DEPARTMENT OF WATER RESOURCES

Estimating Historical California Precipitation Phase Trends Using Gridded Precipitation, Precipitation Phase, and Elevation Data

Memorandum Report

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7/7/2014

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Abstract

Climate change projections for California indicate reduction in the percentage of precipitation that falls as snow, and increase in the percentage that falls as rain, due to warmer temperatures in the future. Previous work has shown overall decreases in rainfall / snowfall ratios for the western US over the last 60 years. Of interest in this study is the quantification of snow/rain ratios for smaller regions, specifically in California. Estimating cumulative precipitation phase ratios for specific regions is difficult due to large differences in local precipitation. In California, the high relief of the surface topography makes such estimates particularly difficult. The low spatial resolution of suitable precipitation/snow water equivalent monitoring stations contributes to the difficulty in quantifying the trends for sub-state sized regions of interest in this study.

The present exploratory study develops and describes a methodology that uses readily available research data sets to produce gridded estimates of historical rainfall as a fraction of total precipitation for areas comprising the major water-supply watersheds of California.

Using this methodology, statistically significant increases in the ratio of annual liquid to total precipitation are seen for large areas in the northern part of the State and northern Sierra over the water year. No significant annual trends are seen for regions in the central and southern portions of the Sierra. Future work extending the analysis to distinct elevation ranges and seasonality would provide more refined conclusions.

1. Introduction

Climate change impacts on California water resources are the subject of much interest and research. One potential impact of climate change on water resources in California is a general shift towards less snow and more rain as temperatures increase, especially near the mean snow level. Previous work, summarized below, indicates this process is already underway across the West. The work presented here aims to verify that hypothesis at a regional scale.

Nomenclature

There are several interrelated types of measurements under discussion, and it is important to distinguish among them. The myriad issues of measurement of snow are thoroughly discussed by Doesken and Judson (The Snow Booklet, 1997).

Precipitation

The melted content of all water that falls from the sky in liquid or solid form. Typically measured in hundredths of an inch. Note that frozen precipitation includes hail, graupel, snow, and pellets.

Snowfall

The accumulated depth of newly fallen snow since the previous measurement. The measurement interval must be at least six hours, and is usually no more than 24 hours. When 24 hours is impractical, accumulated snowfall can be measured over multiple days. Typically measured in tenths of an inch.

Snow depth
The distance from the top of the snow to the surface. Typically measured in whole inches.

Snow water equivalent (SWE)
The liquid depth of a vertical core of the snow on the ground after melting. Also called liquid water content (LWC). Typically reported in tenths of an inch.

Snowpack
Generally refers to the water content of snow on the ground.

Snow
As used in this report, a generic term that can refer to any of the above depending on context.

Water Year
A water year, as used in this report, refers to a year ending September 31. The year is assigned to the calendar year of the ending month. , e.g. Water Year 2011 starts October 1, 2010, and ends September 30, 2011.

Previous Work
The impact of climate change on California's snow has been the subject of a variety of avenues of research, including studies on runoff, snowfall, snowpack, and rain-snow ratios.

Freeman (2012) has documented a shift from April-July runoff flows in the Sierra Nevada and Southern Cascades to earlier occurrence in the year. He noted increases in March runoff throughout these areas, and attributed them to a combination of earlier snowmelt and an increase in proportion of March precipitation that now occurs as rainfall, both due to warming temperatures. Kapnick and Hall (2010) studied climate-snowpack relationships in California and found an overall trend toward earlier dates of peak snow water equivalent by 0.6 days per decade from 1930 to 2008. Christy (2012) found no statistically significant trend in annual winter-centered snowfall for the western slopes of the Sierra Nevada, based primarily on NOAA station archives spanning from 1878-2011. Knowles et al (2006) found that the ratio of liquid to solid precipitation was slowly increasing at National Weather Service Cooperative Stations throughout the West. Feng and Hu (2007) conducted a similar snow/total precipitation study and found declines in snow to total precipitation ratios in the Pacific Northwest, and attributed them to both declines in total precipitation and total snowfall, with snowfall declining faster than total precipitation. Das, et al (2009) studied a variety of modeled hydrometeorological variables across the Western US, and concluded that negative trends in 1 April SWE as fraction of Oct-Mar precipitation, and seasonal runoff compared to water-year accumulated runoff are strongly related to large-scale warming.

The CA Department of Water Resources tracks a number of climate-related variables that may or may not lend themselves to climate change analysis. Observed data collected by the Department that has been used to investigate climate trends include streamflow timing in the Sacramento and San Joaquin River basins and Full Natural Flow (Roos & Sahota, 2012).

Snow course, snow water equivalents, and rainfall indices are not easily translatable into climate trend analysis because of large year-to-year variability in the data values, variability in the collection of data and changes in the landscape and vegetation that can impact the measured values. A thorough analysis of the data collected and the site conditions over the time period of data collected would need to be completed prior to using the data in any trend analysis. The large year-to-year variability in values makes trend identification difficult as well.

These studies examine different snow quantities that are not necessarily strictly comparable. It is possible and even likely that many of the apparent discrepancies between these various studies can be resolved by consideration of the difference between snowfall and snow water equivalent, and also the time of the year that the measurements (especially of SWE) are made. A variety of rather different sequences of combined temperature and precipitation histories can lead to similar snowfall and SWE values on a given date in the spring.

Present study

In the present study, precipitation phase trends in four major water supply basins of California are analyzed using PRISM precipitation gridded data and WRCC rain/snow ratio estimates based on NCAR/NCEP global reanalysis (Kalnay, et al., 1996) (Kistler, et al., 2001) temperature and precipitation data. Precipitation phase has been well studied in the western US (e.g., Knowles, Dettinger & Cayan, 2006); this study focuses on a limited spatial area in the mountainous regions of California. The temporal range for the present study is restricted by the reanalysis data to the October-September Water Years 1949-2012.

This paper analyzes California climate data beyond that collected by CA-DWR in order to isolate one variable very relevant to water resource management; the fraction of total precipitation that falls as rain. This effort has been pursued to develop a metric more directly matching colloquial language used to describe the concept of “more rain, less snow.”

This study is an attempt to obtain to use a relatively simple technique and a daily data set that is widely and readily accessible and has no missing values from 1948 to the present day (Kalnay, et al., 1996) (Kistler, et al., 2001). For a full analysis, other more standard techniques that make more direct use of surface data would be preferable, but these entail a very significant amount of data development and preparation prior to analysis, far beyond available resources.

2. Data and Methodology

Overview

This paper develops and applies a methodology for integrating established gridded datasets to estimate the percent of historical total precipitation that fell as rain and provides calculated results for areas comprising the major water supply basins of California.

The methodology combines spatially coarse atmospheric reanalysis data with finer-scale precipitation data and a digital elevation model of the land surface in order to estimate average rain and snow contributions to total precipitation for different regions of California. The underlying coarse atmospheric data is limited to the years 1948 to present. This analysis produced annual time series of total precipitation, average rain, average snow, and percent total precipitation that fell as rain, for water years 1949-2012.

Analysis Area

The present study examines trends in precipitation phase in the focus area of the California Cooperative Snow Survey (CCSS) unimpaired runoff forecasts detailed in DWR Bulletin 120 (California Department of Water Resources, 2013; hereafter, B120). B120 provides forecasts of the volume of snowmelt runoff for April through July, and is updated monthly from February through May. This time period provides the primary surface water supply for the majority of California. The four regions correspond to different reanalysis points that coincide well with those used to produce regional values of snow water equivalent used in B120 and corresponding real-time regional snow pillow summary reports.

