Where We've Been: Drought in the Southern California Paleo Record

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Paleo Drought Workshop: Using the Past to Improve Drought Preparedness Now
April 19, 2018
San Pedro, CA

THE UNIVERSITY OF ARIZONA

Laboratory of Tree-Ring Research
University of Arizona

Acknowledgements: Research and photo contributions from Dave Meko, Erica Bigio, Brewster Malevich, & Chris Zemp
Project funding from CADWR

A Hot, Dry Winter in California. Could It Be Drought Again?

Feb. 14, 2018

Can one monster storm save California from drought?

Mammoth Mountain could get up to five feet of snow

March 2, 2018

Late-winter storms ease California's dive back into drought

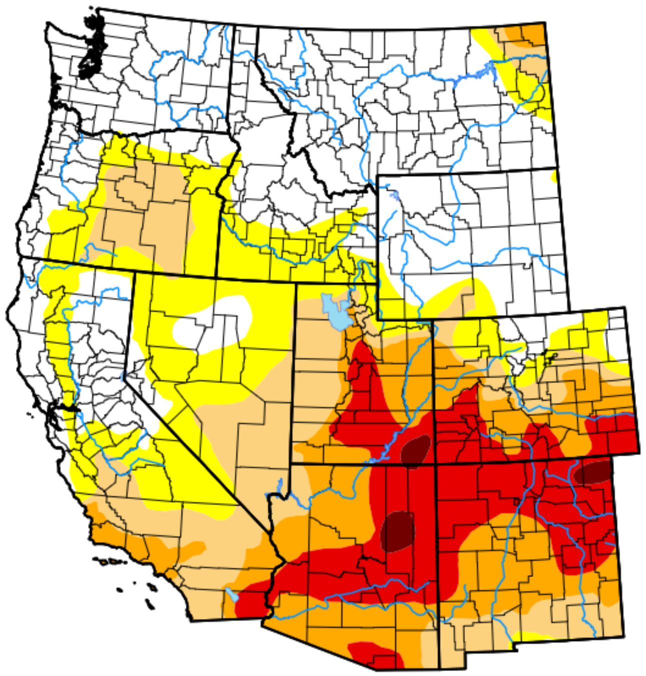
April 2, 2018 by Rich Pedroncelli And Ellen Knickmeyer

Another Atmospheric River Soaks Northern California

FLOOD , WEATHER

APR 12, 2018

Drought Conditions as of April 12



Map released: Thurs. April 12, 2018

Data valid: April 10, 2018 at 8 a.m. EDT

Intensity:

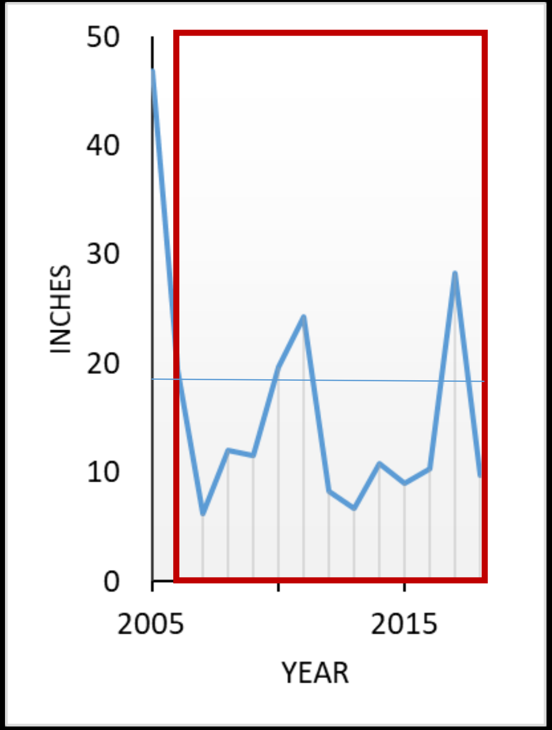
- ☐ **None**
- 🟨 **D0** (Abnormally Dry)
- 🟧 **D1** (Moderate Drought)
- 🟧 **D2** (Severe Drought)
- 🟥 **D3** (Extreme Drought)
- 🟫 **D4** (Exceptional Drought)

From US Drought Monitor

Why consider the past when planning for the future?

