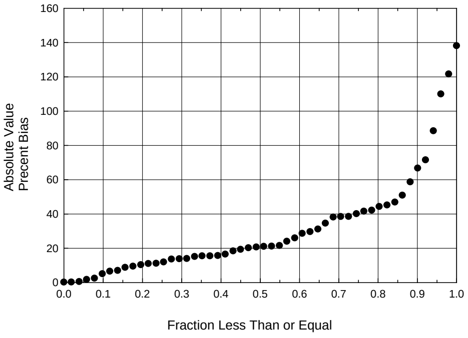
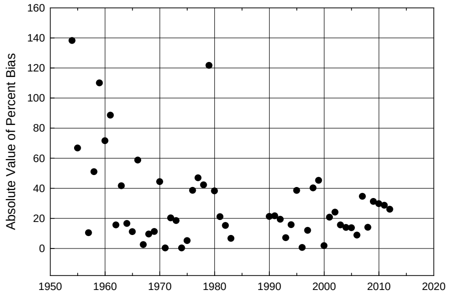
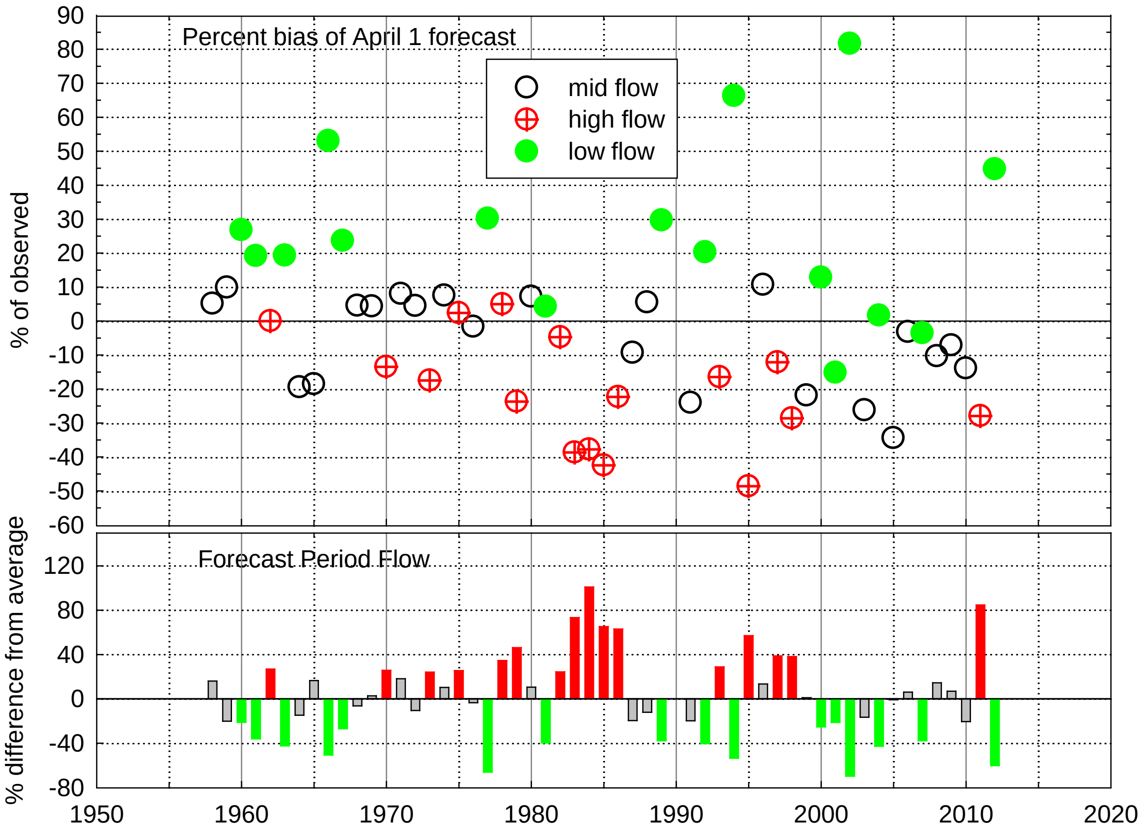
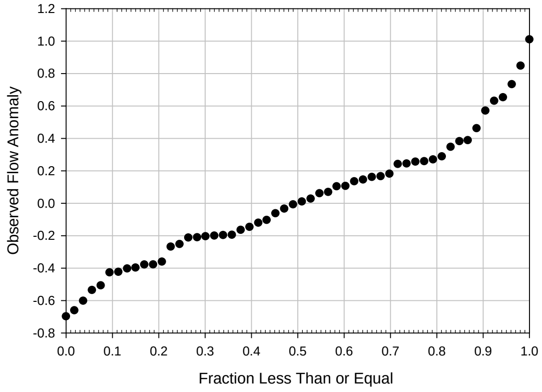


Figure D26: Duchesne River near Tabiona, UT. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.







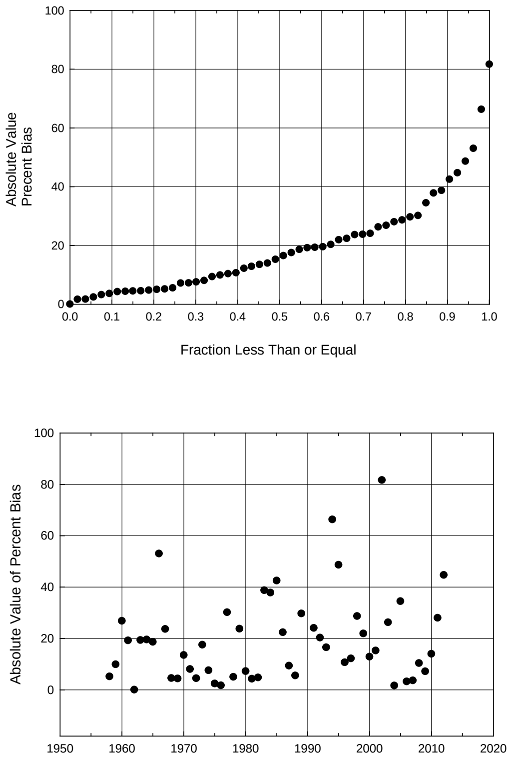


Figure D27: White River near Meeker, CO. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.