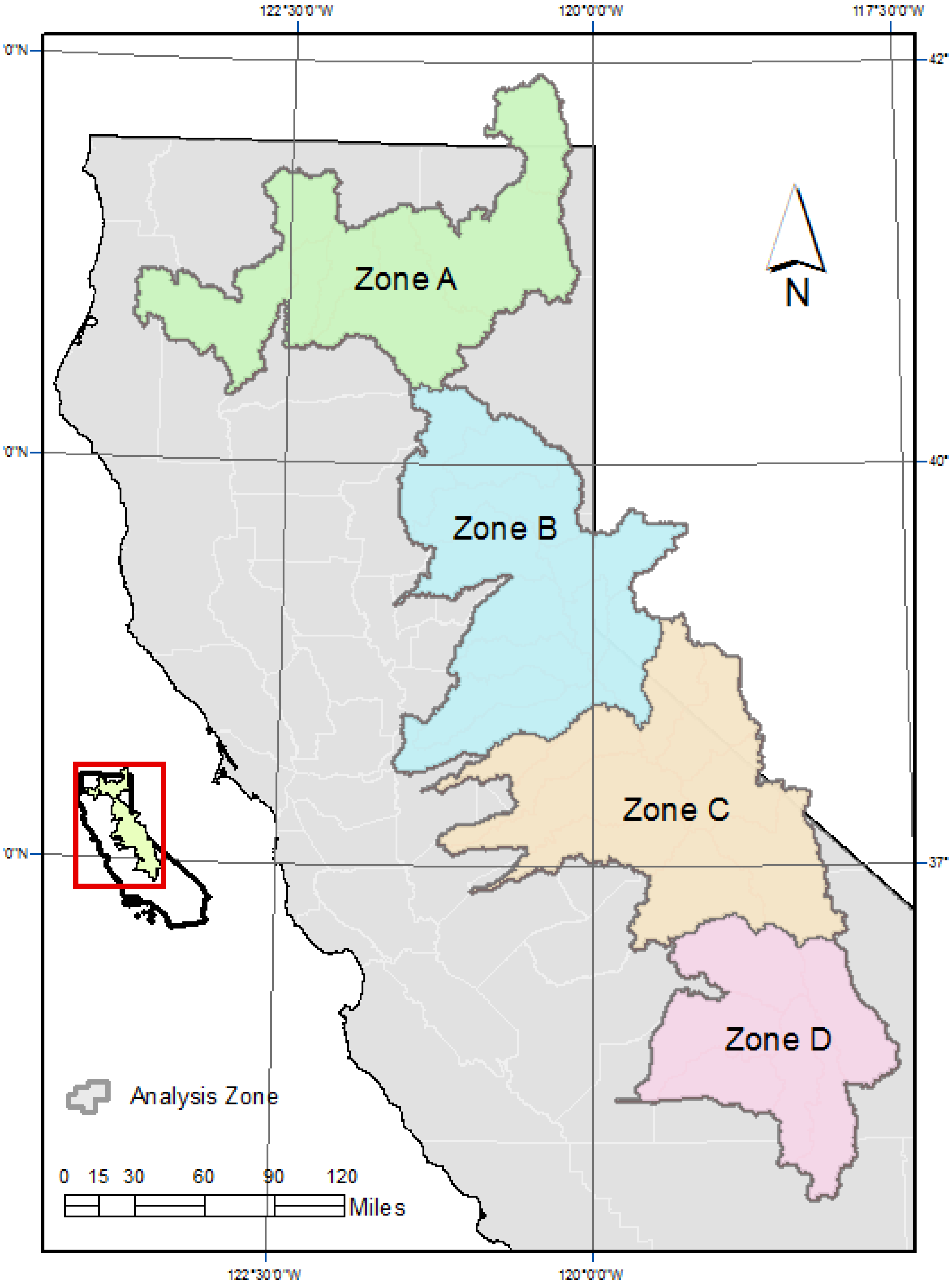

Figure 1 shows the study analysis area.

The analysis area is further broken up into latitudinal zones of width similar to the spatial resolution of the reanalysis grid. This also allows representation of latitudinal gradients in the average height of the freezing level during storm passages. Average freezing levels vary much more by latitude than by longitude in California.

It is assumed that historical freezing levels at the chosen analysis points (and percent rain, by proxy) are representative of relatively large-scale atmospheric phenomena, and therefore provide a reasonable approximation of the historical freezing level throughout each analysis zone associated with climate and its associated variability.

Zone A

Zone A, the northernmost analysis zone, is comprised of the following watersheds: Trinity, Shasta, McCloud, Sacramento Headwaters, Upper and Lower Pit, and Goose Lake.

Zone B

Zone B, in the northern Sierra Nevada, includes these watersheds: North Fork Feather, E. Branch North Fork Feather, Middle Fork Feather, North, Middle, and South Fork American, Upper Yuba, Truckee, Lake Tahoe, Upper Carson, Upper Cosumnes, and Upper Mokelumne.

Zone C

Zone C covers the majority of the high Sierra range. This zone has a significantly higher median elevation than the other zones (1901m vs. about 1500m for the other 3 zones). Watersheds in this zone: Crowley Lake, West Walker, East Walker, Mono Lake, Upper Calaveras, Upper Merced, Upper San Joaquin, Upper Stanislaus, and Upper Tuolumne.

Zone D

Zone D covers the southernmost portion of the Sierra Nevada. Watersheds include: Upper Kern, South Fork Kern, Upper Kaweah, Upper Tule, Owens and Upper King.

The zones have distinctly different elevation signatures. Figure 2 shows boxplots of elevation ranges for each zone and the total analysis area. Table 1 shows statistics on elevations for the analysis zones. Zones A and B have lower 1st quartile, median and 3rd quartile elevations than Zones C and D. Zone C, corresponding to the highest areas of the central and southern Sierra Nevada, had the highest median and 3rd quartile elevations by a large margin. Zone A has the lowest median and 3rd quartile elevations.