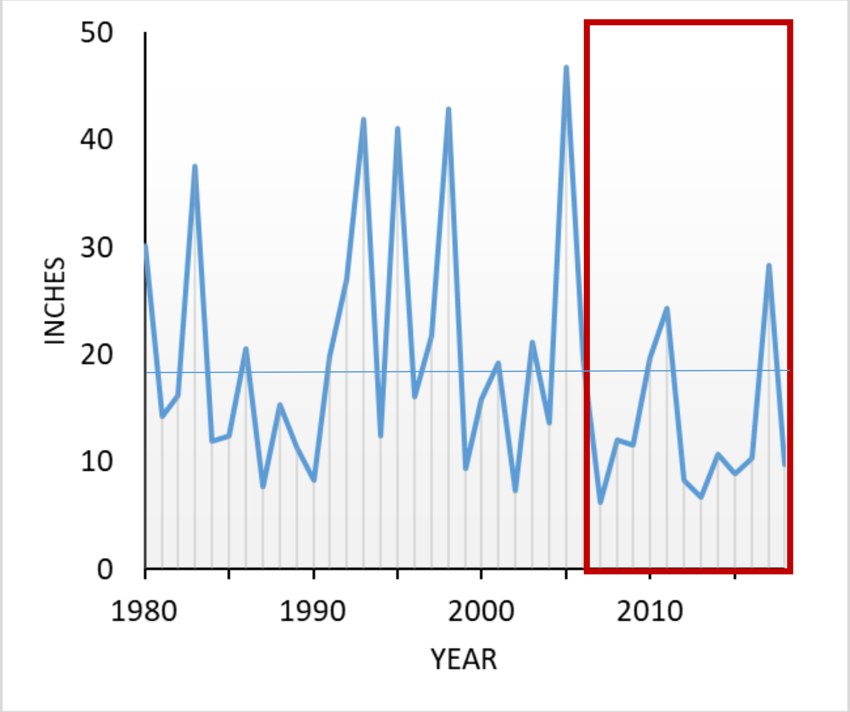
perspective

Ojai, CA
total precipitation
Oct-March 2005-2018



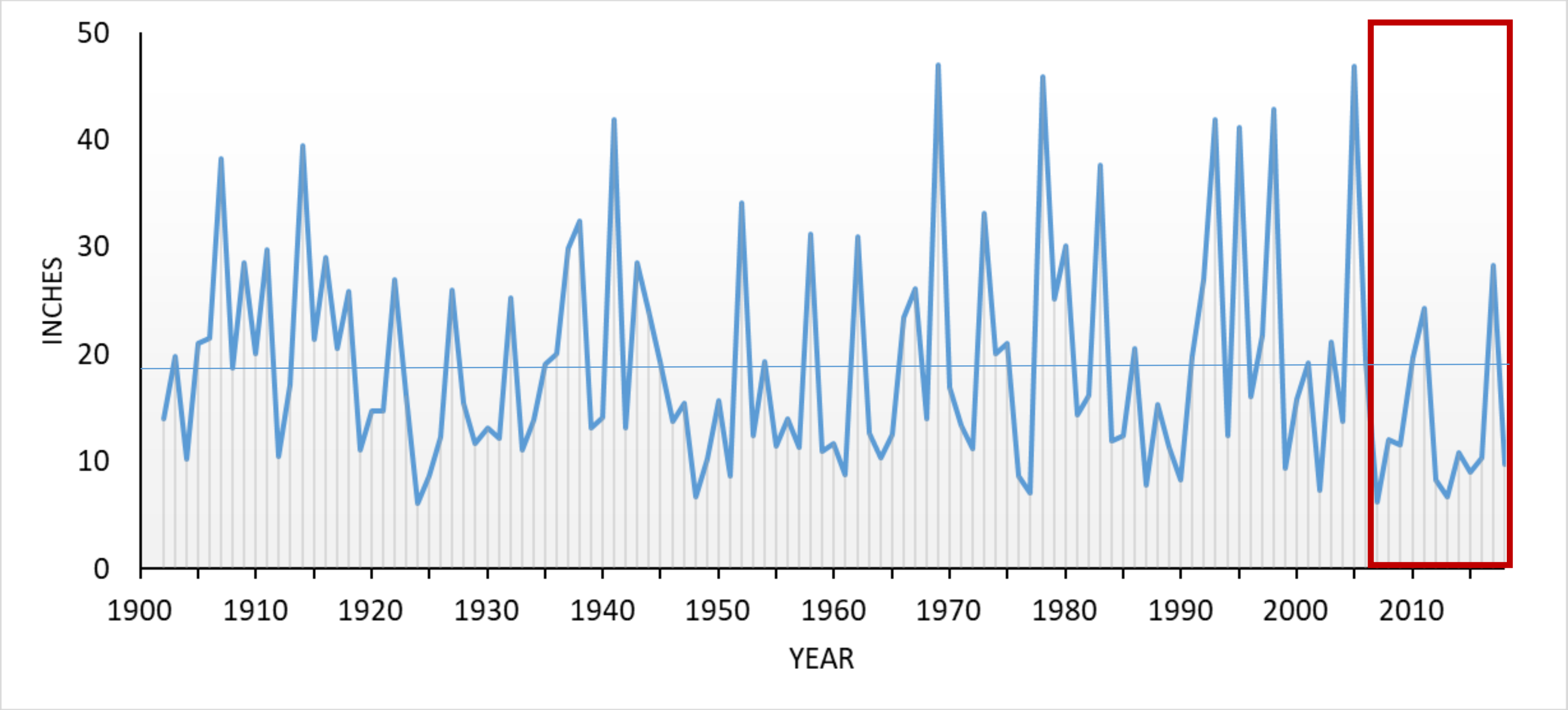
perspective

Ojai, CA
total precipitation
Oct-March 1980-2018

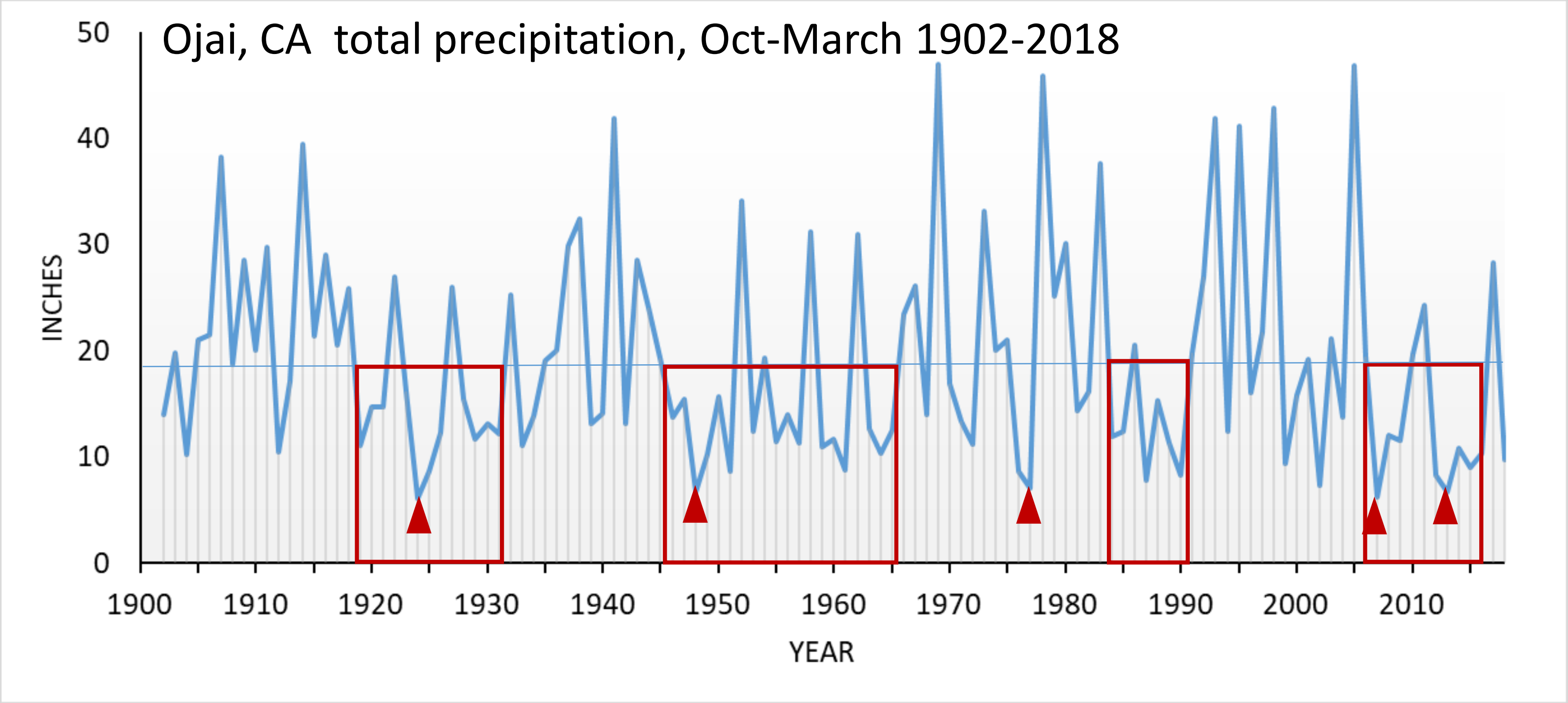


perspective

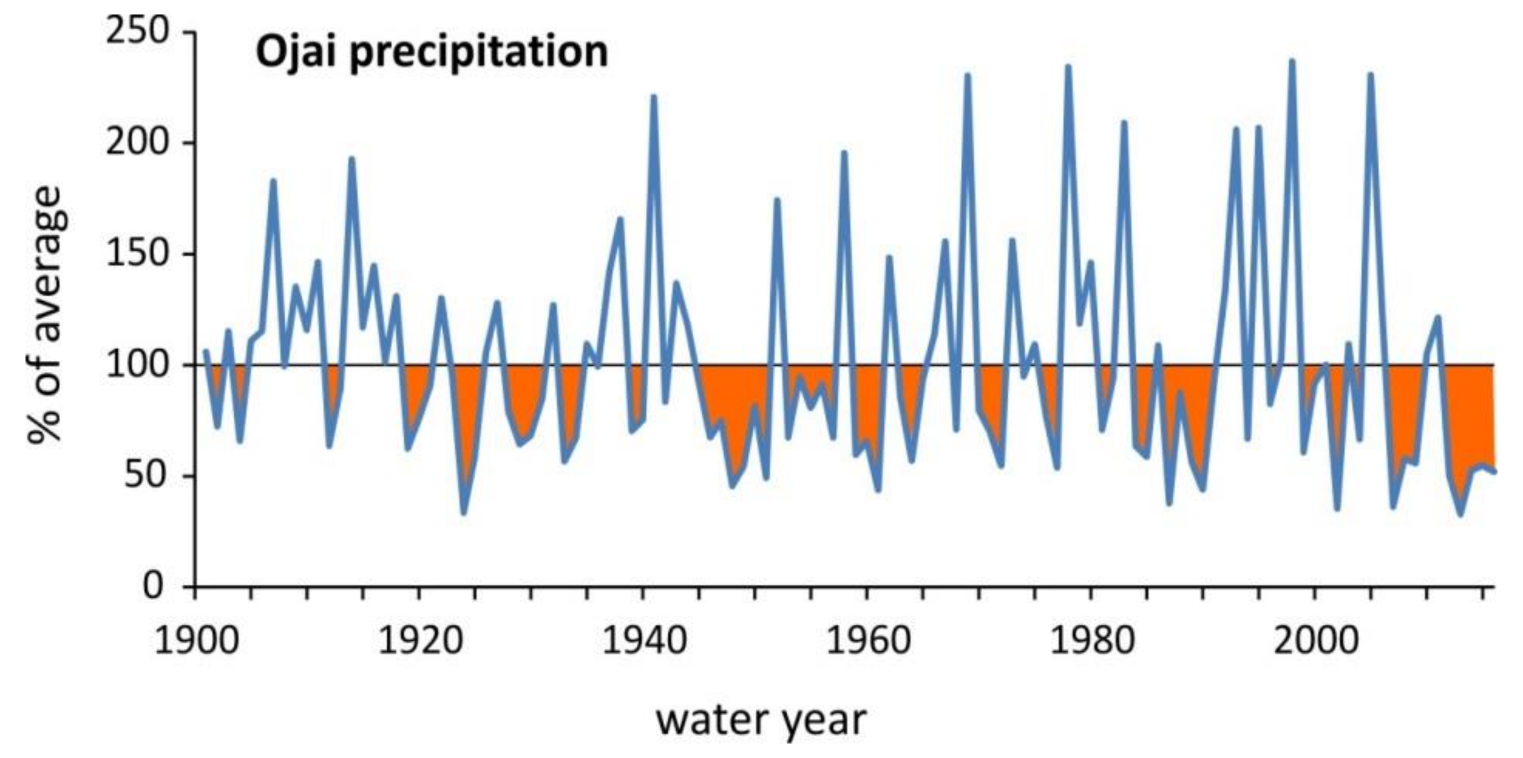
Ojai, CA
total precipitation
Oct-March 1902-2018



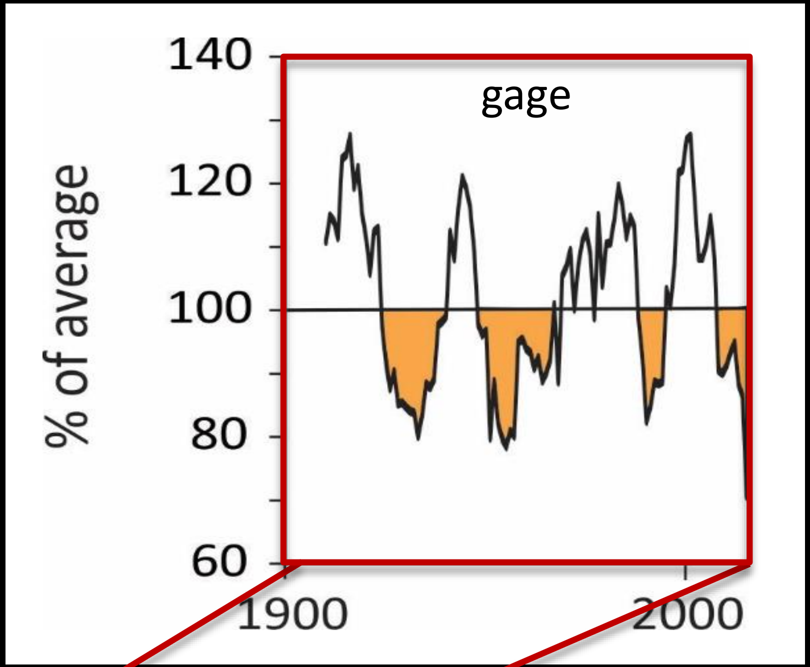
Most gage record extend 100 years or so, at best. These records document extreme dry years and persistent drought.

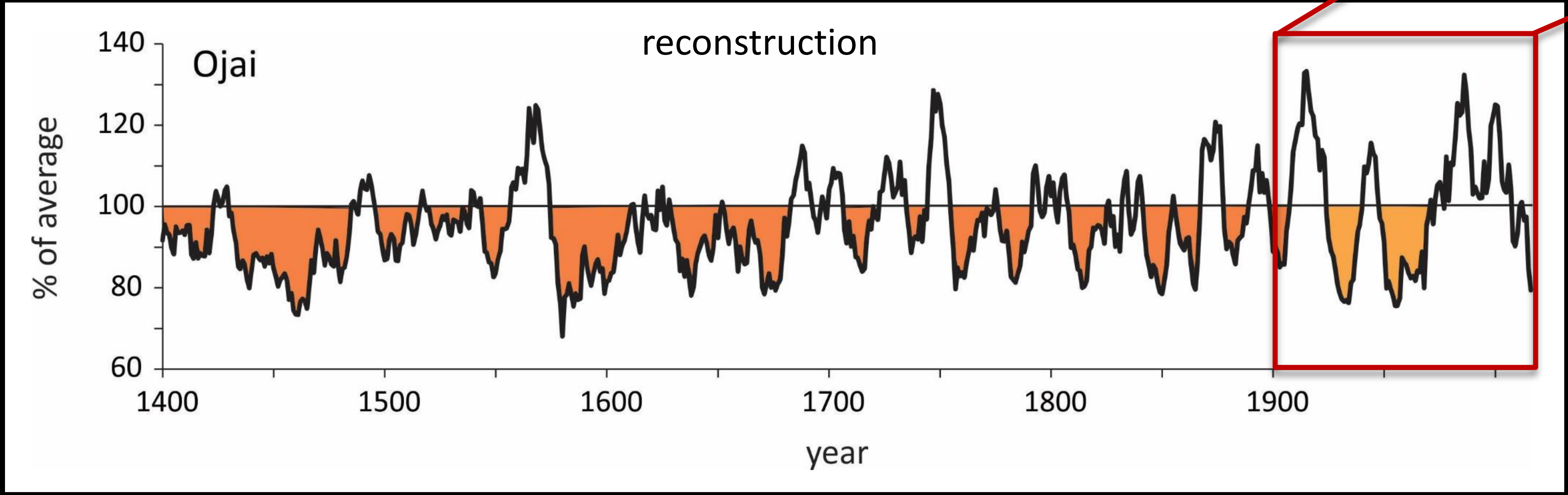


Are these droughts representative of the past, and a good indication of what we can expect in the future?


Ojai precipitation
% of average
250
200
150
100
50
0
1900
1920
1940
1960
1980
2000
water year