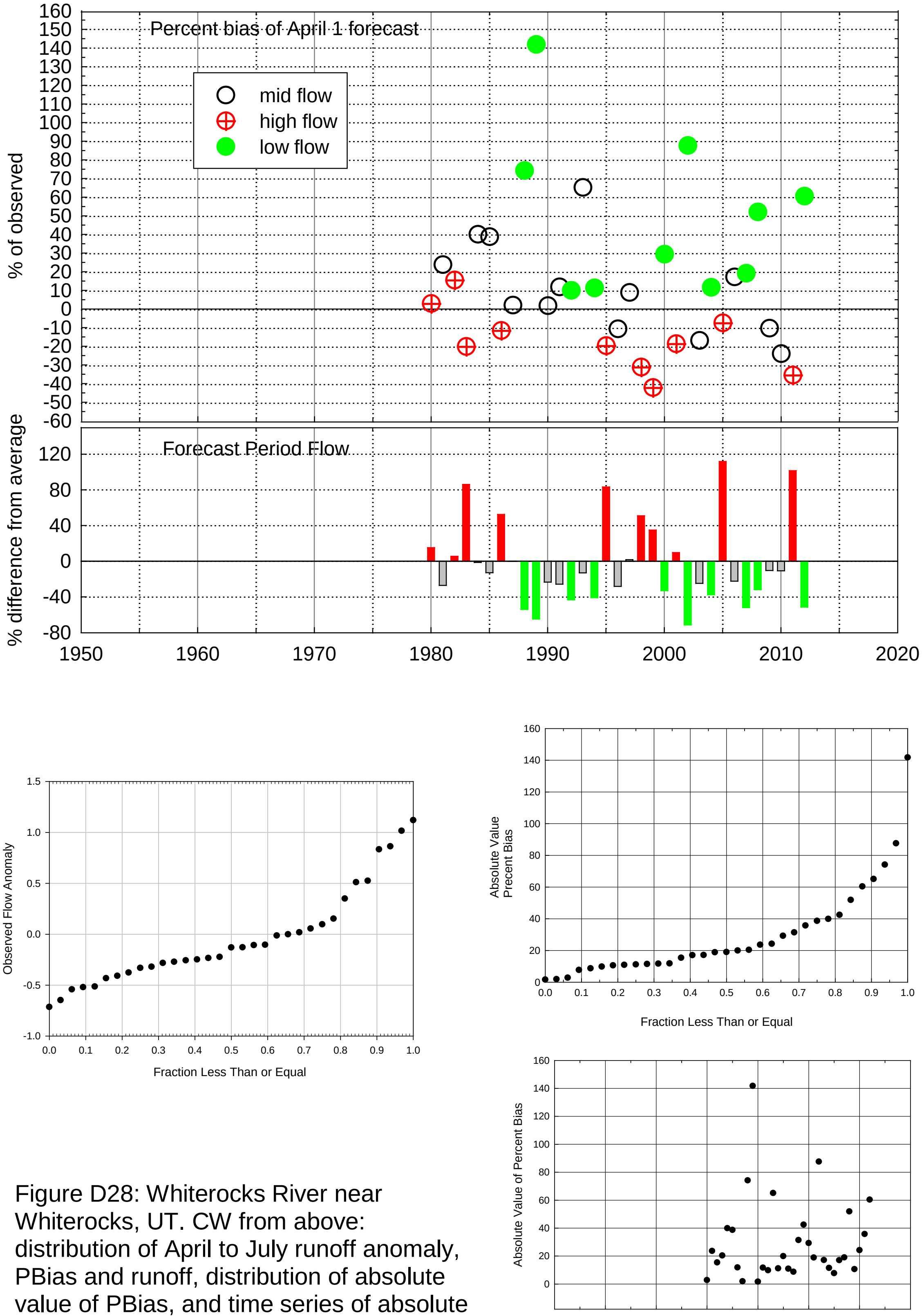


Figure D28: Whiterocks River near Whiterocks, UT. CW from above: distribution of April to July runoff anomaly, PBias and runoff, distribution of absolute value of PBias, and time series of absolute value of PBias.

Appendix E

Colorado Basin Skill Scores

Table 19: Skill Score Mean Absolute Error

Site No.	Location	Jan	Feb	Mar	Apr	May
1	Virgin River at Virgin, UT	0.187	0.416	0.465	0.699	0.821
2	Colorado River below Lake Granby, CO	0.173	0.232	0.258	0.348	0.495
3	Eagle River below Gypsum, CO	0.229	0.320	0.324	0.441	0.565
4	Green River at Warren Bridge, near Daniel, WY	0.198	0.383	0.427	0.431	0.547
5	East River at Almont, CO	0.344	0.431	0.495	0.544	0.638
6	Gunnison River inflow to Blue Mesa Reservoir	0.318	0.405	0.498	0.529	0.667
7	Colorado River near Cameo, CO	0.317	0.424	0.422	0.443	0.582
8	Uncompahgre River at Colona, CO	0.261	0.308	0.294	0.364	0.512
9	Colorado River near Cisco, UT	0.276	0.379	0.387	0.453	0.560
10	Blue River inflow to Dillon Reservoir, CO	0.232	0.320	0.299	0.368	0.561
11	Dolores River at Dolores, CO	0.238	0.318	0.391	0.476	0.643
12	Gunnison River near Grand Junction, CO	0.309	0.350	0.350	0.437	0.538
13	Blue River inflow to Green Mountain Reservoir, CO	0.251	0.349	0.344	0.403	0.546
14	Roaring Fork at Glenwood Springs, CO	0.289	0.423	0.433	0.490	0.639
15	Ashley Creek near Vernal, UT	0.221	0.267	0.284	0.343	0.448
16	San Juan River near Bluff, UT	0.151	0.276	0.297	0.457	0.583
17	New Fork River near Big Piney, WY	0.264	0.331	0.384	0.435	0.574
18	Animas River at Durango, CO	0.256	0.329	0.389	0.492	0.632
19	Lake Powell at Glen Canyon Dam, AZ	0.315	0.408	0.444	0.534	0.679
20	Green River at Green River, UT	0.292	0.409	0.449	0.484	0.627
21	Yampa River near Maybell, CO	0.250	0.392	0.385	0.462	0.601

22	Piedra River near Arboles, CO	0.243	0.319	0.400	0.614	0.656
23	Rock Creek near Mtn Home, UT	0.281	0.382	0.401	0.467	0.574
24	Strawberry River near Duchesne, UT	0.224	0.283	0.312	0.343	0.472
25	Yampa River at Steamboat Springs, CO	0.255	0.418	0.442	0.491	0.629
26	Duchesne River near Tabiona, UT	0.182	0.325	0.385	0.392	0.454
27	White River near Meeker, CO	0.268	0.375	0.353	0.400	0.512
28	Whiterocks River near Whiterocks, UT	0.176	0.233	0.281	0.343	0.469

Table 20: R^2 between forecasts and observations by month for April to July runoff

Site No.	Location	Jan	Feb	Mar	Apr	May
1	Virgin River at Virgin, UT	0.584	0.811	0.868	0.945	0.975
2	Colorado River below Lake Granby, CO	0.604	0.633	0.680	0.778	0.842
3	Eagle River below Gypsum, CO	0.636	0.662	0.671	0.785	0.858
4	Green River at Warren Bridge, near Daniel, WY	0.689	0.805	0.851	0.843	0.894
5	East River at Almont, CO	0.632	0.766	0.818	0.834	0.885
6	Gunnison River inflow to Blue Mesa Reservoir	0.703	0.777	0.841	0.878	0.933
7	Colorado River near Cameo, CO	0.725	0.755	0.749	0.794	0.868
8	Uncompahgre River at Colona, CO	0.616	0.620	0.594	0.687	0.842
9	Colorado River near Cisco, UT	0.543	0.675	0.669	0.782	0.864
10	Blue River inflow to Dillon Reservoir, CO	0.608	0.642	0.656	0.728	0.877
11	Dolores River at Dolores, CO	0.554	0.656	0.722	0.779	0.866
12	Gunnison River near Grand Junction, CO	0.630	0.674	0.667	0.785	0.846
13	Blue River inflow to Green Mountain Reservoir, CO	0.631	0.679	0.675	0.752	0.855
14	Roaring Fork at Glenwood Springs, CO	0.628	0.748	0.761	0.808	0.886
15	Ashley Creek near Vernal, UT	0.613	0.640	0.671	0.739	0.810
16	San Juan River near Bluff, UT	0.504	0.656	0.677	0.811	0.884
17	New Fork River near Big Piney, WY	0.654	0.728	0.785	0.832	0.911
18	Animas River at Durango, CO	0.652	0.705	0.741	0.819	0.901
19	Lake Powell at Glen Canyon Dam, AZ	0.708	0.777	0.786	0.852	0.915
20	Green River at Green River, UT	0.668	0.775	0.808	0.832	0.915
21	Yampa River near Maybell, CO	0.657	0.786	0.769	0.822	0.891
22	Piedra River near Arboles, CO	0.665	0.739	0.765	0.897	0.926