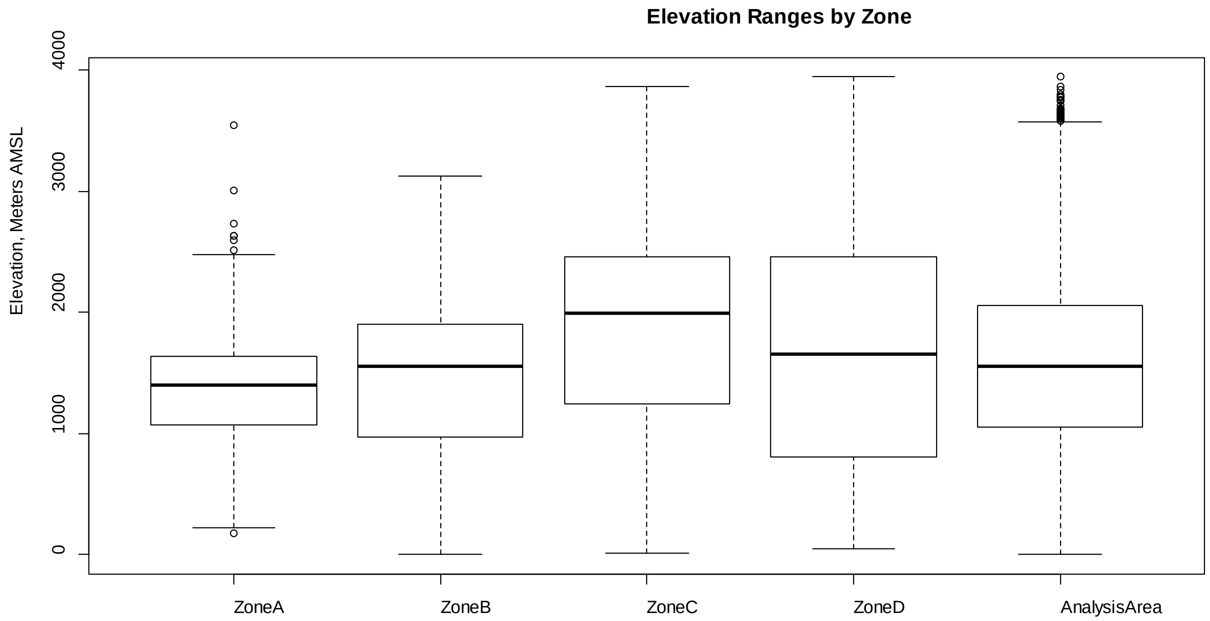

Figure 1: Boxplot of Elevation Ranges by Analysis Zone. This shows that Zones C and D are of generally higher elevation than zones A and B, with zone A being the lowest overall zone with the lowest median and 3rd quartile elevations, and zone C having the highest 1st quartile, median and 3rd quartile elevations.

Data Sources

The data for this analysis came from three sources: the Western Regional Climate Center's Freezing Level Tracker tool, the Oregon State University PRISM Climate Group precipitation data, and PRISM Climate Group Digital Elevation Model.

Coarse Precipitation Phase Data from Western Regional Climate Data Center

The Western Regional Climate Center (WRCC) North American Freezing Level Tracker (WRCC NAFLT, 2013) makes use of the NCEP/NCAR Global Reanalysis (NNGR) to compute the height of the freezing level on a daily basis. The NNGR is a global gridded 17-level upper air data set, computed on a 2.5x2.5 degree latitude/longitude for the globe every six hours from 1948 through present. Original observations are "re-analyzed" using this modern atmospheric model that is frozen in its development to avoid introduction of false variability from model evolution. This model provides smooth fields of temperature and height for fixed standard pressure levels. Precipitation at the surface, as an output of this model, is thus a calculated rather than observed quantity. Fortunately, most California precipitation in the areas of interest falls during large cyclonic mid-latitude storms, which such models represent reasonably faithfully.

Freezing level is determined as the first instance of 0°C working downward from the cold upper atmosphere, which is always far below freezing. Precipitation is taken directly as the amount calculated by the model used for reanalysis. If the temperature at some elevation of interest is below freezing, any precipitation occurring at that time is categorized as "snow." The snow level is often 100-300 meters below the freezing level, depending on precise temperature and humidity vertical structure, so that freezing level and snow level (the real level of interest) are highly correlated through time. Because it is only variations through time that are of interest, this small systematic and nearly constant bias is of negligible concern. A major motivation for the use of NNGR data is that there are no gaps in temporal or spatial coverage since 1948. Data are updated daily, with a delay of about two days. In addition, the geometry of the Sierra Nevada is fairly simple and large scale, commensurate with the gridding scale of the model.

For any point of interest, the vertical temperature profile for any given day can be determined, using bi-linear interpolation in latitude and longitude from the four closest grid points for each successive level in the atmosphere. As part of an analysis tool developed by WRCC, these values are computed daily at every grid point in North America for 200 meter increments from sea level to 4000 meters and stored for further manipulation by the application. The estimate of fractional "precipitation as snow" for a duration of interest (a month or season) is simply the weighted average of the ratio of the amount of precipitation estimated to occur as "snow" divided by the total amount of precipitation for that same duration. Temperature varies with altitude, so that this fraction also varies with altitude, increasing with height because temperature generally decreases with height.

For this study, a single point near the center of each of the four zones was chosen to represent each of the zones. Figure 3 shows the four analysis zones and the representative points used for deriving the WRCC percent snow estimate. In such manner, snow/rain ratios are computed for each of the four analysis zones, for each 200m elevation band, with medians ranging from 0 to 4000m.

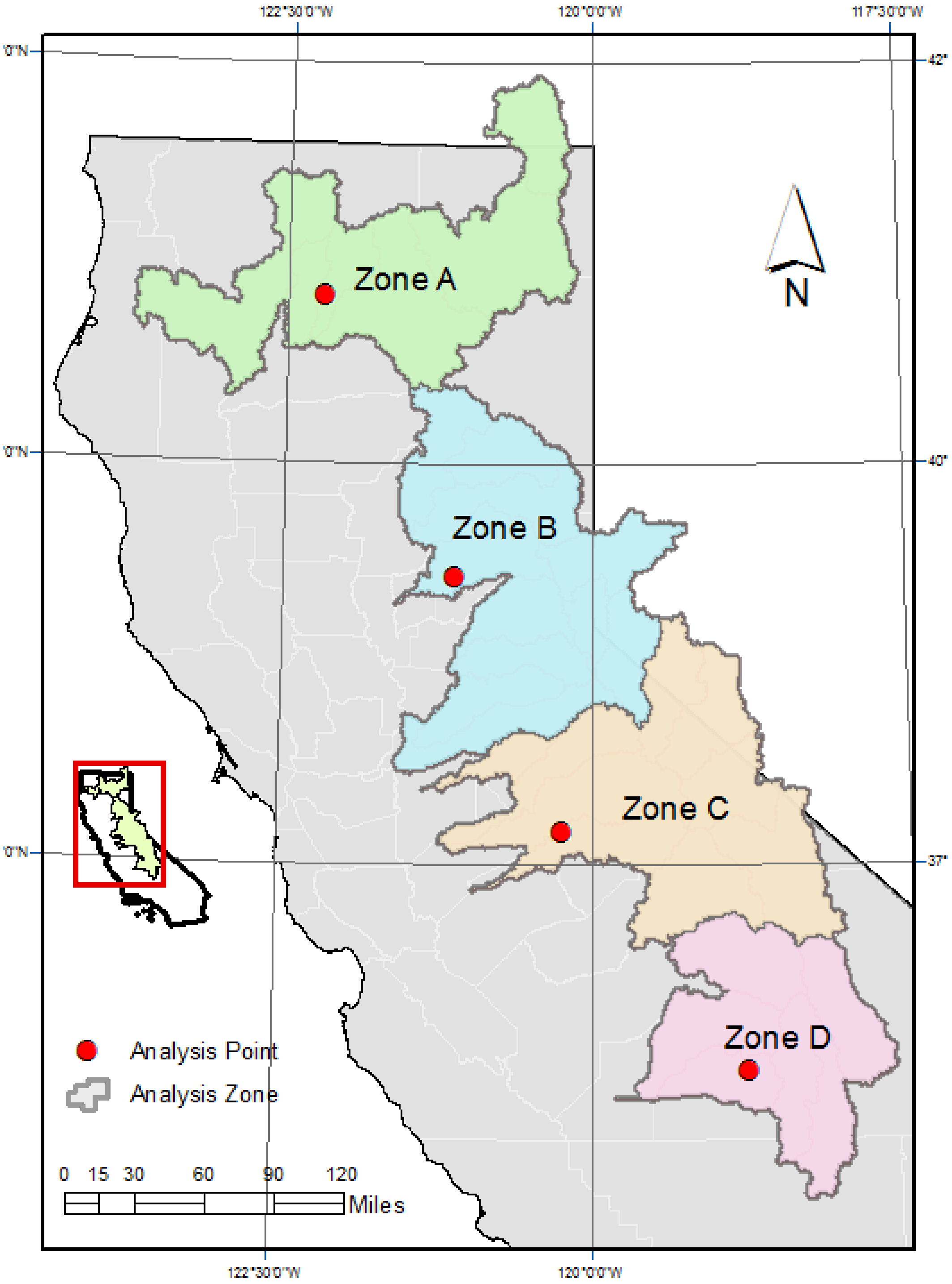

Figure 2: Analysis zones and corresponding representing points used to extract percent-rain data