Tree-ring records can document droughts over past centuries and place the gage record into a long-term context

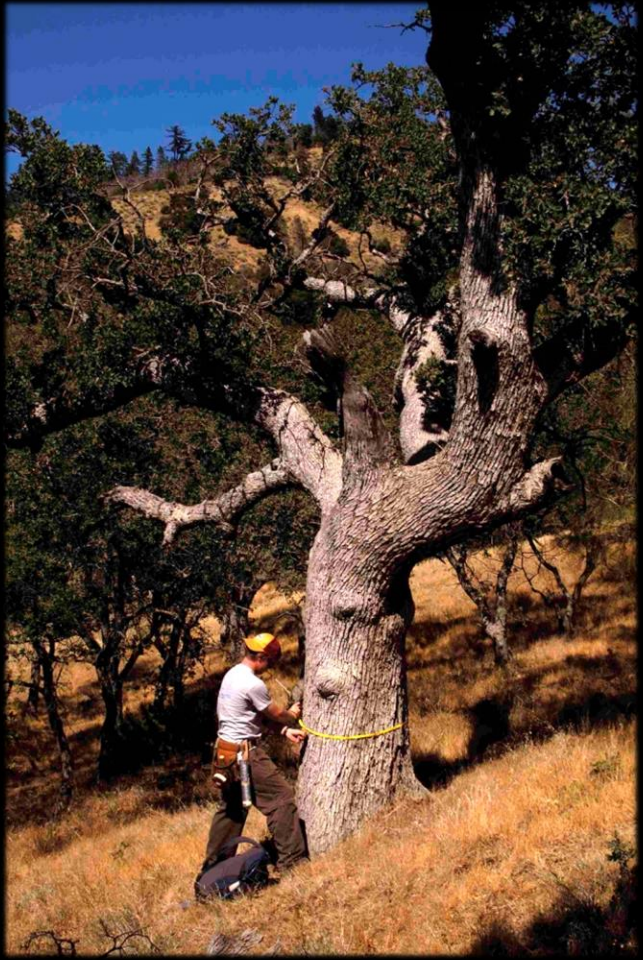




Extending the instrumental records of climate using tree rings

What trees are the best recorders of precipitation and drought?

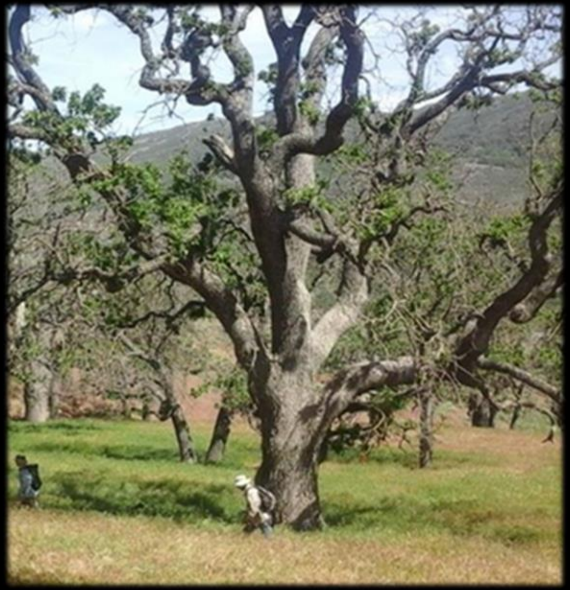
Moisture-sensitive tree species growing on open, well-drained sites



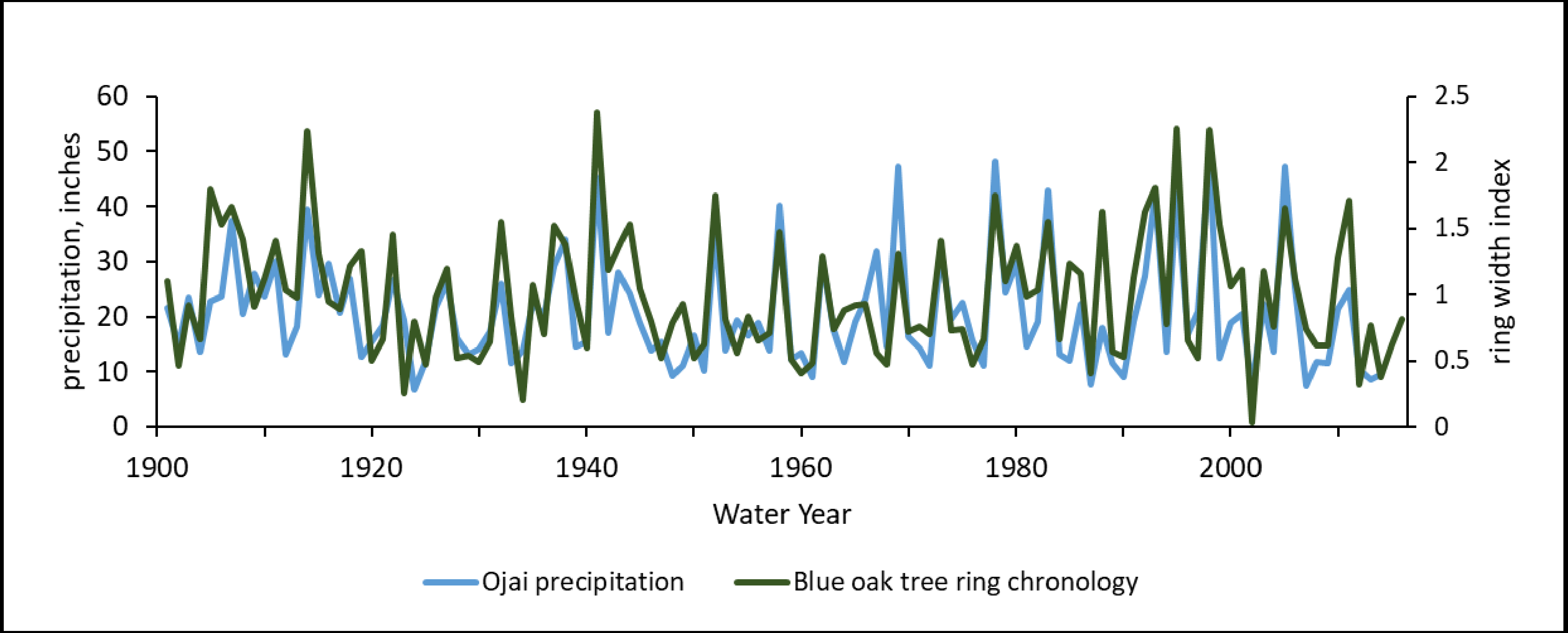
In southern California, these species include:

- bigcone Douglas-fir
- ponderosa pine
- Jeffrey pine
- foxtail pine
- blue oak

Moisture-stressed trees closely track variations in precipitation



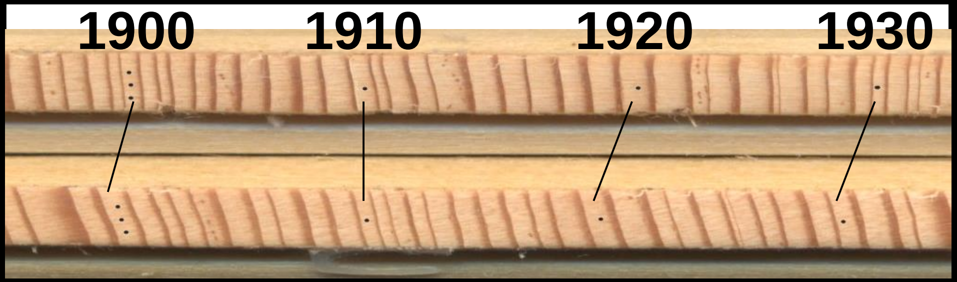
Ojai water year precipitation with annual ring widths averaged from a set of trees about 40 miles north of Ojai.