23	Rock Creek near Mtn Home, UT	0.731	0.789	0.797	0.820	0.899
24	Strawberry River near Duchesne, UT	0.458	0.573	0.627	0.709	0.843
25	Yampa River at Steamboat Springs, CO	0.685	0.825	0.818	0.840	0.901
26	Duchesne River near Tabiona, UT	0.452	0.631	0.662	0.674	0.731
27	White River near Meeker, CO	0.657	0.712	0.681	0.718	0.804
28	Whiterocks River near Whiterocks, UT	0.576	0.687	0.707	0.742	0.849

Table 21: Nash Sutcliffe score for April - July forecasts

Site No.	Location	Jan	Feb	Mar	Apr	May
1	Virgin River at Virgin, UT	0.330	0.634	0.747	0.905	0.958
2	Colorado River below Lake Granby, CO	0.339	0.377	0.427	0.561	0.713
3	Eagle River below Gypsum, CO	0.400	0.416	0.433	0.609	0.767
4	Green River at Warren Bridge, near Daniel, WY	0.537	0.661	0.742	0.752	0.827
5	East River at Almont, CO	0.541	0.558	0.623	0.695	0.781
6	Gunnison River inflow to Blue Mesa Reservoir	0.503	0.588	0.684	0.783	0.886
7	Colorado River near Cameo, CO	0.482	0.514	0.516	0.600	0.749
8	Uncompahgre River at Colona, CO	0.378	0.380	0.345	0.467	0.678
9	Colorado River near Cisco, UT	0.209	0.343	0.335	0.454	0.619
10	Blue River inflow to Dillon Reservoir, CO	0.336	0.378	0.388	0.489	0.747
11	Dolores River at Dolores, CO	0.288	0.429	0.520	0.624	0.785
12	Gunnison River near Grand Junction, CO	0.356	0.394	0.371	0.535	0.665
13	Blue River inflow to Green Mountain Reservoir, CO	0.399	0.447	0.436	0.559	0.737
14	Roaring Fork at Glenwood Springs, CO	0.417	0.547	0.563	0.652	0.792
15	Ashley Creek near Vernal, UT	0.370	0.404	0.448	0.546	0.649
16	San Juan River near Bluff, UT	0.246	0.425	0.451	0.637	0.750
17	New Fork River near Big Piney, WY	0.403	0.497	0.587	0.676	0.803
18	Animas River at Durango, CO	0.421	0.497	0.548	0.690	0.829
19	Lake Powell at Glen Canyon Dam, AZ	0.494	0.588	0.597	0.703	0.823
20	Green River at Green River, UT	0.432	0.581	0.621	0.660	0.821
21	Yampa River near Maybell, CO	0.416	0.556	0.541	0.627	0.773
22	Piedra River near Arboles, CO	0.394	0.506	0.570	0.776	0.837
23	Rock Creek near Mtn	0.530	0.621	0.633	0.665	0.797

	Home, UT					
24	Strawberry River near Duchesne, UT	0.003	0.146	0.224	0.281	0.537
25	Yampa River at Steamboat Springs, CO	0.491	0.636	0.625	0.687	0.809
26	Duchesne River near Tabiona, UT	0.091	0.361	0.451	0.473	0.627
27	White River near Meeker, CO	0.430	0.502	0.459	0.527	0.660
28	Whiterocks River near Whiterocks, UT	0.331	0.469	0.468	0.540	0.716

Table 22: Probability of detection for low flow years

Site No.	Location	Jan	Feb	Mar	Apr	May
1	Virgin River at Virgin, UT	0.000	0.170	0.170	0.670	1.000
2	Colorado River below Lake Granby, CO	0.571	0.571	0.714	0.857	1.000
3	Eagle River below Gypsum, CO	0.429	0.286	0.571	0.714	0.833
4	Green River at Warren Bridge, near Daniel, WY	0.167	0.333	0.667	0.833	0.833
5	East River at Almont, CO	0.429	0.571	0.429	0.714	0.833
6	Gunnison River inflow to Blue Mesa Reservoir	0.333	0.429	0.286	0.500	0.667
7	Colorado River near Cameo, CO	0.429	0.286	0.714	0.571	0.833
8	Uncompahgre River at Colona, CO	0.429	0.714	0.571	0.714	1.000
9	Colorado River near Cisco, UT	0.500	0.500	0.400	0.900	0.900
10	Blue River inflow to Dillon Reservoir, CO	0.571	0.286	0.429	0.857	1.000
11	Dolores River at Dolores, CO	0.571	0.714	0.571	0.857	1.000
12	Gunnison River near Grand Junction, CO	0.143	0.714	0.286	0.714	1.000
13	Blue River inflow to Green Mountain Reservoir, CO	0.286	0.143	0.143	0.571	0.667
14	Roaring Fork at Glenwood Springs, CO	0.286	0.714	0.714	0.857	1.000
15	Ashley Creek near Vernal, UT	0.200	0.300	0.400	0.500	1.000
16	San Juan River near Bluff, UT	0.500	0.600	0.600	0.700	0.800
17	New Fork River near Big Piney, WY	0.286	0.286	0.000	0.429	0.571
18	Animas River at Durango, CO	0.100	0.100	0.300	0.600	0.600
19	Lake Powell at Glen Canyon Dam, AZ	0.100	0.100	0.300	0.600	0.600
20	Green River at Green River, UT	0.000	0.000	0.200	0.600	0.800
21	Yampa River near Maybell, CO	0.000	0.143	0.000	0.714	0.714
22	Piedra River near Arboles, CO	0.714	0.714	0.714	0.857	0.857
23	Rock Creek near Mtn	0.300	0.500	0.500	0.800	0.857

	Home, UT					
24	Strawberry River near Duchesne, UT	0.100	0.100	0.100	0.300	0.571
25	Yampa River at Steamboat Springs, CO	0.286	0.571	0.429	0.857	1.000
26	Duchesne River near Tabiona, UT	0.500	0.875	0.444	0.667	1.000
27	White River near Meeker, CO	0.286	0.571	0.429	0.714	0.857
28	Whiterocks River near Whiterocks, UT	0.429	0.462	0.231	0.571	0.727