Four zones were chosen based on two factors. First, the reanalysis data that the WRCC Freezing Level Tracker is based on is relatively coarse, at 2.5 degrees latitude/longitude cell size. Figure 3, showing the analysis area, has a 2.5 degree graticule overlay for reference. As can be seen in the figure, the majority of the analysis area corresponds to 4 grid cells. Note that the WRCC Freezing Level Tracker interpolates data between grid center points. A scheme of 4 analysis points arranged approximately north to south, with more or less the same spatial spacing as the grid cells, is sufficient to capture the large-scale variations in the atmosphere recorded in the reanalysis data.

Secondly, the use of four zones allows for differentiation from north to south, which enables analysis of differences between the Sacramento and San Joaquin watersheds, the dominant watersheds utilized in Bulletin 120. Typically, these are described as rain-dominated and snow-dominated watersheds, respectively. It was hoped that this analysis might provide other insights into differences between these regions. Figure 4 shows the locations of the Sacramento and San Joaquin rivers in relation to the analysis zones used for this report.

It is thought that a few more or less analysis zones and representative points would not make much difference to the results, as the changes across the state are relatively small. Alternatives that used three or two zones and representative points would most likely not make much difference in the resulting calculated percent rain time-series for each analysis zone.

The WRCC tool provides “percent snow” but for this study the complementary quantity “percent rain” (one hundred minus percent snow) is depicted and analyzed.

Fine-grained Precipitation Data from PRISM Climate Group

PRISM Climate group total annual precipitation data with a 2.5-arcminute latitude/longitude cell-size grid was obtained for water years 1949-2012 (PRISM Climate Group at Oregon State University, 2012).

Digital Elevation Model from PRISM Climate Group

A 2.5 arc-minute grid Digital Elevation Model (DEM) (PRISM Climate Group at Oregon State University, 1995) was classified by elevation range values that correspond to the WRCC freezing level tracker elevation ranges. Each cell in the DEM was assigned to a corresponding 200m elevation band defined in the NAFLT. Bands are denoted by their median elevation: e.g. a cell at 301m would be assigned to the 400m band, whereas a cell at 299 would be assigned to the 200m band.

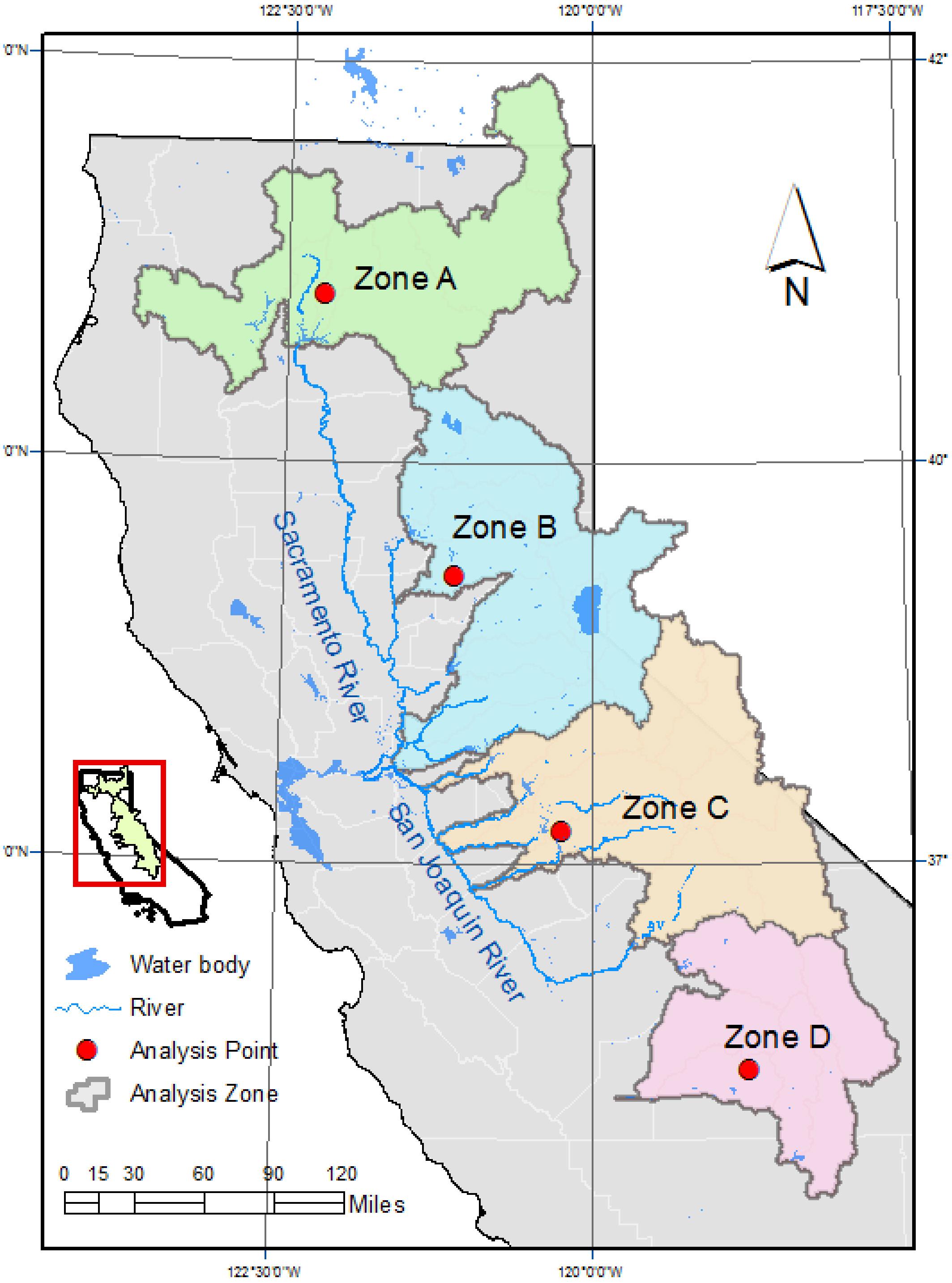

Figure 3: Analysis zones in relation to Sacramento and San Joaquin rivers

Data Processing

The WRCC Freezing Level tracker provides coarse percent-rain data for 20 different levels of the atmosphere, in 200m elevation bands. However, this tool does not provide a number for total rain/total precipitation for regions that span more than one elevation range. For this, PRISM data provides annual total precipitation at approximately 2000m grid cells, and the associated DEM provides ground-surface elevation for each cell. The PRISM precipitation data is used to provide a more refined estimate of the precipitation ratio by better accounting for elevation effects. The DEM links the NCAR/NCEP-derived annual percent rain data to the PRISM annual total precipitation data.