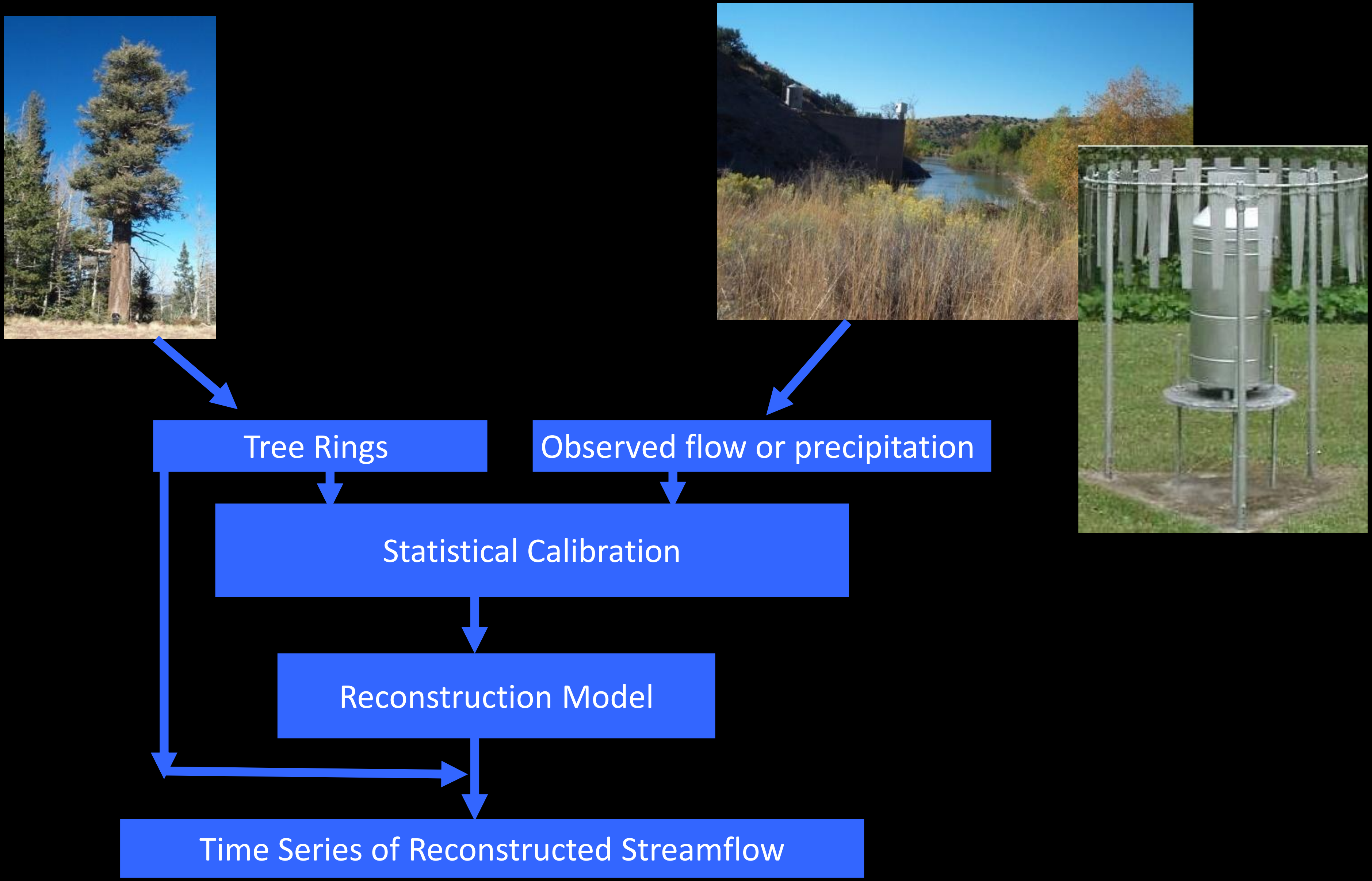
Relationship between streamflow and tree growth

How are trees sampled for climate records?

Back at the lab: Sample preparation, then dating and measuring tree-ring widths



Reconstruction process in a nutshell



Tree Rings

Observed flow or precipitation

Statistical Calibration

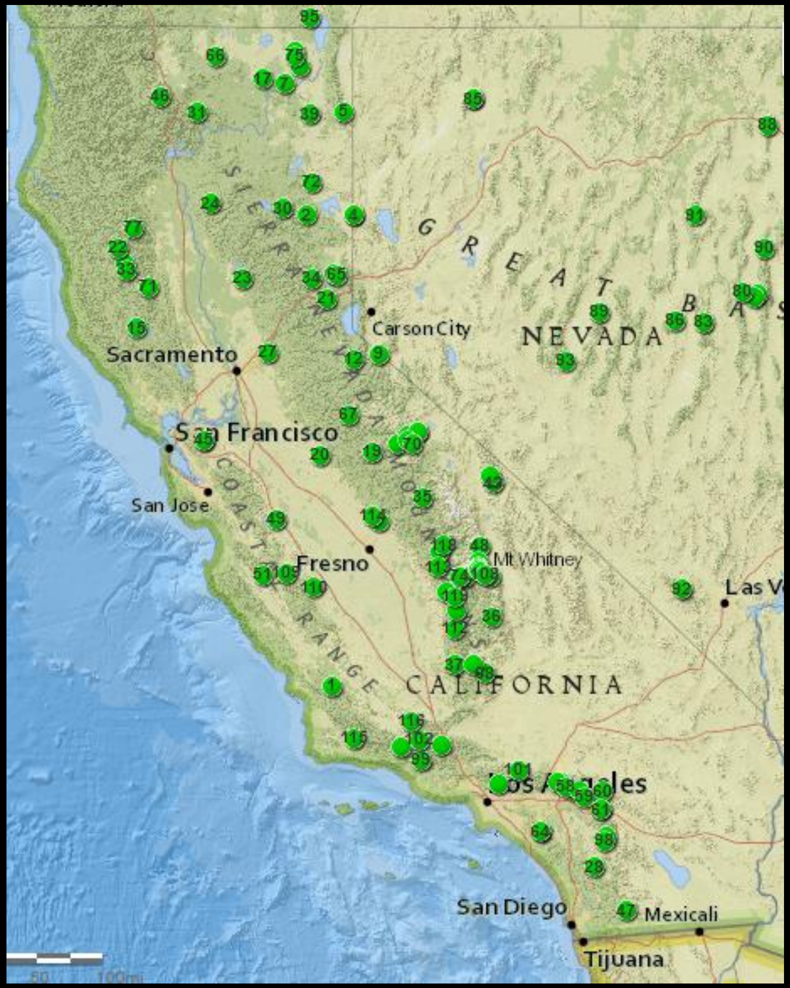
Reconstruction Model

Time Series of Reconstructed Streamflow

California Precipitation and Streamflow Reconstructions

California Precipitation and Streamflow Reconstructions

California region tree-ring chronology locations



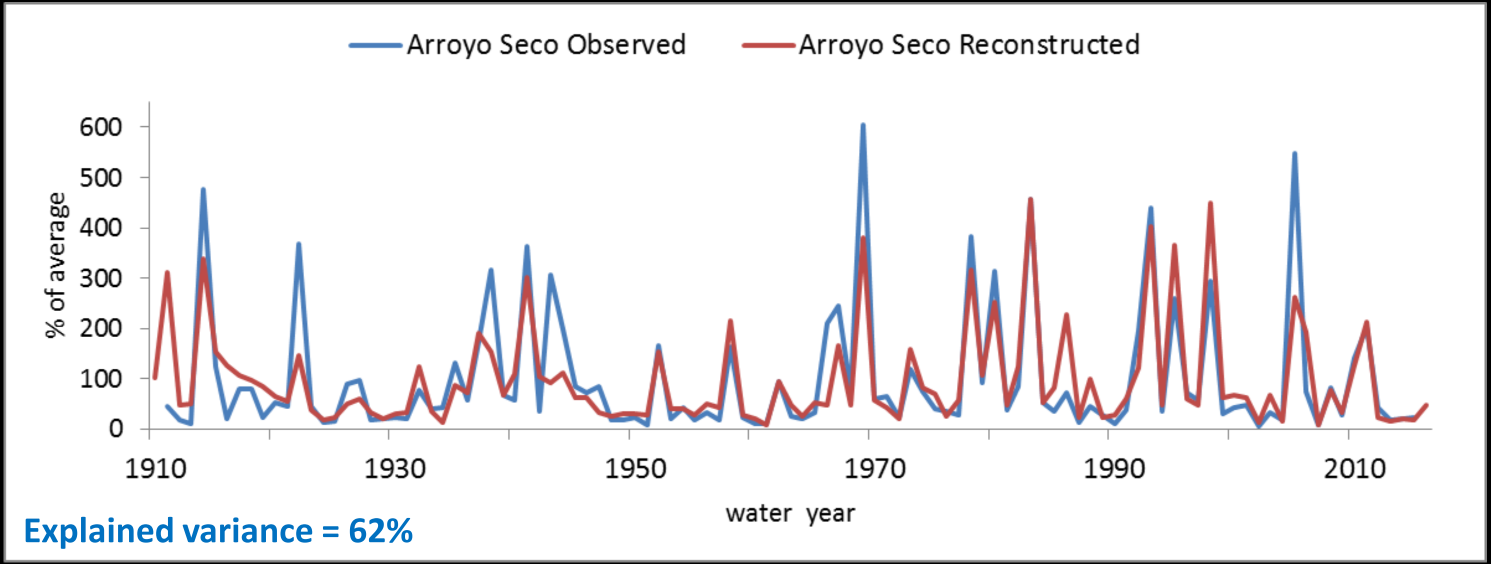
New Southern California Water Year Precipitation and Streamflow Reconstructions

Southern California tree-ring chronology locations

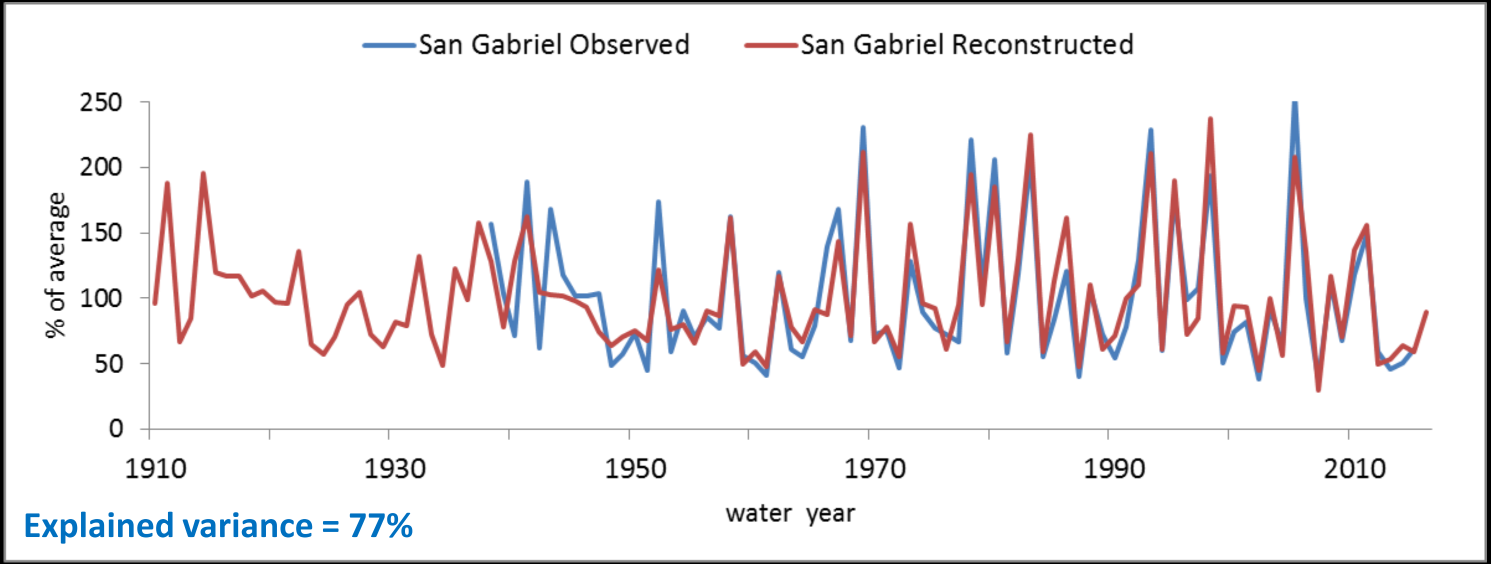
How can tree-ring reconstructions of past flow and precipitation assist in drought planning?