Table 23: Probability of detection for mid flow years

Site No.	Location	Jan	Feb	Mar	Apr	May
1	Virgin River at Virgin, UT	0.630	0.140	0.250	0.670	0.860
2	Colorado River below Lake Granby, CO	0.375	0.556	0.333	0.250	0.375
3	Eagle River below Gypsum, CO	0.375	0.625	0.625	0.375	0.750
4	Green River at Warren Bridge, near Daniel, WY	0.714	1.000	1.000	1.000	0.857
5	East River at Almont, CO	0.750	0.500	0.625	0.875	0.875
6	Gunnison River inflow to Blue Mesa Reservoir	0.750	0.750	0.750	0.750	0.714
7	Colorado River near Cameo, CO	0.625	0.500	0.625	0.375	0.625
8	Uncompahgre River at Colona, CO	0.500	0.875	0.750	0.625	0.750
9	Colorado River near Cisco, UT	0.769	0.769	0.786	0.857	0.857
10	Blue River inflow to Dillon Reservoir, CO	0.500	0.375	0.375	0.625	0.625
11	Dolores River at Dolores, CO	0.375	0.375	0.625	0.625	0.500
12	Gunnison River near Grand Junction, CO	0.875	0.750	0.750	0.625	0.500
13	Blue River inflow to Green Mountain Reservoir, CO	0.500	0.750	0.625	0.500	0.250
14	Roaring Fork at Glenwood Springs, CO	0.750	0.625	0.625	0.625	0.625
15	Ashley Creek near Vernal, UT	0.538	0.538	0.286	0.286	0.400
16	San Juan River near Bluff, UT	0.833	0.833	0.833	0.692	0.846
17	New Fork River near Big Piney, WY	0.875	0.875	0.875	0.750	0.750
18	Animas River at Durango, CO	0.923	0.923	0.857	0.929	0.929
19	Lake Powell at Glen Canyon Dam, AZ	0.923	0.923	0.857	0.929	0.929
20	Green River at Green River, UT	0.846	0.615	0.714	0.643	0.714
21	Yampa River near Maybell, CO	0.750	0.750	0.750	0.625	1.000
22	Piedra River near Arboles, CO	0.625	0.625	0.875	0.625	0.875
23	Rock Creek near Mtn	0.917	0.846	0.571	0.643	0.700

	Home, UT					
24	Strawberry River near Duchesne, UT	0.923	0.769	0.846	0.692	0.600
25	Yampa River at Steamboat Springs, CO	0.375	0.625	0.750	0.500	0.750
26	Duchesne River near Tabiona, UT	0.818	0.636	0.700	0.600	0.556
27	White River near Meeker, CO	0.625	0.625	0.625	0.375	0.625
28	Whiterocks River near Whiterocks, UT	0.688	0.389	0.222	0.467	0.538

Table 24: Probability of detection for high flow years

Site No.	Location	Jan	Feb	Mar	Apr	May
1	Virgin River at Virgin, UT	0.670	0.830	1.000	0.830	1.000
2	Colorado River below Lake Granby, CO	0.429	0.429	0.571	0.429	0.667
3	Eagle River below Gypsum, CO	0.167	0.714	0.714	0.500	1.000
4	Green River at Warren Bridge, near Daniel, WY	0.333	0.333	0.333	0.333	0.500
5	East River at Almont, CO	0.333	0.714	0.714	1.000	1.000
6	Gunnison River inflow to Blue Mesa Reservoir	0.333	0.667	0.833	1.000	0.833
7	Colorado River near Cameo, CO	0.333	0.714	0.857	0.667	1.000
8	Uncompahgre River at Colona, CO	0.667	0.571	0.714	0.667	0.667
9	Colorado River near Cisco, UT	0.300	0.400	0.300	0.200	0.500
10	Blue River inflow to Dillon Reservoir, CO	0.000	0.429	0.429	0.333	0.333
11	Dolores River at Dolores, CO	0.500	0.571	0.571	0.667	0.500
12	Gunnison River near Grand Junction, CO	0.667	0.714	0.857	0.833	1.000
13	Blue River inflow to Green Mountain Reservoir, CO	0.000	0.429	0.571	0.333	0.667
14	Roaring Fork at Glenwood Springs, CO	0.500	0.571	0.714	0.667	0.833
15	Ashley Creek near Vernal, UT	0.600	0.800	0.800	0.800	1.000
16	San Juan River near Bluff, UT	0.300	0.400	0.400	0.700	0.700
17	New Fork River near Big Piney, WY	0.143	0.286	0.286	0.286	0.571
18	Animas River at Durango, CO	0.500	0.600	0.800	0.800	0.900
19	Lake Powell at Glen Canyon Dam, AZ	0.500	0.600	0.800	0.800	0.900
20	Green River at Green River, UT	0.400	0.400	0.500	0.500	0.500
21	Yampa River near Maybell, CO	0.286	0.429	0.429	0.571	0.571
22	Piedra River near Arboles, CO	0.571	0.714	0.857	0.857	0.857

23	Rock Creek near Mtn Home, UT	0.700	0.500	0.500	0.600	0.571
24	Strawberry River near Duchesne, UT	0.200	0.200	0.200	0.200	0.857
25	Yampa River at Steamboat Springs, CO	0.429	0.714	0.714	0.857	0.857
26	Duchesne River near Tabiona, UT	0.500	0.375	0.444	0.556	0.429
27	White River near Meeker, CO	0.286	0.429	0.429	0.429	0.714
28	Whiterocks River near Whiterocks, UT	0.538	0.615	1.000	0.615	0.889

Table 25: False alarm rate for low flow years

Site No.	Location	Jan	Feb	Mar	Apr	May
1	Virgin River at Virgin, UT	1.000	0.750	0.670	0.200	0.170
2	Colorado River below Lake Granby, CO	0.636	0.600	0.615	0.538	0.462
3	Eagle River below Gypsum, CO	0.571	0.600	0.333	0.375	0.167
4	Green River at Warren Bridge, near Daniel, WY	0.750	0.000	0.000	0.000	0.000
5	East River at Almont, CO	0.250	0.333	0.400	0.167	0.167
6	Gunnison River inflow to Blue Mesa Reservoir	0.500	0.250	0.333	0.400	0.200
7	Colorado River near Cameo, CO	0.500	0.600	0.286	0.429	0.286
8	Uncompahgre River at Colona, CO	0.400	0.000	0.200	0.286	0.143
9	Colorado River near Cisco, UT	0.500	0.444	0.500	0.250	0.250
10	Blue River inflow to Dillon Reservoir, CO	0.500	0.750	0.571	0.333	0.250
11	Dolores River at Dolores, CO	0.000	0.167	0.200	0.250	0.333
12	Gunnison River near Grand Junction, CO	0.000	0.167	0.333	0.286	0.250
13	Blue River inflow to Green Mountain Reservoir, CO	0.667	0.750	0.667	0.500	0.429
14	Roaring Fork at Glenwood Springs, CO	0.333	0.286	0.375	0.333	0.333
15	Ashley Creek near Vernal, UT	0.600	0.500	0.500	0.500	0.417
16	San Juan River near Bluff, UT	0.286	0.143	0.143	0.300	0.111
17	New Fork River near Big Piney, WY	0.333	0.333	1.000	0.400	0.333
18	Animas River at Durango, CO	0.000	0.000	0.000	0.000	0.000
19	Lake Powell at Glen Canyon Dam, AZ	0.000	0.000	0.000	0.000	0.000
20	Green River at Green River, UT	1.000	1.000	0.500	0.250	0.111
21	Yampa River near Maybell, CO	1.000	0.500	1.000	0.286	0.000
22	Piedra River near Arboles, CO	0.167	0.167	0.000	0.333	0.143
23	Rock Creek near Mtn	0.000	0.167	0.444	0.200	0.250

	Home, UT					
24	Strawberry River near Duchesne, UT	0.667	0.750	0.667	0.571	0.429
25	Yampa River at Steamboat Springs, CO	0.714	0.429	0.400	0.333	0.222
26	Duchesne River near Tabiona, UT	0.333	0.300	0.333	0.333	0.364
27	White River near Meeker, CO	0.500	0.333	0.500	0.500	0.333
28	Whiterocks River near Whiterocks, UT	0.143	0.455	0.700	0.200	0.273