Using the data described above, the total average region-wide annual precipitation and total average annual percent rainfall (calculated % precipitation that fell as rain, of the total annual precipitation) for each water year 1949-2012, for each analysis zone, were calculated, using the following formulas:

$$Zone - average\ precipitation = \overline{P} = \left(\sum_{i=1}^{n} P_i\right)/n$$

$$Zone - average\ rainfall = \overline{R} = \left(\sum_{i=1}^{n} P_i F_i\right)/n$$

$$Zone - average\ fraction\ of\ precipitation\ as\ rainfall = \overline{R}/\overline{P}$$

$Where,$

$n = number\ of\ grid\ cells\ in\ zone$
$i = individual\ grid\ cell\ (PRISM\ 2.5 arcminute\ grid)\ in\ zone$
$F_i = fraction\ of\ precipitation\ falling\ as\ rain\ at\ elevation\ bin\ of\ specific\ grid\ cell$
$P_i = Total\ annual\ solid\ and\ liquid\ precipitation\ falling\ in\ specific\ grid\ cell$

Average precipitation is the annual precipitation averaged for all PRISM cells in an analysis zone.

Average rainfall is the annual liquid precipitation averaged for all per PRISM cell in an analysis zone.

3. Results

Time series were generated of total annual precipitation, percent precipitation falling as rain, and of average annual precipitation for each region and for the total analysis area, using the data processing methodology described above. We chose to represent the data as “percent rain” to more easily visualize any trend towards more rain versus snow, as commonly discussed in the public dialogue.

Figures 5 through 9 show the annual time series by water year for the entire analysis area and for each analysis zone. There is substantial inter-annual variability in all zones due to climate signals that occur on annual and decadal scales. The charts are shown as variations from the analysis period mean. Years with red bars have a higher percentage of rain than the mean, and years with blue bars have a lower percentage of rain than the mean. For the entire analysis area (figure 5), and for zones A and B (figures 6 and 7), years with a higher percentage of rain are clearly more common in the later period of record, in agreement with expectations under a warming climate and previous studies. Zone C (figure 8) does not have an apparent annual trend. Zone D (figure 9) shows a marginal apparent annual trend towards more rain.

Figures 10 and 11 are boxplots of water year average precipitation and percent precipitation falling as rain. Note that average precipitation and percent precipitation falling as rain for zones A and B (Figures 6 and 7) are significantly greater than for zones C and D (Figures 8 and 9), which have higher median elevations and larger spreads.

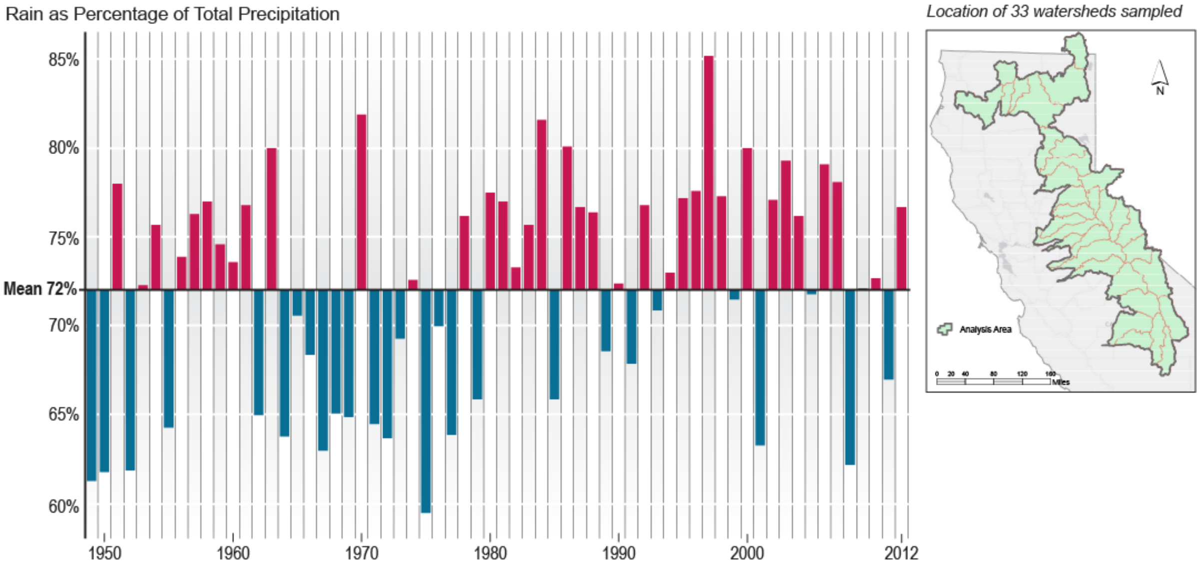

Figure 4: Percentage of precipitation falling as rain over the 33 main water supply watersheds of the State is shown for water years ending 1949 through 2012 (October 1948 – Sept 2012), using Western Region Climate Center historic precipitation and freezing level reanalysis. Mean percentage rain for the analysis period is 72%. (This is also Figure 3-19, Volume 1, Chapter 3, California Water Today, in California Water Plan Update 2013).

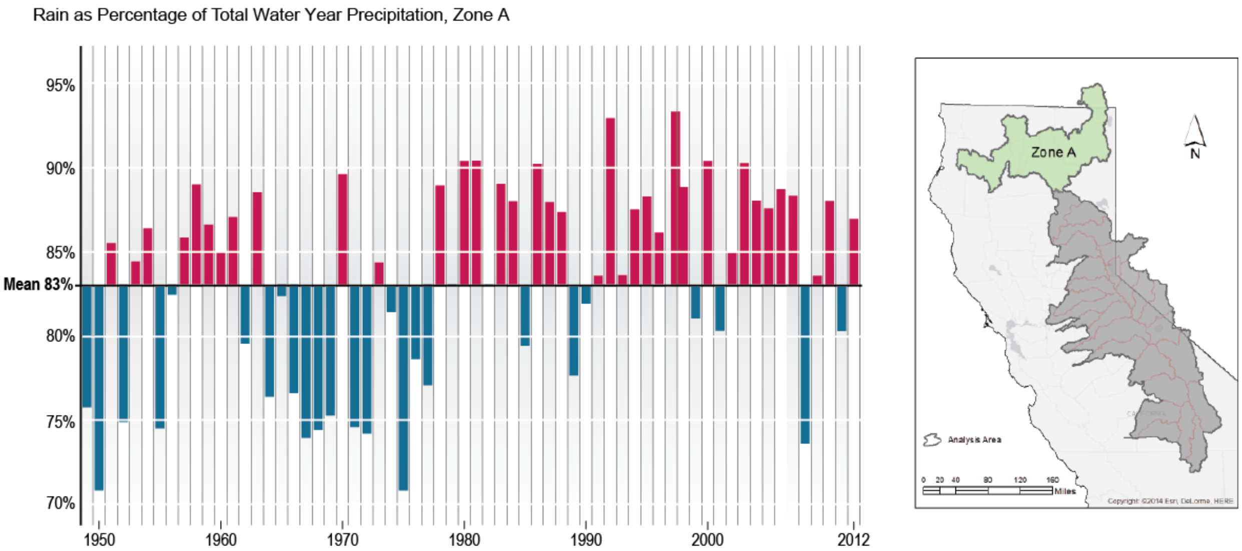

Figure 5: Percent of Total Water Year Precipitation Falling as Rain, Zone A Water Years 1949-2012. Mean percent rain in Zone A over the analysis period is 83%. Median annual precipitation in Zone A is 38.3 inches.