But first, how good are the reconstructions?

Two examples: Arroyo Seco streamflow and San Gabriel Dam precipitation

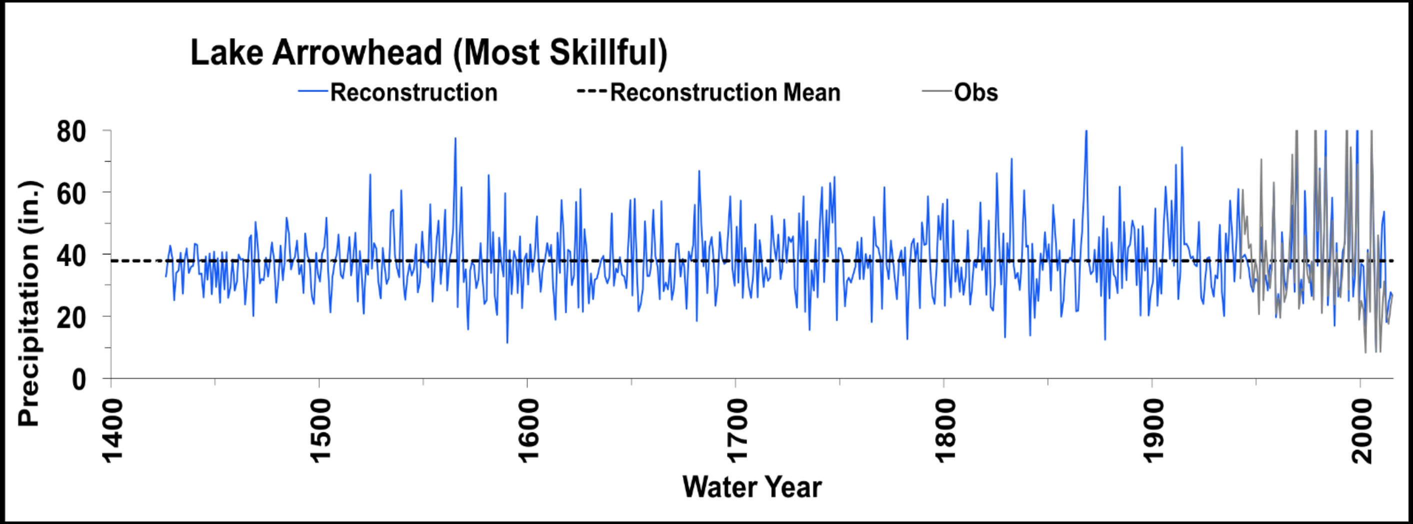


Explained variance = 62%

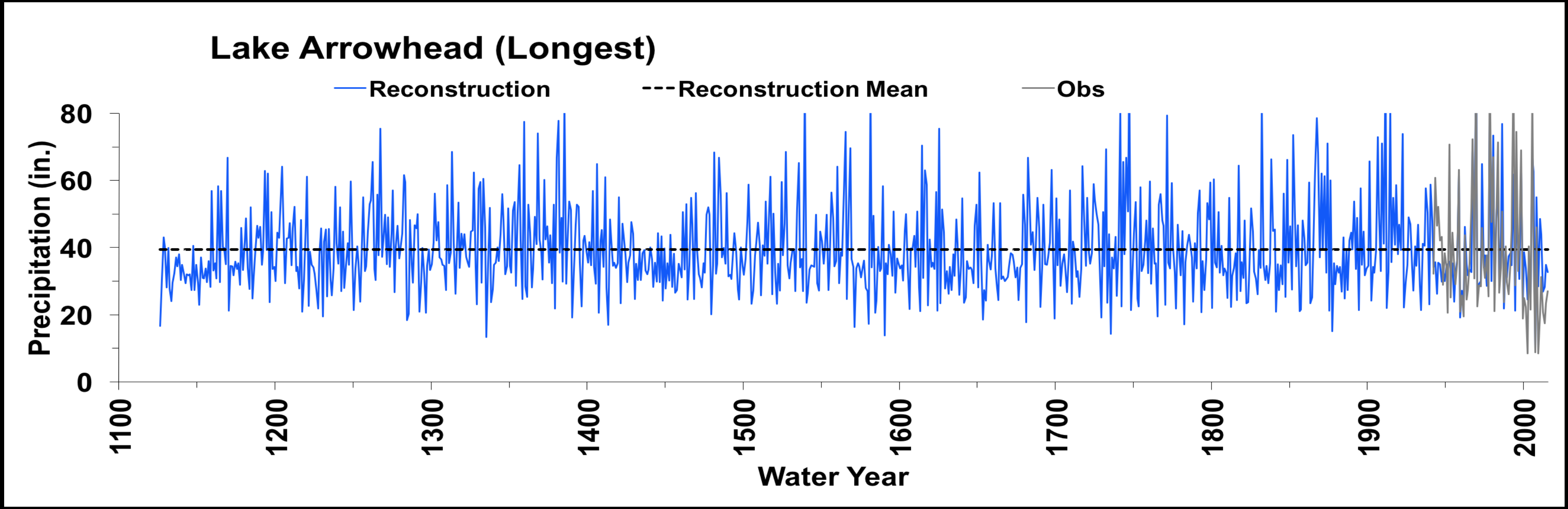


Explained variance = 77%

How far back in time do the reconstruction extend?



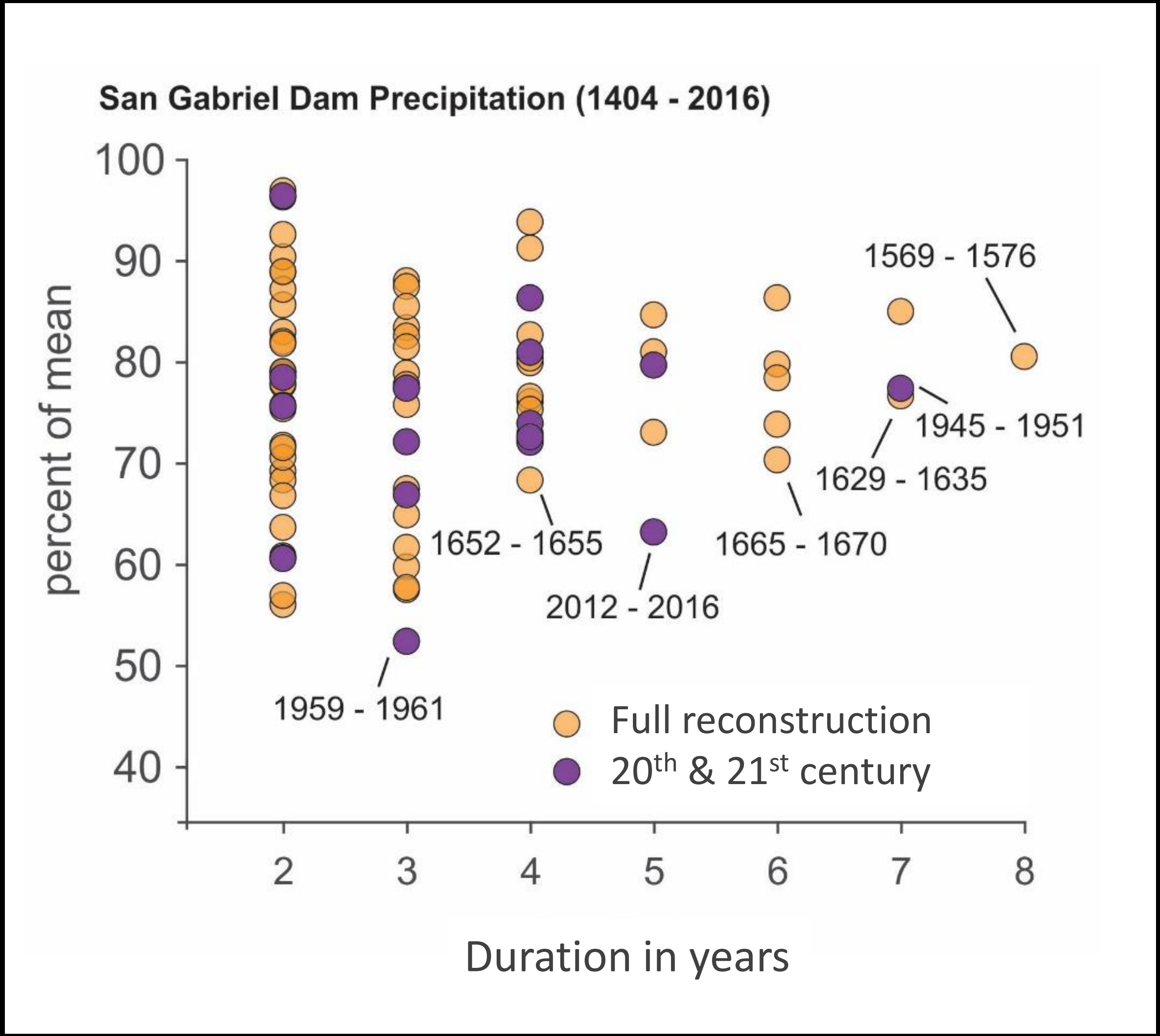
Lake Arrowhead (Most Skillful)



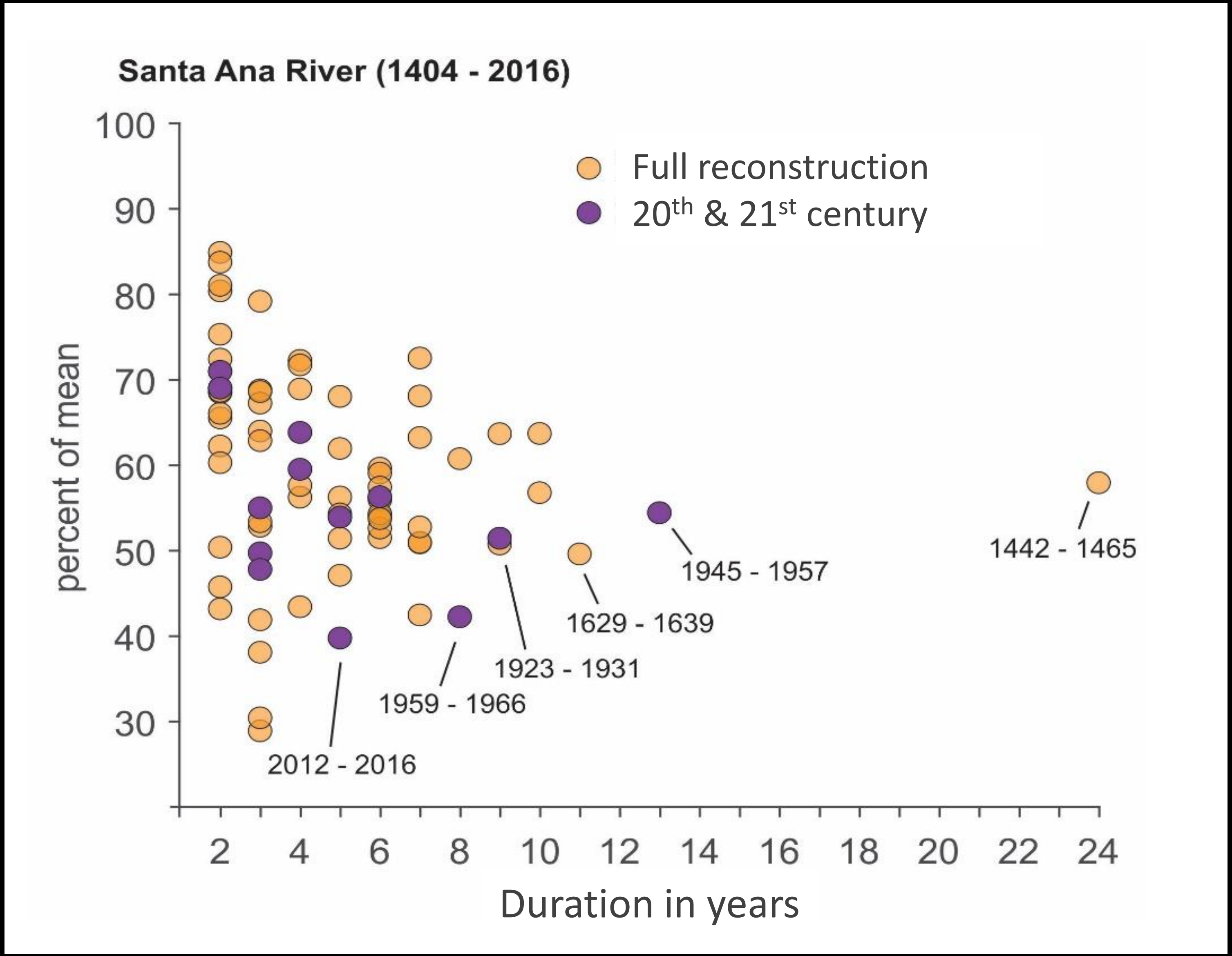
Lake Arrowhead (Longest)

What do these records say about the risk of drought?