Table 26: False alarm rate for mid flow years

Site No.	Location	Jan	Feb	Mar	Apr	May
1	Virgin River at Virgin, UT	0.550	0.830	0.710	0.430	0.000
2	Colorado River below Lake Granby, CO	0.571	0.444	0.500	0.667	0.250
3	Eagle River below Gypsum, CO	0.727	0.545	0.500	0.625	0.143
4	Green River at Warren Bridge, near Daniel, WY	0.615	0.500	0.429	0.417	0.400
5	East River at Almont, CO	0.571	0.556	0.545	0.222	0.125
6	Gunnison River inflow to Blue Mesa Reservoir	0.571	0.500	0.500	0.333	0.375
7	Colorado River near Cameo, CO	0.583	0.636	0.375	0.625	0.167
8	Uncompahgre River at Colona, CO	0.556	0.417	0.455	0.444	0.250
9	Colorado River near Cisco, UT	0.500	0.500	0.522	0.400	0.294
10	Blue River inflow to Dillon Reservoir, CO	0.667	0.700	0.700	0.444	0.444
11	Dolores River at Dolores, CO	0.625	0.571	0.444	0.167	0.333
12	Gunnison River near Grand Junction, CO	0.533	0.400	0.500	0.375	0.000
13	Blue River inflow to Green Mountain Reservoir, CO	0.714	0.571	0.643	0.600	0.667
14	Roaring Fork at Glenwood Springs, CO	0.571	0.500	0.444	0.375	0.167
15	Ashley Creek near Vernal, UT	0.632	0.563	0.636	0.636	0.000
16	San Juan River near Bluff, UT	0.524	0.500	0.500	0.400	0.313
17	New Fork River near Big Piney, WY	0.611	0.588	0.632	0.600	0.500
18	Animas River at Durango, CO	0.538	0.520	0.429	0.316	0.278
19	Lake Powell at Glen Canyon Dam, AZ	0.538	0.520	0.429	0.316	0.278
20	Green River at Green River, UT	0.593	0.667	0.565	0.500	0.412
21	Yampa River near Maybell, CO	0.667	0.625	0.647	0.500	0.385
22	Piedra River near Arboles, CO	0.444	0.375	0.222	0.286	0.222
23	Rock Creek near Mtn	0.476	0.476	0.556	0.400	0.364

	Home, UT					
24	Strawberry River near Duchesne, UT	0.571	0.630	0.607	0.625	0.400
25	Yampa River at Steamboat Springs, CO	0.750	0.500	0.500	0.333	0.143
26	Duchesne River near Tabiona, UT	0.471	0.462	0.588	0.538	0.444
27	White River near Meeker, CO	0.667	0.583	0.615	0.667	0.375
28	Whiterocks River near Whiterocks, UT	0.560	0.611	0.692	0.611	0.364

Table 27: False alarm rate for high flow years

Site No.	Location	Jan	Feb	Mar	Apr	May
1	Virgin River at Virgin, UT	0.500	0.440	0.400	0.170	0.000
2	Colorado River below Lake Granby, CO	0.250	0.250	0.000	0.000	0.000
3	Eagle River below Gypsum, CO	0.667	0.167	0.167	0.400	0.143
4	Green River at Warren Bridge, near Daniel, WY	0.000	0.000	0.000	0.000	0.250
5	East River at Almont, CO	0.333	0.286	0.167	0.000	0.000
6	Gunnison River inflow to Blue Mesa Reservoir	0.000	0.200	0.167	0.000	0.167
7	Colorado River near Cameo, CO	0.333	0.167	0.143	0.333	0.143
8	Uncompahgre River at Colona, CO	0.429	0.200	0.167	0.200	0.200
9	Colorado River near Cisco, UT	0.000	0.000	0.000	0.000	0.000
10	Blue River inflow to Dillon Reservoir, CO	1.000	0.250	0.400	0.333	0.333
11	Dolores River at Dolores, CO	0.667	0.556	0.500	0.429	0.400
12	Gunnison River near Grand Junction, CO	0.200	0.167	0.143	0.167	0.250
13	Blue River inflow to Green Mountain Reservoir, CO	1.000	0.250	0.200	0.333	0.429
14	Roaring Fork at Glenwood Springs, CO	0.250	0.200	0.000	0.000	0.000
15	Ashley Creek near Vernal, UT	0.333	0.273	0.467	0.385	0.125
16	San Juan River near Bluff, UT	0.250	0.200	0.200	0.125	0.125
17	New Fork River near Big Piney, WY	0.000	0.000	0.000	0.000	0.000
18	Animas River at Durango, CO	0.167	0.143	0.200	0.111	0.100
19	Lake Powell at Glen Canyon Dam, AZ	0.167	0.143	0.200	0.111	0.100
20	Green River at Green River, UT	0.200	0.429	0.286	0.375	0.375
21	Yampa River near Maybell, CO	0.333	0.250	0.250	0.200	0.000
22	Piedra River near Arboles, CO	0.429	0.375	0.250	0.000	0.000

23	Rock Creek near Mtn Home, UT	0.125	0.167	0.286	0.333	0.200
24	Strawberry River near Duchesne, UT	0.000	0.000	0.000	0.000	0.143
25	Yampa River at Steamboat Springs, CO	0.000	0.000	0.000	0.143	0.000
26	Duchesne River near Tabiona, UT	0.000	0.250	0.200	0.167	0.000
27	White River near Meeker, CO	0.333	0.250	0.000	0.000	0.000
28	Whiterocks River near Whiterocks, UT	0.364	0.467	0.381	0.429	0.273

Table 28: Bias for low flow years

Site No.	Location	Jan	Feb	Mar	Apr	May
1	Virgin River at Virgin, UT	0.170	0.670	0.500	0.830	1.200
2	Colorado River below Lake Granby, CO	1.571	1.429	1.857	1.857	1.857
3	Eagle River below Gypsum, CO	1.000	0.714	0.857	1.143	1.000
4	Green River at Warren Bridge, near Daniel, WY	0.667	0.333	0.667	0.833	0.833
5	East River at Almont, CO	0.571	0.857	0.714	0.857	1.000
6	Gunnison River inflow to Blue Mesa Reservoir	0.667	0.571	0.429	0.833	0.833
7	Colorado River near Cameo, CO	0.857	0.714	1.000	1.000	1.167
8	Uncompahgre River at Colona, CO	0.714	0.714	0.714	1.000	1.167
9	Colorado River near Cisco, UT	1.000	0.900	0.800	1.200	1.200
10	Blue River inflow to Dillon Reservoir, CO	1.143	1.143	1.000	1.286	1.333
11	Dolores River at Dolores, CO	0.571	0.857	0.714	1.143	1.500
12	Gunnison River near Grand Junction, CO	0.143	0.857	0.429	1.000	1.333
13	Blue River inflow to Green Mountain Reservoir, CO	0.857	0.571	0.429	1.143	1.167
14	Roaring Fork at Glenwood Springs, CO	0.429	1.000	1.143	1.286	1.500
15	Ashley Creek near Vernal, UT	0.500	0.600	0.800	1.000	1.714
16	San Juan River near Bluff, UT	0.700	0.700	0.700	1.000	0.900
17	New Fork River near Big Piney, WY	0.429	0.429	0.143	0.714	0.857
18	Animas River at Durango, CO	0.100	0.100	0.300	0.600	0.600
19	Lake Powell at Glen Canyon Dam, AZ	0.100	0.100	0.300	0.600	0.600
20	Green River at Green River, UT	0.100	0.200	0.400	0.800	0.900
21	Yampa River near Maybell, CO	0.143	0.286	0.143	1.000	0.714
22	Piedra River near Arboles, CO	0.857	0.857	0.714	1.286	1.000
23	Rock Creek near Mtn	0.300	0.600	0.900	1.000	1.143