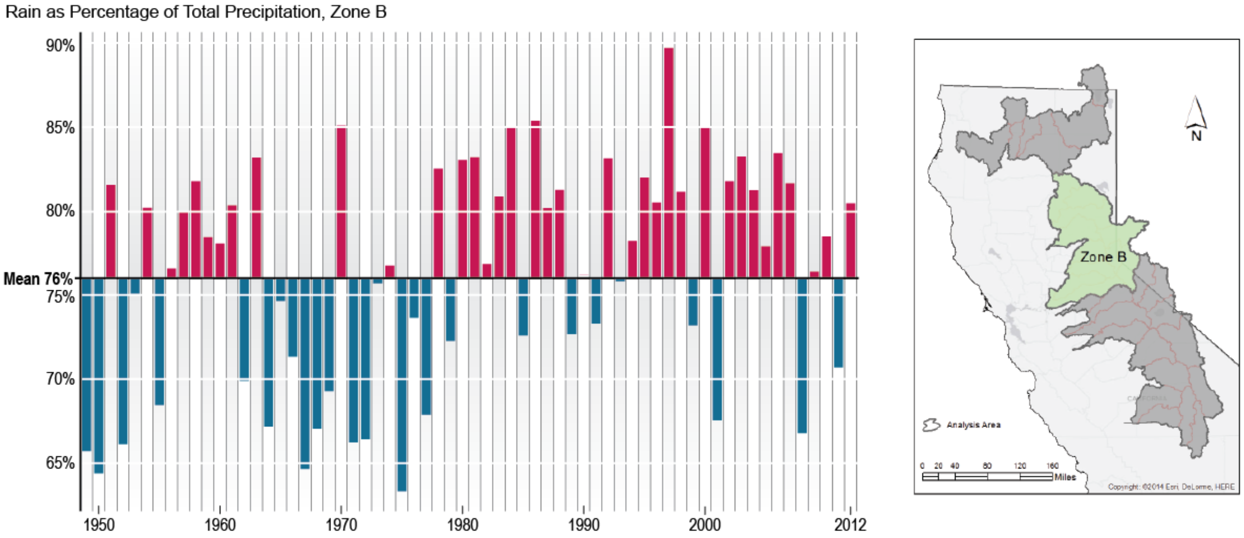

Figure 6: Percent of Total Annual Precipitation Falling as Rain, Zone B, Water Years 1949-2012. Mean percent rain in Zone B over the analysis period is 76%. Median annual precipitation in Zone B is 39.8 inches.

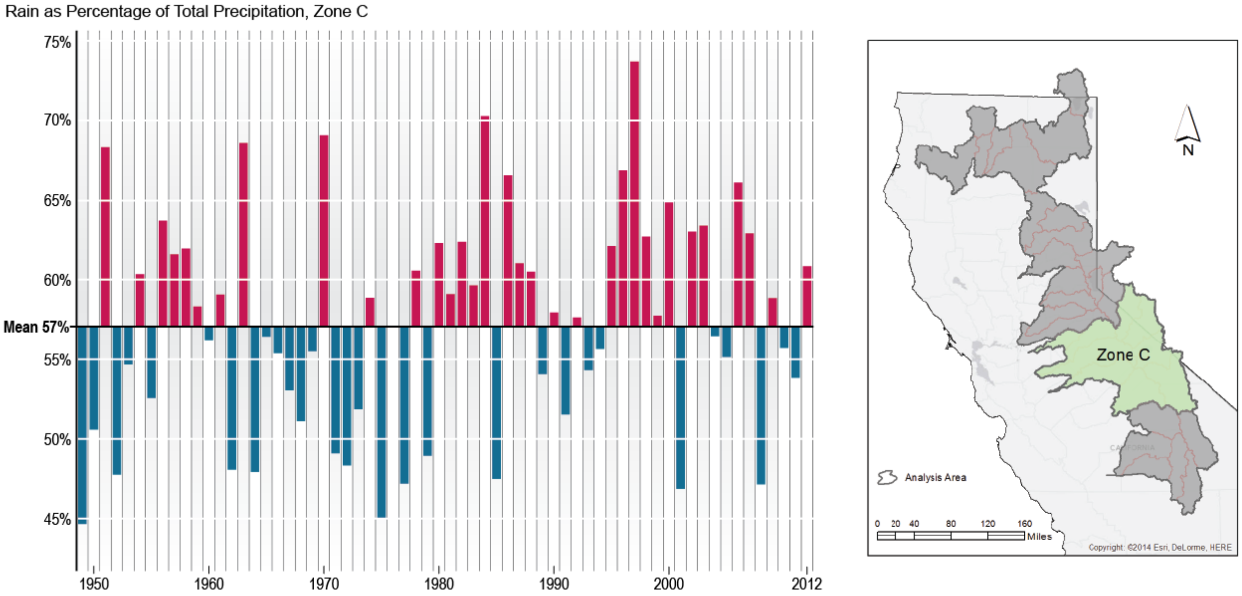

Figure 7: Percent of Total Annual Precipitation Falling as Rain, Zone C, ,Water Years 1949-2012. Mean percent rain in Zone C over the analysis period is 57%. Median annual precipitation in Zone C is 25.1 inches.

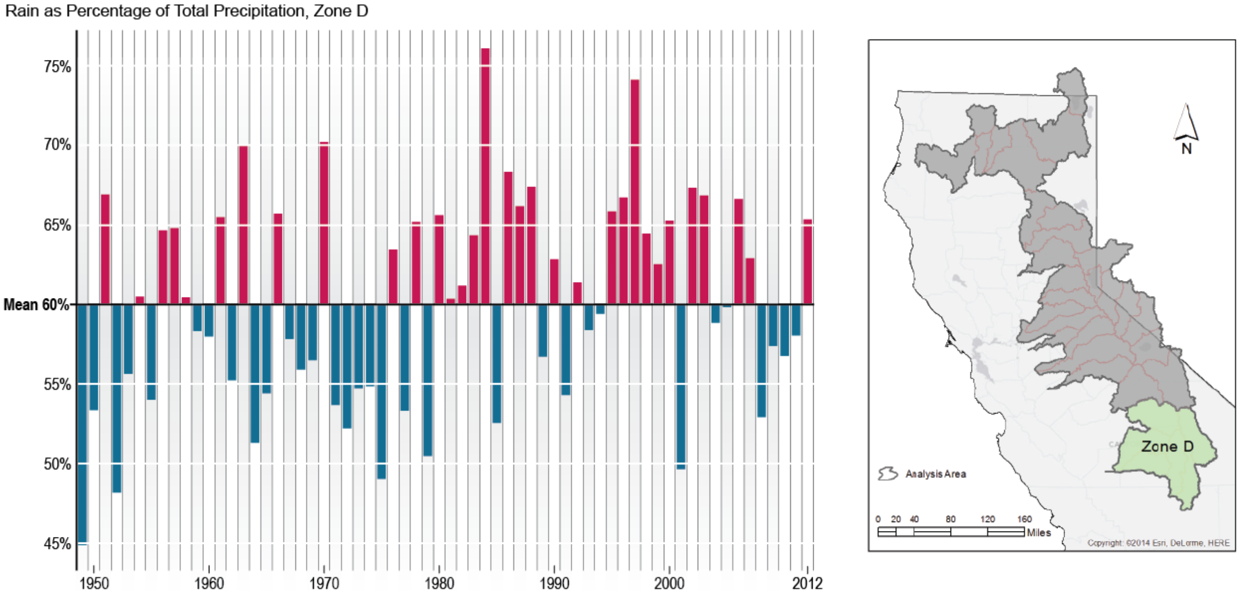

Figure 8: Percent of Total Annual Precipitation Falling as Rain, Zone D, Water Years 1949-2012. Mean percent rain in Zone D over the analysis period is 60%. Median annual precipitation in Zone D is 18.1 inches.