Droughts: how long and how frequent

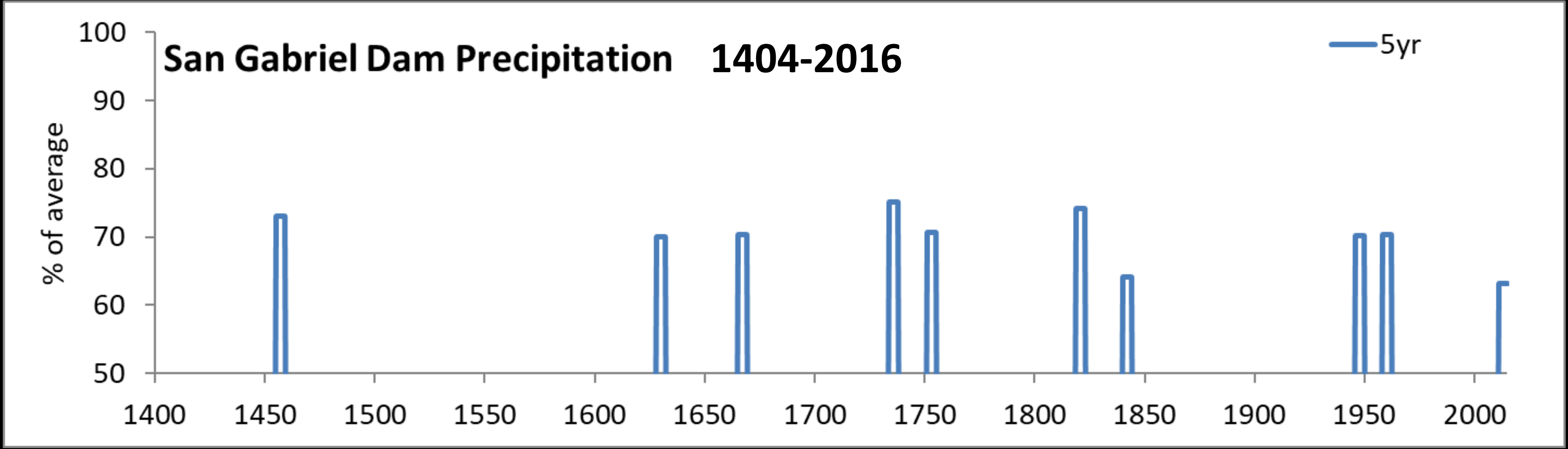


Droughts: how long and how frequent



Driest periods

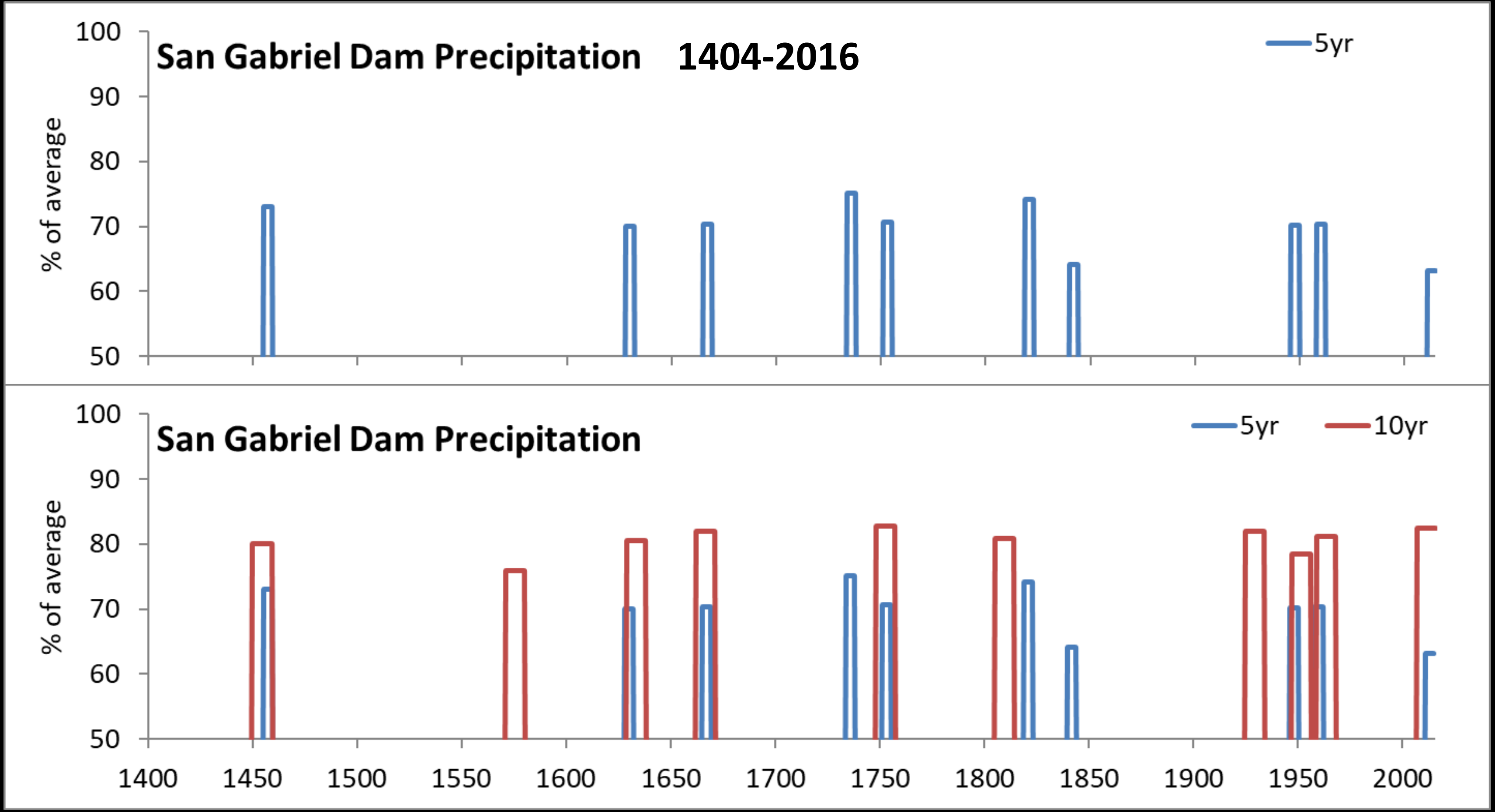
- 5-year periods
  (non-overlapping)



Driest periods

- 5-year periods
- 10-year periods

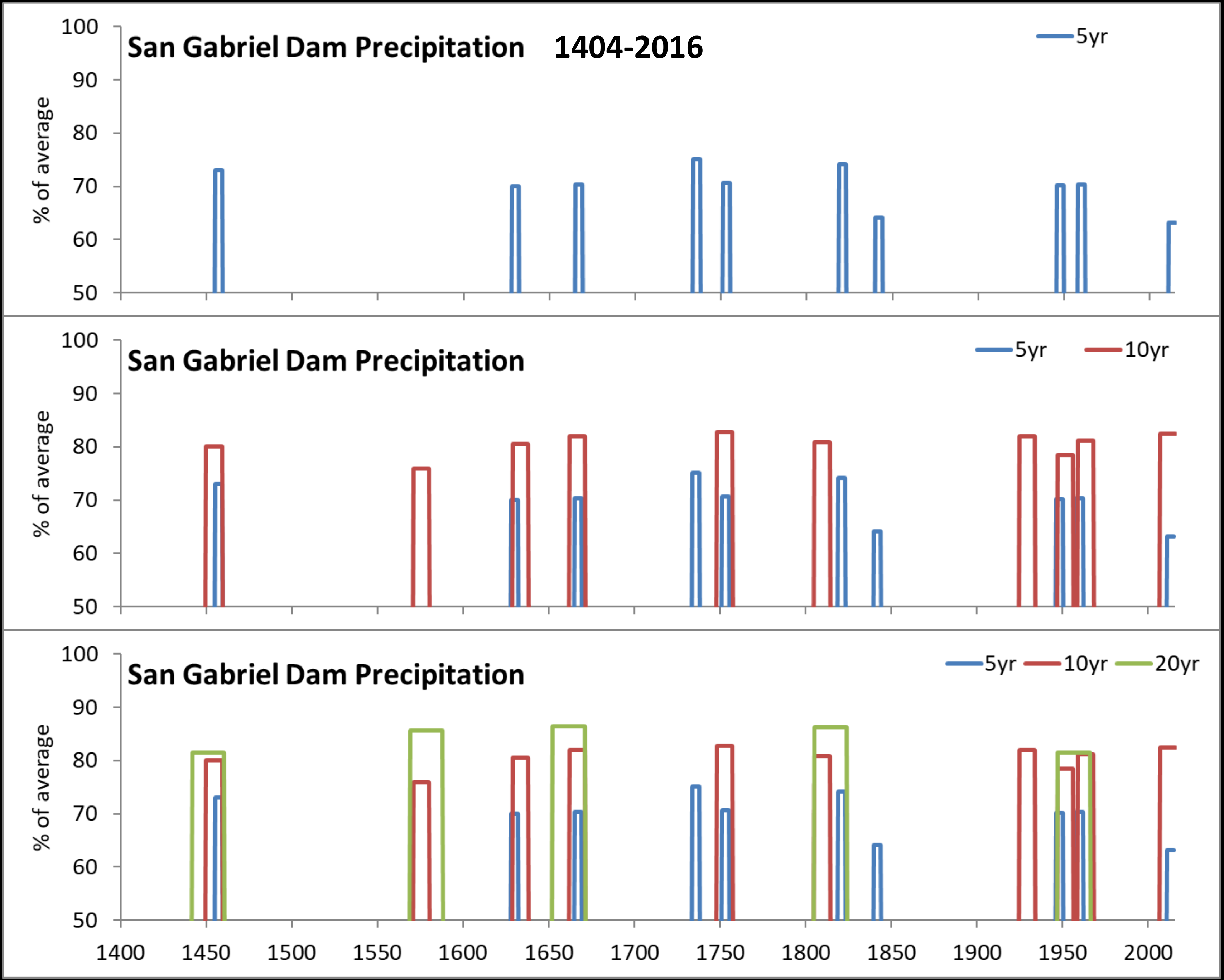
  (non-overlapping)



Driest periods

- 5-year periods
- 10-year periods
- 20-year periods

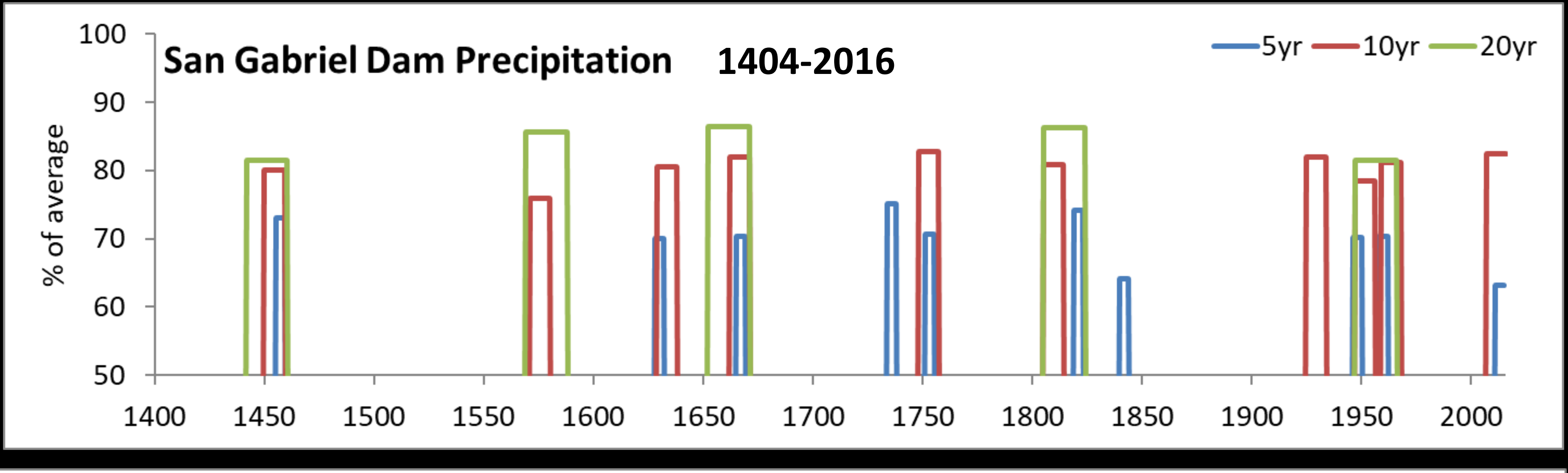
(non-overlapping)

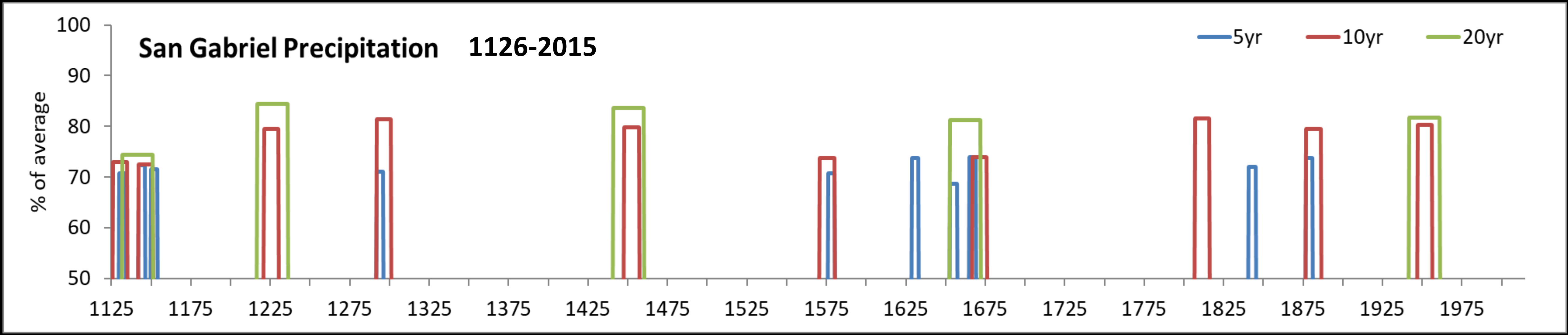


Driest periods

- 5-year periods
- 10-year periods
- 20-year periods

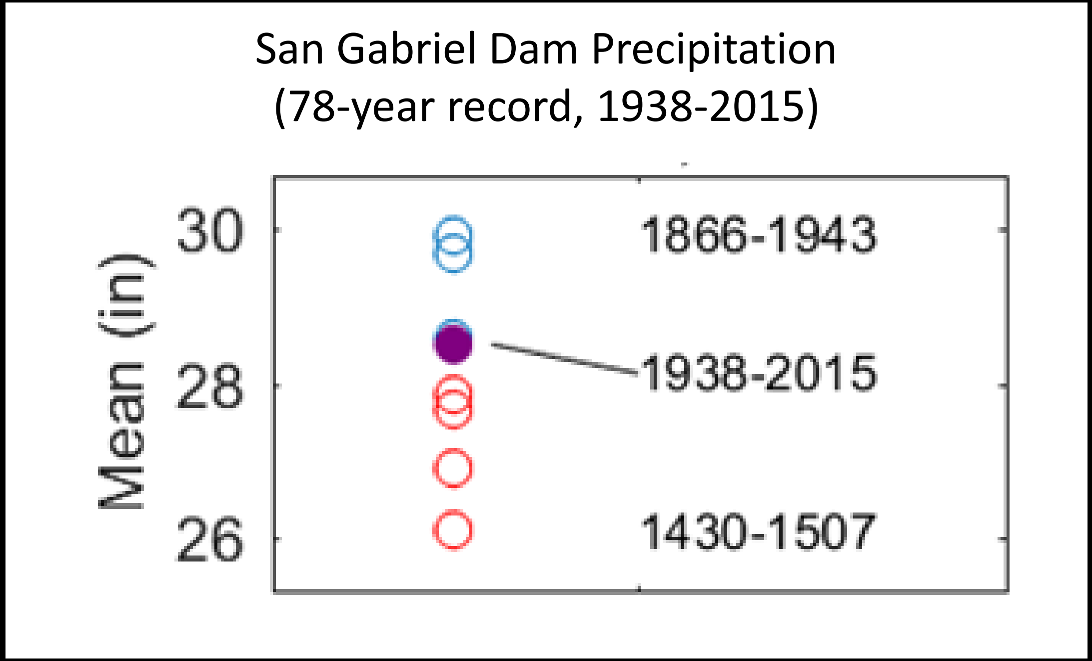
(non-overlapping)