	Home, UT					
24	Strawberry River near Duchesne, UT	0.300	0.400	0.300	0.700	1.000
25	Yampa River at Steamboat Springs, CO	1.000	1.000	0.714	1.286	1.286
26	Duchesne River near Tabiona, UT	0.750	1.250	0.667	1.000	1.571
27	White River near Meeker, CO	0.571	0.857	0.857	1.429	1.286
28	Whiterocks River near Whiterocks, UT	0.500	0.846	0.769	0.714	1.000

Table 29: Bias for mid flow years

Site No.	Location	Jan	Feb	Mar	Apr	May
1	Virgin River at Virgin, UT	1.380	0.860	0.880	1.170	0.860
2	Colorado River below Lake Granby, CO	0.875	1.000	0.667	0.750	0.500
3	Eagle River below Gypsum, CO	1.375	1.375	1.250	1.000	0.875
4	Green River at Warren Bridge, near Daniel, WY	1.857	2.000	1.750	1.714	1.429
5	East River at Almont, CO	1.750	1.125	1.375	1.125	1.000
6	Gunnison River inflow to Blue Mesa Reservoir	1.750	1.500	1.500	1.125	1.143
7	Colorado River near Cameo, CO	1.500	1.375	1.000	1.000	0.750
8	Uncompahgre River at Colona, CO	1.125	1.500	1.375	1.125	1.000
9	Colorado River near Cisco, UT	1.538	1.538	1.643	1.429	1.214
10	Blue River inflow to Dillon Reservoir, CO	1.500	1.250	1.250	1.125	1.125
11	Dolores River at Dolores, CO	1.000	0.875	1.125	0.750	0.750
12	Gunnison River near Grand Junction, CO	1.875	1.250	1.500	1.000	0.500
13	Blue River inflow to Green Mountain Reservoir, CO	1.750	1.750	1.750	1.250	0.750
14	Roaring Fork at Glenwood Springs, CO	1.750	1.250	1.125	1.000	0.750
15	Ashley Creek near Vernal, UT	1.462	1.231	0.786	0.786	0.400
16	San Juan River near Bluff, UT	1.750	1.667	1.667	1.154	1.231
17	New Fork River near Big Piney, WY	2.250	2.125	2.375	1.875	1.500
18	Animas River at Durango, CO	2.000	1.923	1.500	1.357	1.286
19	Lake Powell at Glen Canyon Dam, AZ	2.000	1.923	1.500	1.357	1.286
20	Green River at Green River, UT	2.077	1.846	1.643	1.286	1.214
21	Yampa River near Maybell, CO	2.250	2.000	2.125	1.250	1.625
22	Piedra River near Arboles, CO	1.125	1.000	1.125	0.875	1.125
23	Rock Creek near Mtn	1.750	1.615	1.286	1.071	1.100

	Home, UT					
24	Strawberry River near Duchesne, UT	2.154	2.077	2.154	1.846	1.000
25	Yampa River at Steamboat Springs, CO	1.500	1.250	1.500	0.750	0.875
26	Duchesne River near Tabiona, UT	1.545	1.182	1.700	1.300	1.000
27	White River near Meeker, CO	1.875	1.500	1.625	1.125	1.000
28	Whiterocks River near Whiterocks, UT	1.563	1.000	0.722	1.200	0.846

Table 30: Bias for high flow years

Site No.	Location	Jan	Feb	Mar	Apr	May
1	Virgin River at Virgin, UT	1.330	1.500	1.670	1.000	1.000
2	Colorado River below Lake Granby, CO	0.571	0.571	0.571	0.429	0.667
3	Eagle River below Gypsum, CO	0.500	0.857	0.857	0.833	1.167
4	Green River at Warren Bridge, near Daniel, WY	0.333	0.333	0.333	0.333	0.667
5	East River at Almont, CO	0.500	1.000	0.857	1.000	1.000
6	Gunnison River inflow to Blue Mesa Reservoir	0.333	0.833	1.000	1.000	1.000
7	Colorado River near Cameo, CO	0.500	0.857	1.000	1.000	1.167
8	Uncompahgre River at Colona, CO	1.167	0.714	0.857	0.833	0.833
9	Colorado River near Cisco, UT	0.300	0.400	0.300	0.200	0.500
10	Blue River inflow to Dillon Reservoir, CO	0.167	0.571	0.714	0.500	0.500
11	Dolores River at Dolores, CO	1.500	1.286	1.143	1.167	0.833
12	Gunnison River near Grand Junction, CO	0.833	0.857	1.000	1.000	1.333
13	Blue River inflow to Green Mountain Reservoir, CO	0.167	0.571	0.714	0.500	1.167
14	Roaring Fork at Glenwood Springs, CO	0.667	0.714	0.714	0.667	0.833
15	Ashley Creek near Vernal, UT	0.900	1.100	1.500	1.300	1.143
16	San Juan River near Bluff, UT	0.400	0.500	0.500	0.800	0.800
17	New Fork River near Big Piney, WY	0.143	0.286	0.286	0.286	0.571
18	Animas River at Durango, CO	0.600	0.700	1.000	0.900	1.000
19	Lake Powell at Glen Canyon Dam, AZ	0.600	0.700	1.000	0.900	1.000
20	Green River at Green River, UT	0.500	0.700	0.700	0.800	0.800
21	Yampa River near Maybell, CO	0.429	0.571	0.571	0.714	0.571
22	Piedra River near Arboles, CO	1.000	1.143	1.143	0.857	0.857

23	Rock Creek near Mtn Home, UT	0.800	0.600	0.700	0.900	0.714
24	Strawberry River near Duchesne, UT	0.200	0.200	0.200	0.200	1.000
25	Yampa River at Steamboat Springs, CO	0.429	0.714	0.714	1.000	0.857
26	Duchesne River near Tabiona, UT	0.500	0.500	0.556	0.667	0.429
27	White River near Meeker, CO	0.429	0.571	0.429	0.429	0.714
28	Whiterocks River near Whiterocks, UT	0.846	1.154	1.615	1.077	1.222

Table 31: Threat score for low flow years

Site No.	Location	Jan	Feb	Mar	Apr	May
1	Virgin River at Virgin, UT	0.000	0.110	0.130	0.570	0.830
2	Colorado River below Lake Granby, CO	0.286	0.308	0.333	0.429	0.538
3	Eagle River below Gypsum, CO	0.273	0.200	0.444	0.500	0.714
4	Green River at Warren Bridge, near Daniel, WY	0.111	0.333	0.667	0.833	0.833
5	East River at Almont, CO	0.375	0.444	0.333	0.625	0.714
6	Gunnison River inflow to Blue Mesa Reservoir	0.250	0.375	0.250	0.375	0.571
7	Colorado River near Cameo, CO	0.300	0.200	0.556	0.400	0.625
8	Uncompahgre River at Colona, CO	0.333	0.714	0.500	0.556	0.857
9	Colorado River near Cisco, UT	0.333	0.357	0.286	0.692	0.692
10	Blue River inflow to Dillon Reservoir, CO	0.364	0.154	0.273	0.600	0.750
11	Dolores River at Dolores, CO	0.571	0.625	0.500	0.667	0.667
12	Gunnison River near Grand Junction, CO	0.143	0.625	0.250	0.556	0.750
13	Blue River inflow to Green Mountain Reservoir, CO	0.182	0.100	0.111	0.364	0.444
14	Roaring Fork at Glenwood Springs, CO	0.250	0.556	0.500	0.600	0.667
15	Ashley Creek near Vernal, UT	0.154	0.231	0.286	0.333	0.583
16	San Juan River near Bluff, UT	0.417	0.545	0.545	0.538	0.727
17	New Fork River near Big Piney, WY	0.250	0.250	0.000	0.333	0.444
18	Animas River at Durango, CO	0.100	0.100	0.300	0.600	0.600
19	Lake Powell at Glen Canyon Dam, AZ	0.100	0.100	0.300	0.600	0.600
20	Green River at Green River, UT	0.000	0.000	0.167	0.500	0.727
21	Yampa River near Maybell, CO	0.000	0.125	0.000	0.556	0.714
22	Piedra River near Arboles, CO	0.625	0.625	0.714	0.600	0.750
23	Rock Creek near Mtn	0.300	0.455	0.357	0.667	0.667