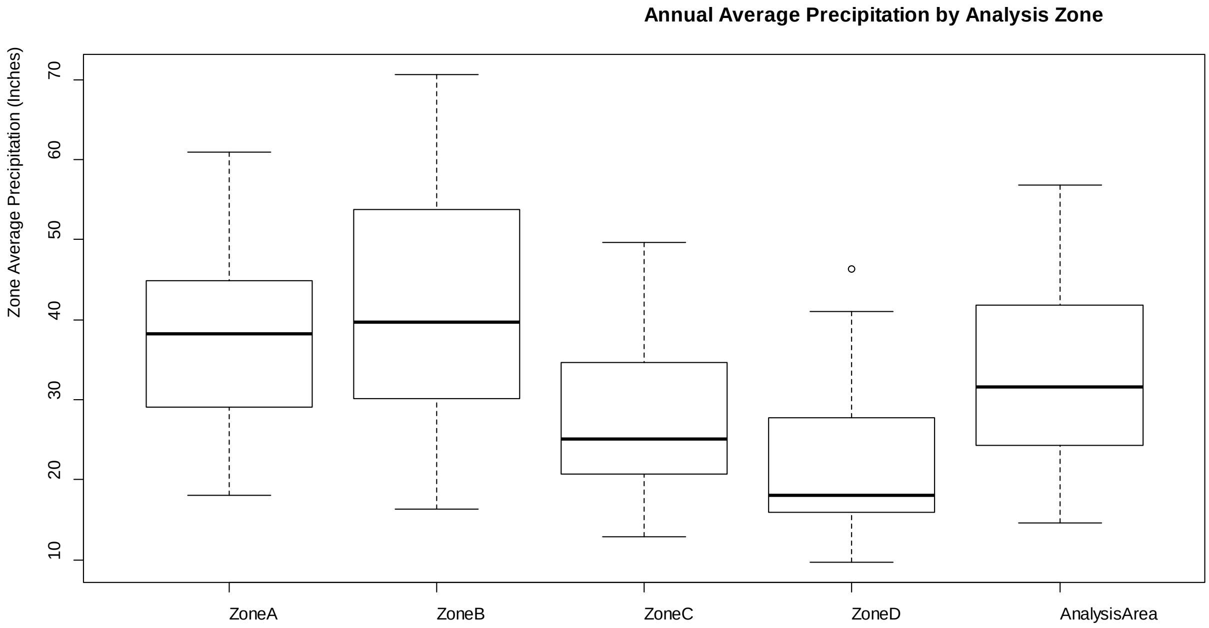

Figure 9: Average Annual Precipitation by Analysis Zone. Note significantly higher precipitation in zones A and B versus zones C and D.

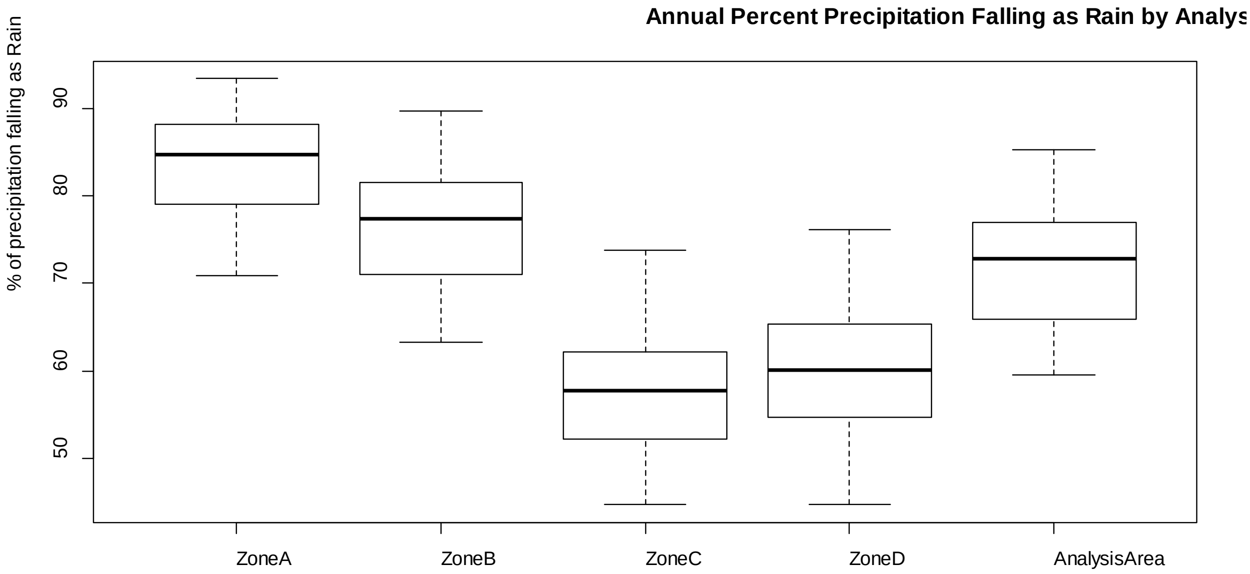

Figure 10: Annual Percent Precipitation Falling as Rain by Analysis Zone. Note difference between zones A and B versus zones C and D. This fits with standard descriptions of the Sacramento River watersheds (corresponding to A and B) as rain-dominated, and the San Joaquin river watersheds (zones C and D) as snow-dominated.

4. Analysis

The time series are not normally distributed, therefore the non-parametric Mann-Kendall test was used evaluate trends. The R statistical package was used to calculate Kendall's tau and the Mann-Kendall test for significance (R Core Team, 2012). The two outputs of this test, Kendall's tau and 2-sided p values, are used to evaluate the significance of the trends. In addition, Theil-Sen slopes are calculated for each trend. The Theil-Sen slope is a non-parametric estimator of the linear trend.

Kendall's tau values are interpreted as follows: a negative value indicates a negative correlation, a positive value indicates a positive correlation, and the value (between -1 and 1) is the strength of the correlation. Values near +1 or -1 indicate stronger correlations. Absolute tau values greater than 0.3 indicate a strong correlation, between 0.1 and 0.3 indicate a moderate correlation; and less than 0.1 indicates a weak to no correlation.

P values are interpreted as follows: $p < 0.01$ indicates very high significance, and $p < 0.05$ is considered significant. Correlations do not necessarily need to be very high to be significant if the sample size is large enough.

Tables 1 to 4 below show Mann-Kendall trend test results for average precipitation, average rain, average snow, and percent rain for each analysis zone and the total analysis region. Yellow highlighted entries indicate very high significance, green indicates significant, and unhighlighted indicates failure to reject the null hypothesis of no significance ($p > 0.05$).

Average Precipitation

Recall that average precipitation is defined as the PRISM-cell-average annual precipitation computed for each analysis zone and the entire analysis region. There is no evidence of a trend in precipitation for any of the analysis zones ($p >> 0.05$).