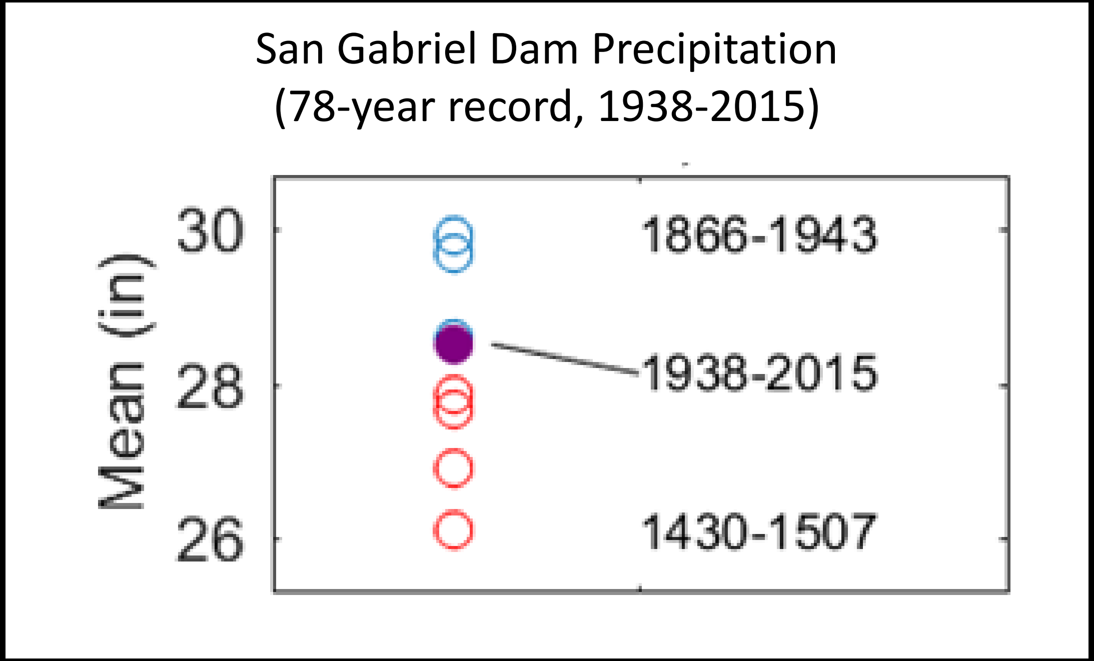


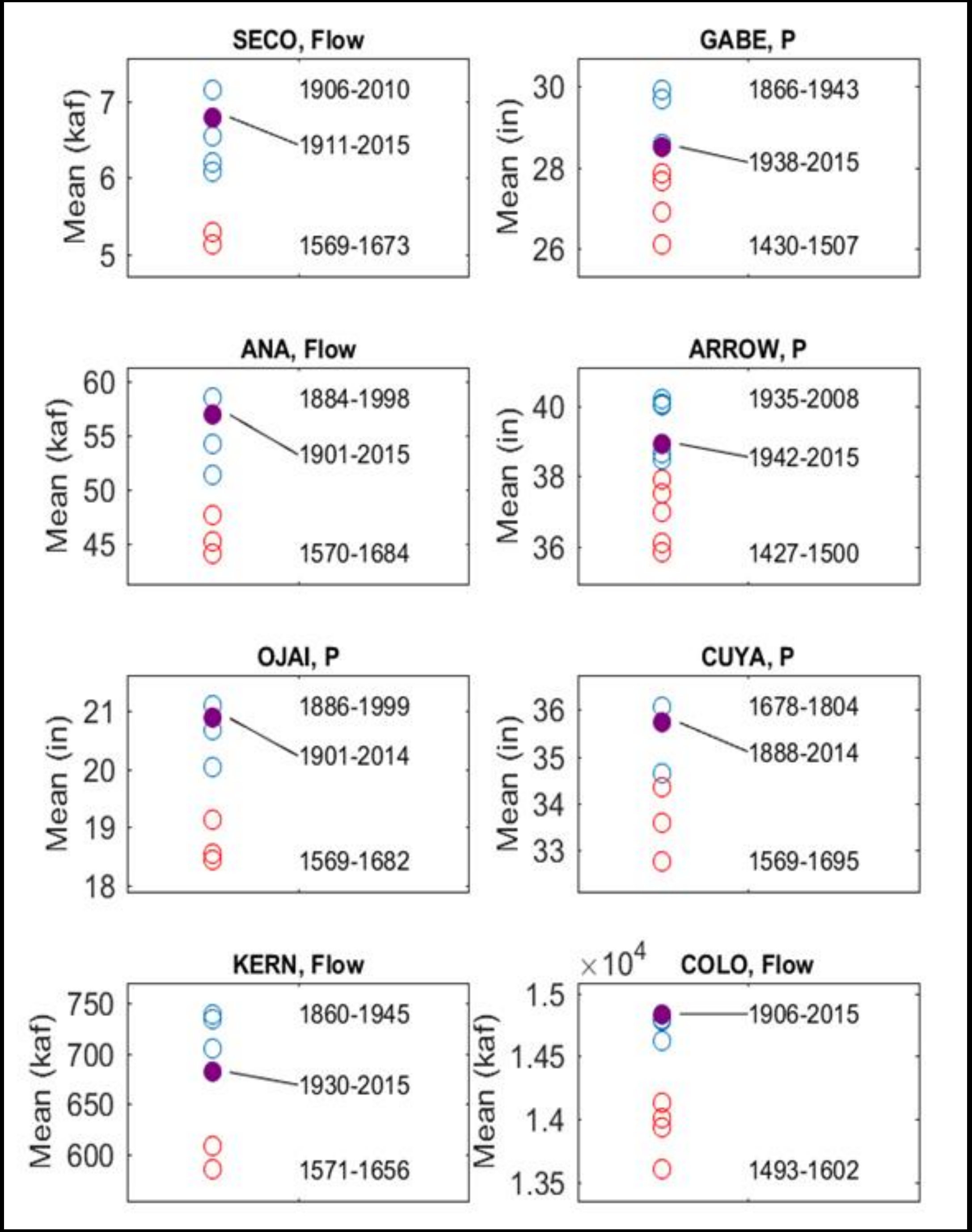
Is the average precipitation or flow over the 20th-21st centuries representative of past centuries?

Gage period average compared to the wettest and driest non-overlapping time periods of the same length, 1404-2016



Gage period average compared to the wettest and driest non-overlapping time periods of the same length, 1404-2016



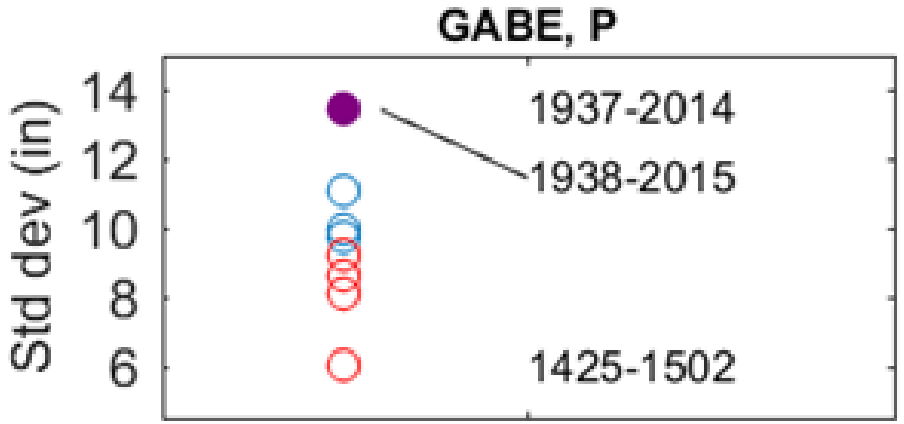


Is the average precipitation or flow over the 20th-21st centuries representative of past centuries?

What about the variability?

Gage period variability compared to the most and least variable non-overlapping time periods of the same length, 1404-2016

San Gabriel Dam Precipitation
(78-year record, 1938-2015)



Gage period variability compared to the most and least variable non-overlapping time periods of the same length, 1404-2016

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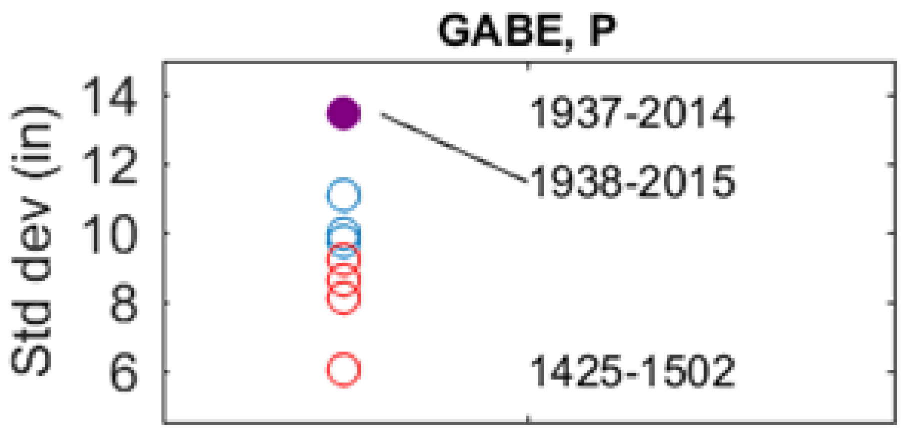
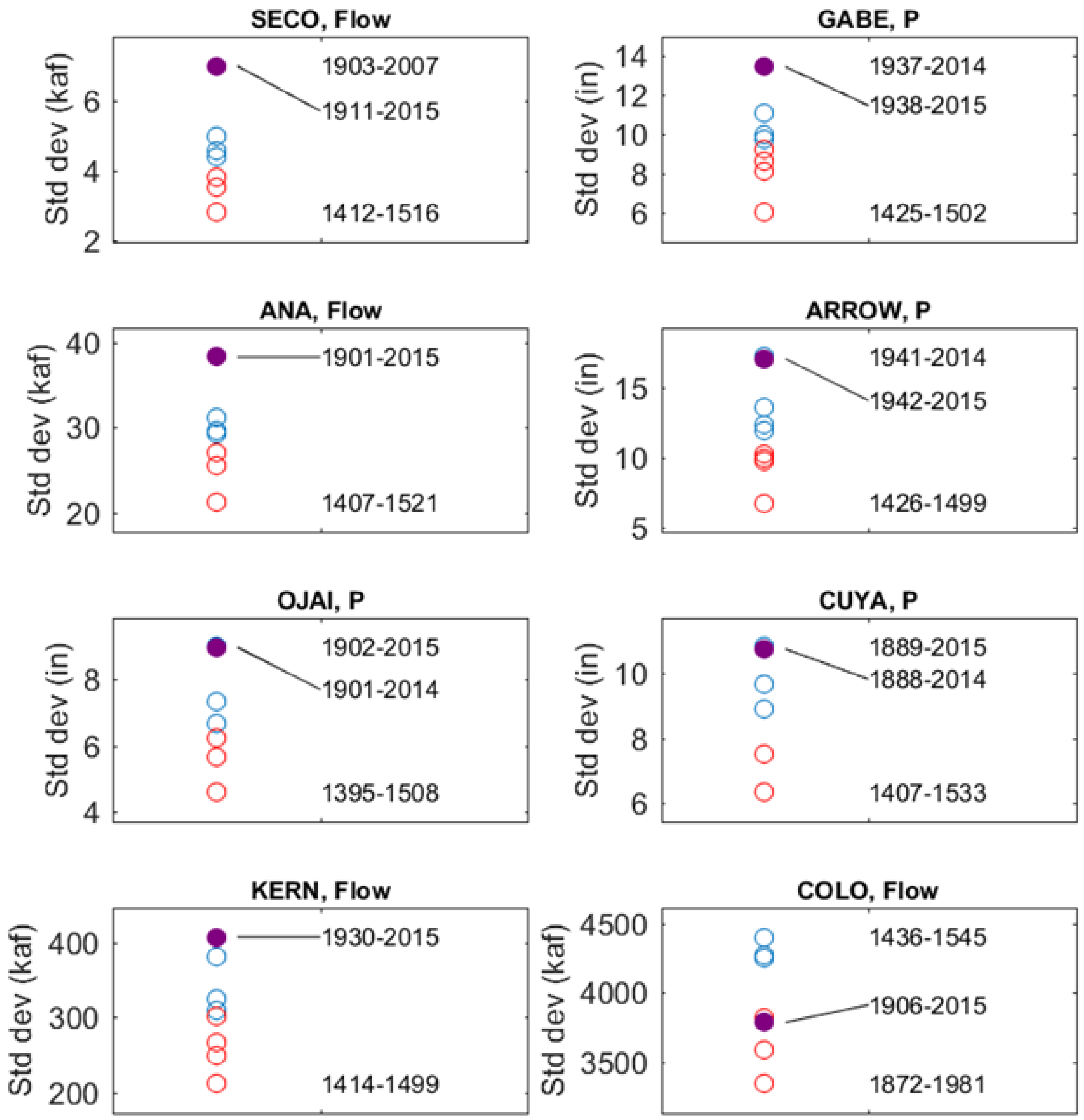
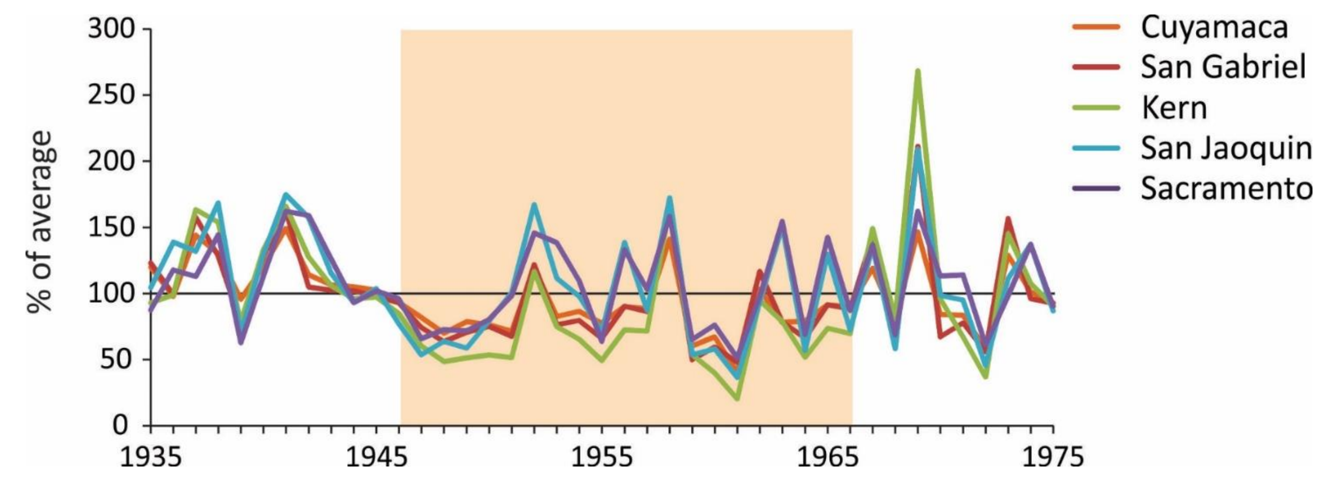