	Home, UT					
24	Strawberry River near Duchesne, UT	0.083	0.077	0.083	0.214	0.400
25	Yampa River at Steamboat Springs, CO	0.167	0.400	0.333	0.600	0.778
26	Duchesne River near Tabiona, UT	0.400	0.636	0.364	0.500	0.636
27	White River near Meeker, CO	0.222	0.444	0.300	0.417	0.600
28	Whiterocks River near Whiterocks, UT	0.400	0.333	0.150	0.500	0.571

Table 32: Threat score for mid flow years

Site No.	Location	Jan	Feb	Mar	Apr	May
1	Virgin River at Virgin, UT	0.360	0.080	0.150	0.440	0.860
2	Colorado River below Lake Granby, CO	0.250	0.385	0.250	0.167	0.333
3	Eagle River below Gypsum, CO	0.188	0.357	0.385	0.231	0.667
4	Green River at Warren Bridge, near Daniel, WY	0.333	0.500	0.571	0.583	0.545
5	East River at Almont, CO	0.375	0.308	0.357	0.700	0.778
6	Gunnison River inflow to Blue Mesa Reservoir	0.375	0.429	0.429	0.545	0.500
7	Colorado River near Cameo, CO	0.333	0.267	0.455	0.231	0.556
8	Uncompahgre River at Colona, CO	0.308	0.538	0.462	0.417	0.600
9	Colorado River near Cisco, UT	0.435	0.435	0.423	0.545	0.632
10	Blue River inflow to Dillon Reservoir, CO	0.250	0.200	0.200	0.417	0.417
11	Dolores River at Dolores, CO	0.231	0.250	0.417	0.556	0.400
12	Gunnison River near Grand Junction, CO	0.438	0.500	0.429	0.455	0.500
13	Blue River inflow to Green Mountain Reservoir, CO	0.222	0.375	0.294	0.286	0.167
14	Roaring Fork at Glenwood Springs, CO	0.375	0.385	0.417	0.455	0.556
15	Ashley Creek near Vernal, UT	0.280	0.318	0.190	0.190	0.400
16	San Juan River near Bluff, UT	0.435	0.455	0.455	0.474	0.611
17	New Fork River near Big Piney, WY	0.368	0.389	0.350	0.353	0.429
18	Animas River at Durango, CO	0.444	0.462	0.522	0.650	0.684
19	Lake Powell at Glen Canyon Dam, AZ	0.444	0.462	0.522	0.650	0.684
20	Green River at Green River, UT	0.379	0.276	0.370	0.391	0.476
21	Yampa River near Maybell, CO	0.300	0.333	0.316	0.385	0.615
22	Piedra River near Arboles, CO	0.417	0.455	0.700	0.500	0.700
23	Rock Creek near Mtn	0.500	0.478	0.333	0.450	0.500

	Home, UT					
24	Strawberry River near Duchesne, UT	0.414	0.333	0.367	0.321	0.429
25	Yampa River at Steamboat Springs, CO	0.176	0.385	0.429	0.400	0.667
26	Duchesne River near Tabiona, UT	0.474	0.412	0.350	0.353	0.385
27	White River near Meeker, CO	0.278	0.333	0.313	0.214	0.455
28	Whiterocks River near Whiterocks, UT	0.367	0.241	0.148	0.269	0.412

Table 33: Threat score for high flow years

Site No.	Location	Jan	Feb	Mar	Apr	May
1	Virgin River at Virgin, UT	0.400	0.500	0.600	0.710	1.000
2	Colorado River below Lake Granby, CO	0.375	0.375	0.571	0.429	0.667
3	Eagle River below Gypsum, CO	0.125	0.625	0.625	0.375	0.857
4	Green River at Warren Bridge, near Daniel, WY	0.333	0.333	0.333	0.333	0.429
5	East River at Almont, CO	0.286	0.556	0.625	1.000	1.000
6	Gunnison River inflow to Blue Mesa Reservoir	0.333	0.571	0.714	1.000	0.714
7	Colorado River near Cameo, CO	0.286	0.625	0.750	0.500	0.857
8	Uncompahgre River at Colona, CO	0.444	0.500	0.625	0.571	0.571
9	Colorado River near Cisco, UT	0.300	0.400	0.300	0.200	0.500
10	Blue River inflow to Dillon Reservoir, CO	0.000	0.375	0.333	0.286	0.286
11	Dolores River at Dolores, CO	0.250	0.333	0.364	0.444	0.375
12	Gunnison River near Grand Junction, CO	0.571	0.625	0.750	0.714	0.750
13	Blue River inflow to Green Mountain Reservoir, CO	0.000	0.375	0.500	0.286	0.444
14	Roaring Fork at Glenwood Springs, CO	0.429	0.500	0.714	0.667	0.833
15	Ashley Creek near Vernal, UT	0.462	0.615	0.471	0.533	0.875
16	San Juan River near Bluff, UT	0.273	0.364	0.364	0.636	0.636
17	New Fork River near Big Piney, WY	0.143	0.286	0.286	0.286	0.571
18	Animas River at Durango, CO	0.455	0.545	0.667	0.727	0.818
19	Lake Powell at Glen Canyon Dam, AZ	0.455	0.545	0.667	0.727	0.818
20	Green River at Green River, UT	0.364	0.308	0.417	0.385	0.385
21	Yampa River near Maybell, CO	0.250	0.375	0.375	0.500	0.571
22	Piedra River near Arboles, CO	0.400	0.500	0.667	0.857	0.857
23	Rock Creek near Mtn	0.636	0.455	0.417	0.462	0.500

	Home, UT					
24	Strawberry River near Duchesne, UT	0.200	0.200	0.200	0.200	0.750
25	Yampa River at Steamboat Springs, CO	0.429	0.714	0.714	0.750	0.857
26	Duchesne River near Tabiona, UT	0.500	0.333	0.400	0.500	0.429
27	White River near Meeker, CO	0.250	0.375	0.429	0.429	0.714
28	Whiterocks River near Whiterocks, UT	0.412	0.400	0.619	0.421	0.667