Table 1: Mann-Kendall Trend Analysis of Average Annual Precipitation by Analysis Zone

Zone	**Kendall's tau**	**2-sided p value**	**Theil-Sen Slope**
Zone A	**-0.044**	**0.614**	**-0.090**
Zone B	**-0.0367**	**0.672**	**-0.071**
Zone C	**0.0050**	**0.958**	**0.007**
Zone D	**0.024**	**0.785**	**0.031**
Total Analysis Region	**-0.020**	**0.821**	**0.032**

Average Rain

The average rain is the PRISM cell average annual liquid precipitation computed for each analysis zone and the entire analysis area. There is no evidence of a trend in average rainfall for any of the analysis zones ($p>>0.05$ for all zones).

Table 2: Mann-Kendall Trend Analysis of Average Annual Rainfall by Analysis Zone

Zone	Kendall's tau	2-sided p value	Theil-Sen Slope
Zone A	0.0179	0.839	0.033
Zone B	0.0367	0.672	0.068
Zone C	0.0486	0.574	0.039
Zone D	0.0784	0.363	0.046
Total Analysis Area	0.0337	0.698	0.054

Average Snow

Average snow is the PRISM cell average annual solid precipitation computed for each analysis zone and the entire analysis area. There is strong evidence of a downward trend in average annual precipitation falling in the form of snow for Zone A ($p < 0.01$), and weak evidence of a downward trend in average annual snow for zone B ($p<0.05$). For the other two zones, and the total analysis region, there is no evidence of significant trend.

Table 3: Mann-Kendall Trend Analysis of Average Annual Snow by Analysis Zone

Zone	Kendall's tau	2-sided p value	Theil-Sen Slope
Zone A	-0.232	0.007	-0.099
Zone B	-0.186	0.031	-0.121
Zone C	-0.039	0.656	-0.0268
Zone D	-0.037	0.672	-0.01
Total Analysis Area	-0.104	0.226	-0.068

Percent Rain

There is strong evidence of an upward trend in Zone A ($p<0.01$), moderate to weak evidence of an upward trend for Zone B and the total analysis area ($0.01<p <0.05$). There is no evidence of a trend for zones C and D ($p>0.05$), though zone D is close to our arbitrary threshold at $p=0.066$, and could be considered borderline.

Zones A and B have Kendall's tau values corresponding to moderate positive correlation for percent rain over time, while Zones C and D have weak to moderate correlation. Aggregated, the entire analysis area has a moderate positive correlation.

Thiel-Sen estimates of slopes in zones A and B are about a 0.1/year increase in annual percentage of precipitation falling as rain, or about a 6.6% increase over the analysis period. For the aggregated analysis area, the Thiel-Sen estimate of slope is 0.09/year increase in annual percentage, or about 5.8% over the analysis period.

Table 4: Kendall-Mann Trend Analysis of Annual Percent Rain by Analysis Zone

Zone	Kendall's tau	2-sided p value	Theil-Sen Slope
Zone A	0.227	0.008	0.103
Zone B	0.214	0.013	0.107
Zone C	0.132	0.125	0.074
Zone D	0.158	0.066	0.083
Total Analysis Area	0.196	0.022	0.090

5. Conclusions

We employ a simple technique to obtain a preliminary assessment of whether the fraction of annual precipitation that falls as rain is increasing or decreasing in the main water supply regions of California. To avoid the necessity for a lengthy and complex process of data rehabilitation and preparation, well beyond the scope of this work and available resources, we instead employ widely used gridded climate data sets.

We assume the weather systems that supply most of the snow and precipitation to the Sierra Nevada and northern California mountains are adequately represented in the NNGR gridded data. With this proviso, the largest unknown in this analysis is the validity of using low-resolution reanalysis-derived atmospheric precipitation phase data and integrating that with higher-resolution PRISM precipitation data. It isn't clear to the authors at this time whether this is a valid approach, but winter-time precipitation tends to be a consequence of large scale cyclonic systems, which should be well represented in the NNGR and PRISM data sets.. Future refinements to the precipitation phase data, through downscaling or other approaches, could potentially decrease the uncertainty associated with the methodology.

The present analysis provides partial support for common assertions regarding climate change effects on snow and rain trends in California. More specifically, there is evidence in northern California of a trend toward a greater fraction of annual precipitation falling as rain for the northern Sierra (analysis zones A and B, figures 6 and 7) but not for the southern Sierra (zones C and D, figures 8 and 9).

There is also a statistically relevant trend towards greater fraction of precipitation falling as rain for the entire aggregated analysis area (figure 5). This aggregated trend can be attributed to the trend seen in the northern Sierra. The aggregated trend is intensified by more heavily weighted northern Sierra, since weighting is based on total precipitation, and the northern Sierra has higher annual average precipitation than the Southern, as shown in Figure 10.

Additionally, no evidence of statistically significant trends over the analysis period in average rainfall or average total precipitation was detected in any zone. There is evidence of significant decreasing trends in average snow in the northern Sierra (zones A and B) but not in the southern Sierra (zones C and D) (table 3).

One possible explanation for apparent trends in zones A and B is that zones A and B have lower average elevations, and have a greater percentage of area in the moderate elevation zones that are thought to be most impacted by warming trends. Zones C and D have higher median elevations, and therefore a greater percentage of the precipitation is falling at higher elevations with colder temperatures, where warming trends are less likely to cause a shift in precipitation phase.

6. Future Work

Evaluating relative roles of climate change and interdecadal variability

Can the apparent trends revealed in this analysis be explained solely by interdecadal climate variability? Mote, et al (2005) concluded that, at least for snow-water equivalent of snowpack, while interdecadal climate variability such as Pacific Decadal Oscillation (PDO) and El Nino Southern Oscillation (ENSO) are contributors, declines in snowpack in the Western US could not be entirely explained by these factors. For the current analysis the relative contributions of long-term climate change and interdecadal and shorter-term variability oscillations were not explored. This is an area for future work.

Elevation

This study does not quantitatively analyze the effect of elevation on precipitation phase, and further research on elevation is warranted.

Additionally, 200m bands of elevation are fairly coarse. A better approach might be to interpolate percent rain across the elevation bands. Depending on the distribution of topography, this could affect the aggregated percent rain calculations somewhat. More importantly, would such refinements materially change the conclusions?

Seasonal effects

Seasonal differences are also not dealt with in this analysis, and repeating this analysis using monthly rather than water-year sums is worthy of future study. There is more evidence of temperature changes in spring than in mid-winter, so perhaps the melt season is preferentially affected by recent variations in climate.

Downscaling

For the purpose of this initial analysis, single centralized locations were used to represent freezing / percent snow data for each analysis zone. This is a reasonable approach, given that the freezing level data is on a 2.5 degree grid. The data for these locations is calculated by interpolating the reanalysis-derived data. A more refined estimation of freezing level (and therefore % of precipitation as snow) might be obtained by downscaling the freezing level data from 2.5 degrees to 2.5 arc minutes and using individually interpolated percent-snow data for each 2.5 arc-minute gridcell.

Alternatively, other downscaling methodologies could potentially be applied to the raw NCEP/NCAR data. This could address the questionable relationship between the coarse precipitation phase data and the finer precipitation sum data. Freezing-level and % snow could then be calculated, using the WRCC methodology, using the downscaled reanalysis data.

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