Table 34: Hit rate for low flow years

Site No.	Location	Jan	Feb	Mar	Apr	May
1	Virgin River at Virgin, UT	0.650	0.580	0.650	0.830	0.940
2	Colorado River below Lake Granby, CO	0.545	0.609	0.565	0.636	0.714
3	Eagle River below Gypsum, CO	0.619	0.636	0.773	0.762	0.900
4	Green River at Warren Bridge, near Daniel, WY	0.579	0.800	0.900	0.947	0.947
5	East River at Almont, CO	0.762	0.773	0.727	0.857	0.900
6	Gunnison River inflow to Blue Mesa Reservoir	0.700	0.762	0.714	0.750	0.842
7	Colorado River near Cameo, CO	0.667	0.636	0.818	0.714	0.850
8	Uncompahgre River at Colona, CO	0.714	0.909	0.818	0.810	0.950
9	Colorado River near Cisco, UT	0.697	0.727	0.706	0.882	0.882
10	Blue River inflow to Dillon Reservoir, CO	0.667	0.500	0.636	0.810	0.900
11	Dolores River at Dolores, CO	0.857	0.864	0.818	0.857	0.850
12	Gunnison River near Grand Junction, CO	0.714	0.864	0.727	0.810	0.900
13	Blue River inflow to Green Mountain Reservoir, CO	0.571	0.591	0.636	0.667	0.750
14	Roaring Fork at Glenwood Springs, CO	0.714	0.818	0.773	0.810	0.850
15	Ashley Creek near Vernal, UT	0.667	0.697	0.706	0.706	0.792
16	San Juan River near Bluff, UT	0.781	0.844	0.844	0.818	0.909
17	New Fork River near Big Piney, WY	0.727	0.727	0.636	0.727	0.773
18	Animas River at Durango, CO	0.727	0.727	0.794	0.882	0.882
19	Lake Powell at Glen Canyon Dam, AZ	0.727	0.727	0.794	0.882	0.882
20	Green River at Green River, UT	0.667	0.636	0.706	0.824	0.912
21	Yampa River near Maybell, CO	0.636	0.682	0.636	0.818	0.909
22	Piedra River near Arboles, CO	0.864	0.864	0.909	0.818	0.909
23	Rock Creek near Mtn	0.781	0.818	0.735	0.882	0.875

	Home, UT					
24	Strawberry River near Duchesne, UT	0.667	0.636	0.667	0.667	0.750
25	Yampa River at Steamboat Springs, CO	0.545	0.727	0.727	0.818	0.909
26	Duchesne River near Tabiona, UT	0.778	0.852	0.750	0.786	0.826
27	White River near Meeker, CO	0.682	0.773	0.682	0.682	0.818
28	Whiterocks River near Whiterocks, UT	0.791	0.727	0.614	0.810	0.818

Table 35: Hit rate for mid flow years

Site No.	Location	Jan	Feb	Mar	Apr	May
1	Virgin River at Virgin, UT	0.550	0.420	0.450	0.720	0.940
2	Colorado River below Lake Granby, CO	0.591	0.652	0.609	0.545	0.714
3	Eagle River below Gypsum, CO	0.381	0.591	0.636	0.524	0.850
4	Green River at Warren Bridge, near Daniel, WY	0.474	0.600	0.700	0.737	0.737
5	East River at Almont, CO	0.524	0.591	0.591	0.857	0.900
6	Gunnison River inflow to Blue Mesa Reservoir	0.500	0.619	0.619	0.750	0.737
7	Colorado River near Cameo, CO	0.524	0.500	0.727	0.524	0.800
8	Uncompahgre River at Colona, CO	0.571	0.727	0.682	0.667	0.800
9	Colorado River near Cisco, UT	0.606	0.606	0.559	0.706	0.794
10	Blue River inflow to Dillon Reservoir, CO	0.429	0.455	0.455	0.667	0.650
11	Dolores River at Dolores, CO	0.524	0.591	0.682	0.810	0.700
12	Gunnison River near Grand Junction, CO	0.571	0.727	0.636	0.714	0.800
13	Blue River inflow to Green Mountain Reservoir, CO	0.333	0.545	0.455	0.524	0.500
14	Roaring Fork at Glenwood Springs, CO	0.524	0.636	0.682	0.714	0.800
15	Ashley Creek near Vernal, UT	0.455	0.545	0.500	0.500	0.750
16	San Juan River near Bluff, UT	0.594	0.625	0.625	0.697	0.788
17	New Fork River near Big Piney, WY	0.455	0.500	0.409	0.500	0.636
18	Animas River at Durango, CO	0.545	0.576	0.676	0.794	0.824
19	Lake Powell at Glen Canyon Dam, AZ	0.545	0.576	0.676	0.794	0.824
20	Green River at Green River, UT	0.455	0.364	0.500	0.588	0.676
21	Yampa River near Maybell, CO	0.364	0.455	0.409	0.636	0.773
22	Piedra River near Arboles, CO	0.682	0.727	0.864	0.773	0.864
23	Rock Creek near Mtn	0.656	0.636	0.529	0.676	0.708

	Home, UT					
24	Strawberry River near Duchesne, UT	0.485	0.394	0.424	0.424	0.667
25	Yampa River at Steamboat Springs, CO	0.364	0.636	0.636	0.727	0.864
26	Duchesne River near Tabiona, UT	0.630	0.630	0.536	0.607	0.652
27	White River near Meeker, CO	0.409	0.545	0.500	0.500	0.727
28	Whiterocks River near Whiterocks, UT	0.558	0.500	0.477	0.548	0.697

Table 36: Hit rate for high flow years

Site No.	Location	Jan	Feb	Mar	Apr	May
1	Virgin River at Virgin, UT	0.700	0.740	0.800	0.890	1.000
2	Colorado River below Lake Granby, CO	0.773	0.783	0.870	0.818	0.905
3	Eagle River below Gypsum, CO	0.667	0.864	0.864	0.762	0.950
4	Green River at Warren Bridge, near Daniel, WY	0.789	0.800	0.800	0.789	0.789
5	East River at Almont, CO	0.762	0.818	0.864	1.000	1.000
6	Gunnison River inflow to Blue Mesa Reservoir	0.800	0.857	0.905	1.000	0.895
7	Colorado River near Cameo, CO	0.762	0.864	0.909	0.810	0.950
8	Uncompahgre River at Colona, CO	0.762	0.818	0.864	0.857	0.850
9	Colorado River near Cisco, UT	0.788	0.818	0.794	0.765	0.853
10	Blue River inflow to Dillon Reservoir, CO	0.667	0.773	0.727	0.762	0.750
11	Dolores River at Dolores, CO	0.571	0.636	0.682	0.762	0.750
12	Gunnison River near Grand Junction, CO	0.857	0.864	0.909	0.905	0.900
13	Blue River inflow to Green Mountain Reservoir, CO	0.667	0.773	0.818	0.762	0.750
14	Roaring Fork at Glenwood Springs, CO	0.810	0.818	0.909	0.905	0.950
15	Ashley Creek near Vernal, UT	0.788	0.848	0.735	0.794	0.958
16	San Juan River near Bluff, UT	0.750	0.781	0.781	0.879	0.879
17	New Fork River near Big Piney, WY	0.727	0.773	0.773	0.773	0.864
18	Animas River at Durango, CO	0.818	0.848	0.882	0.912	0.941
19	Lake Powell at Glen Canyon Dam, AZ	0.818	0.848	0.882	0.912	0.941
20	Green River at Green River, UT	0.788	0.727	0.794	0.765	0.765
21	Yampa River near Maybell, CO	0.727	0.773	0.773	0.818	0.864
22	Piedra River near Arboles, CO	0.727	0.773	0.864	0.955	0.955
23	Rock Creek near Mtn	0.875	0.818	0.794	0.794	0.833

	Home, UT					
24	Strawberry River near Duchesne, UT	0.758	0.758	0.758	0.758	0.917
25	Yampa River at Steamboat Springs, CO	0.818	0.909	0.909	0.909	0.955
26	Duchesne River near Tabiona, UT	0.852	0.778	0.786	0.821	0.826
27	White River near Meeker, CO	0.727	0.773	0.818	0.818	0.909
28	Whiterocks River near Whiterocks, UT	0.767	0.727	0.818	0.738	0.879