What have been some of the worst droughts across California?

Iconic Droughts of California

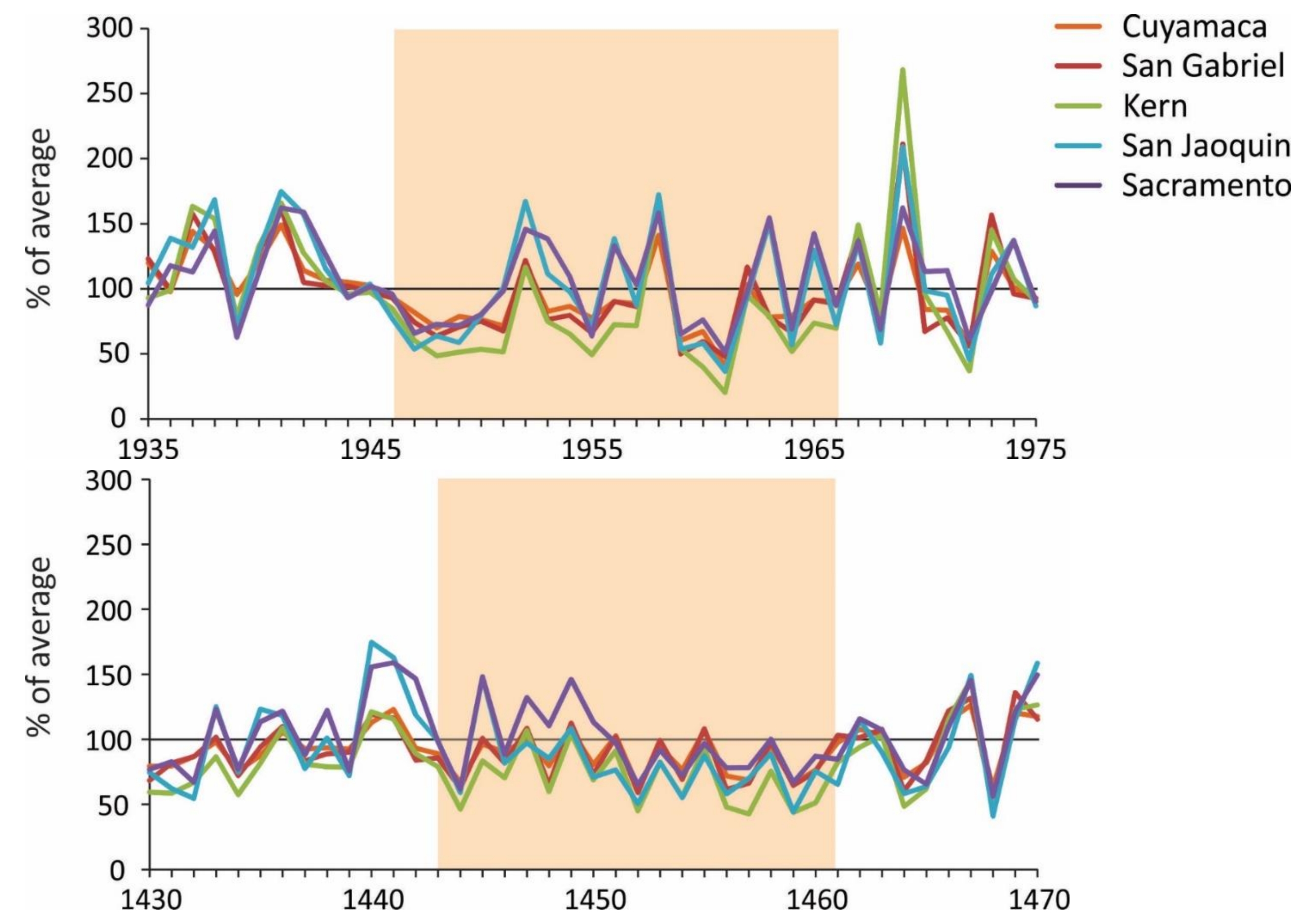
1946-1966



Iconic Droughts of California

1946-1966

1443-1461

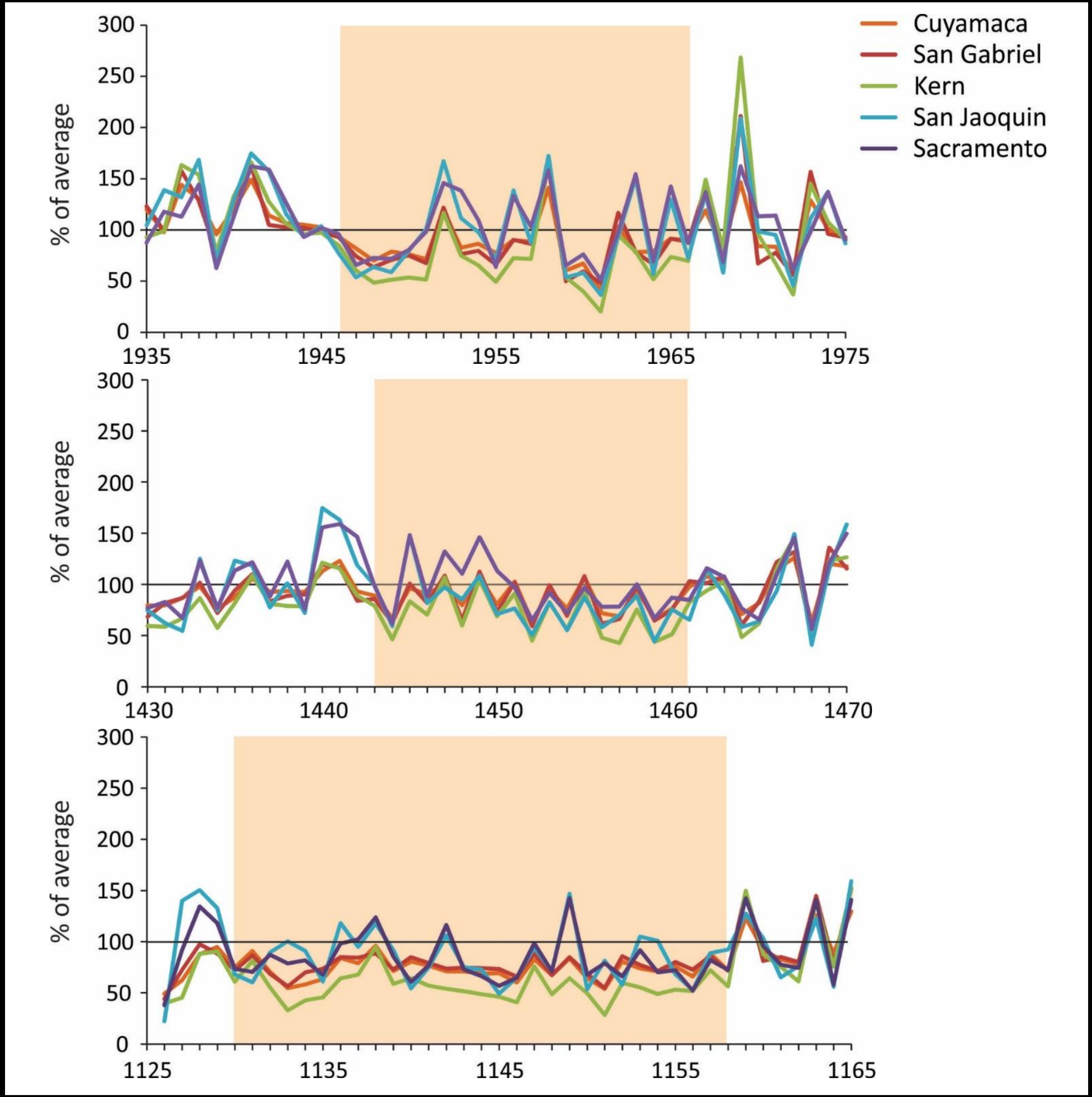


Iconic Droughts of California

1946-1966

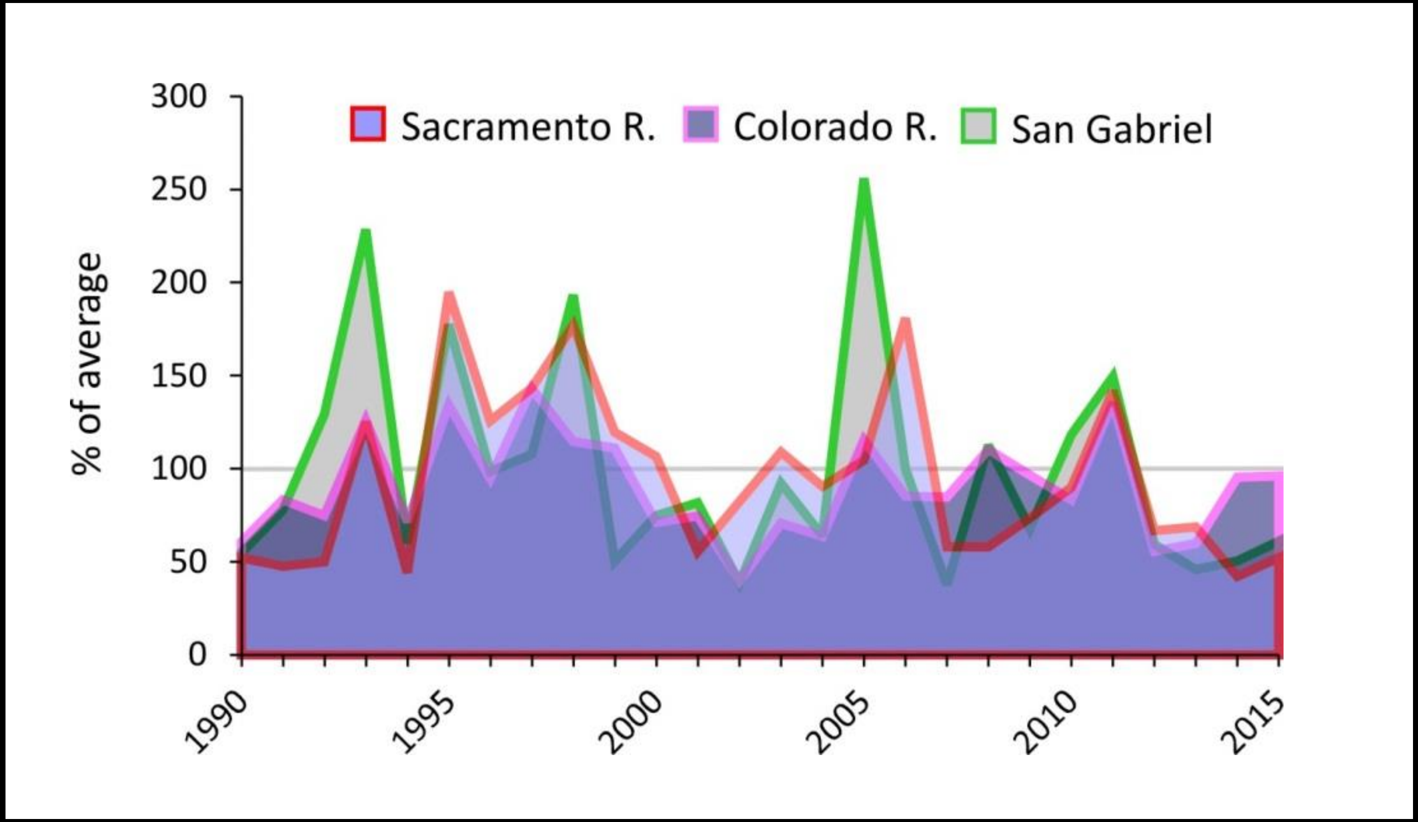
1443-1461

1130-1158

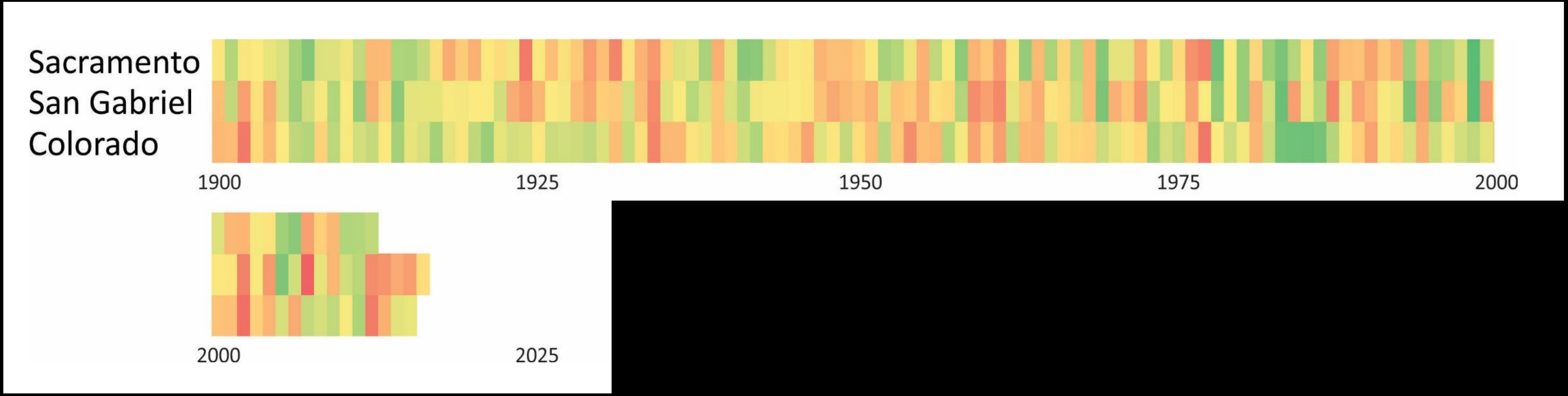


How often does drought impact SoCal, the Sacramento River basin, *and* the upper Colorado River basin?

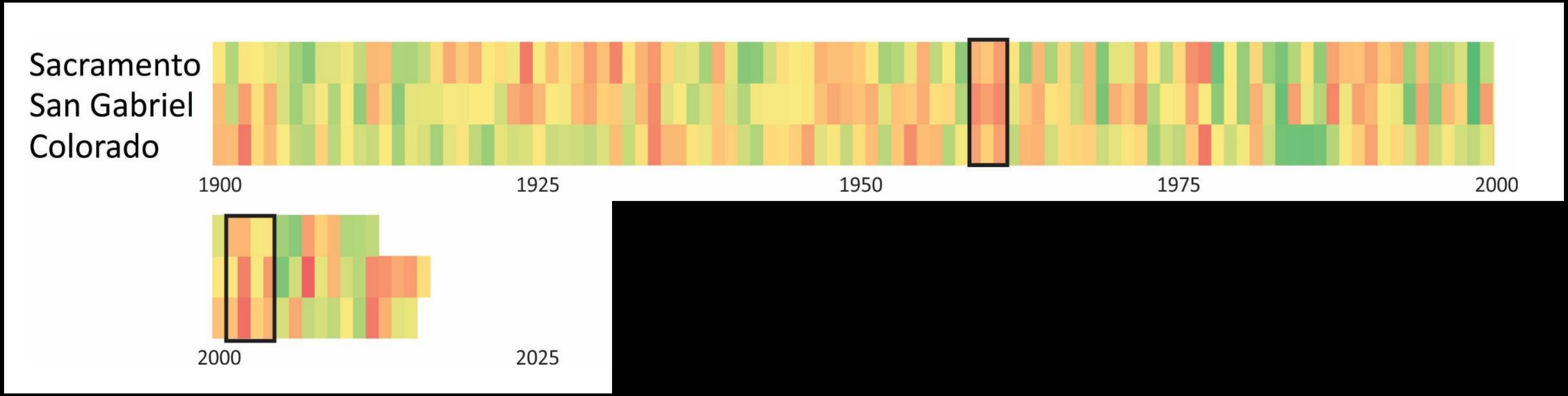
Regional-wide drought since 1999



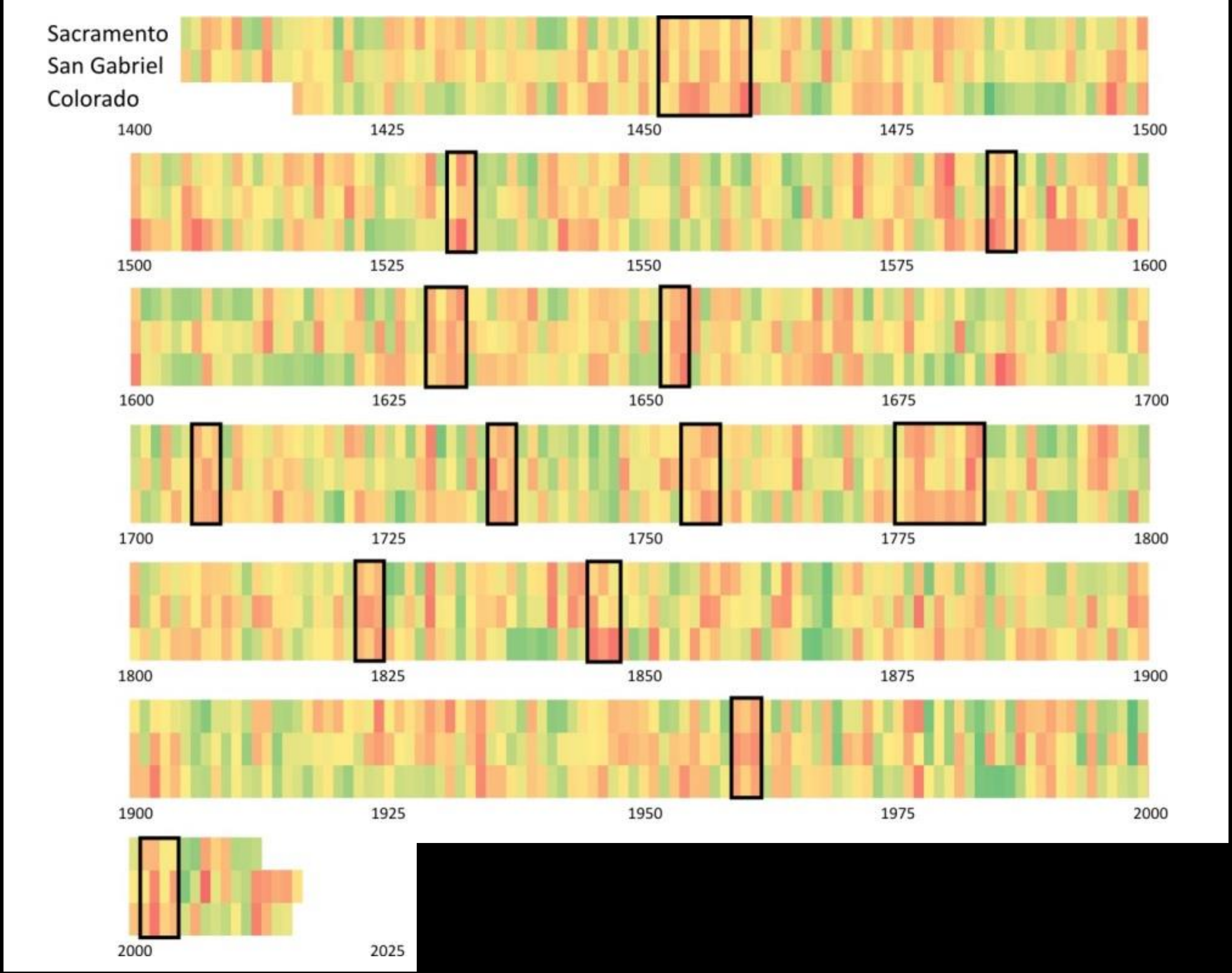
Concurrent drought across 3 regions
20th and 21st centuries



Concurrent drought across 3 regions 20th and 21st centuries



Concurrent drought across 3 regions, 1400s - present



Are reconstructions of past streamflow and precipitation relevant to future planning?

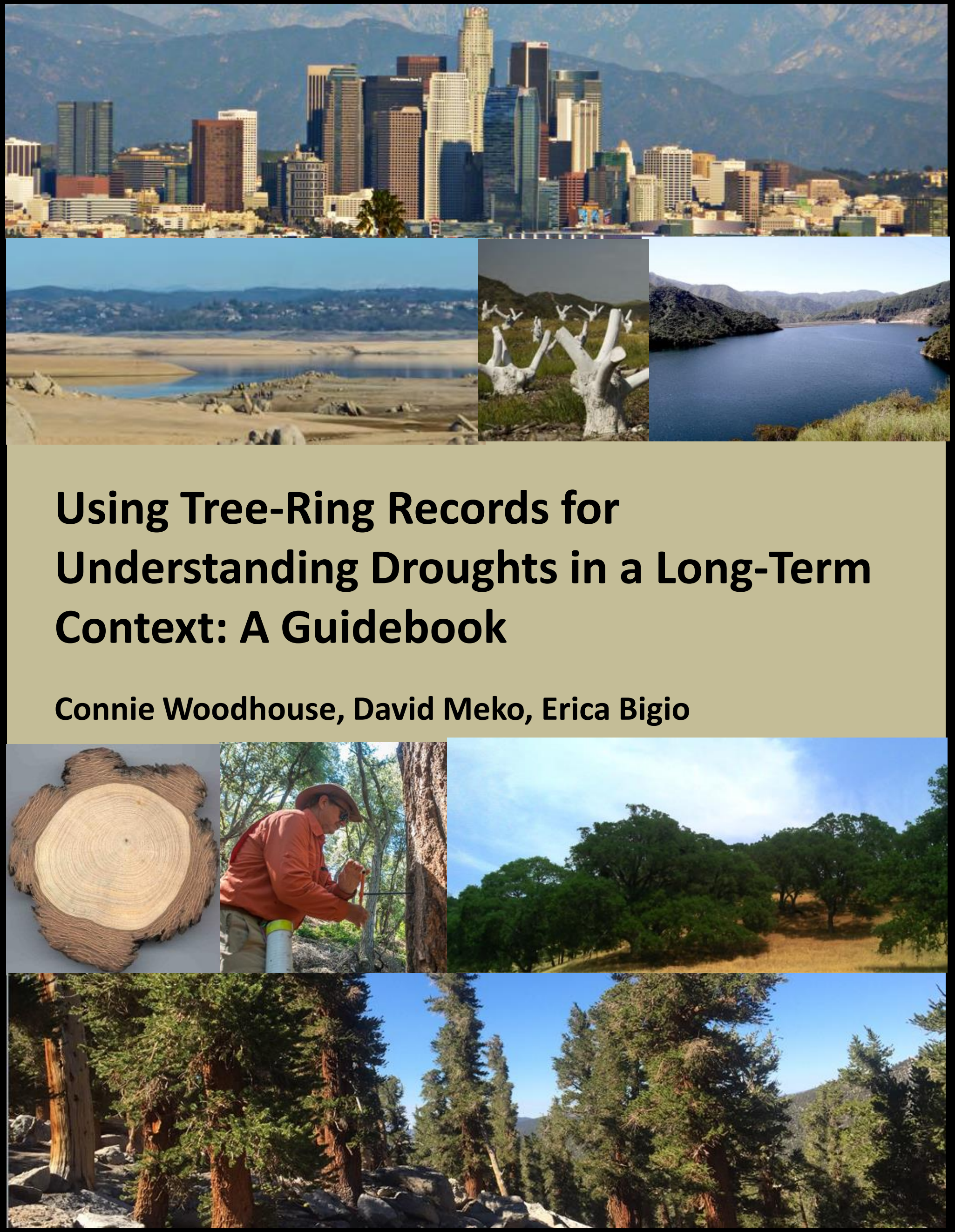
- The climate of the past will not be replicated in the future, but the range of natural climate variability is likely to continue, underlying warming trends.

- Reconstructions of past conditions cannot be used to predict the future, but can be used to guide expectations for future drought.

2 Resources

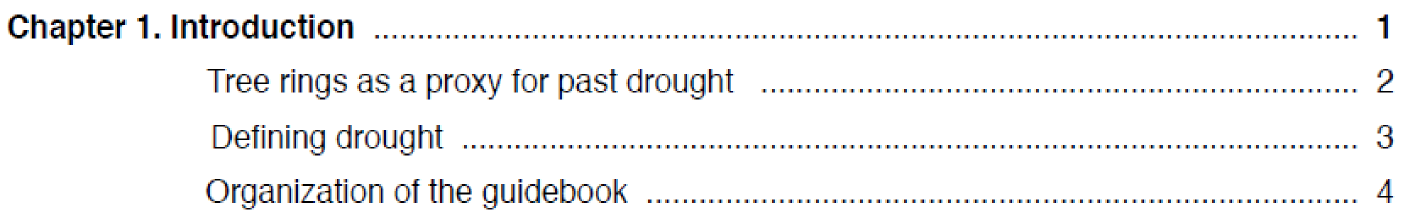
Use of Paleo Reconstructions for Drought Risk Management: A Guidebook for Water Managers

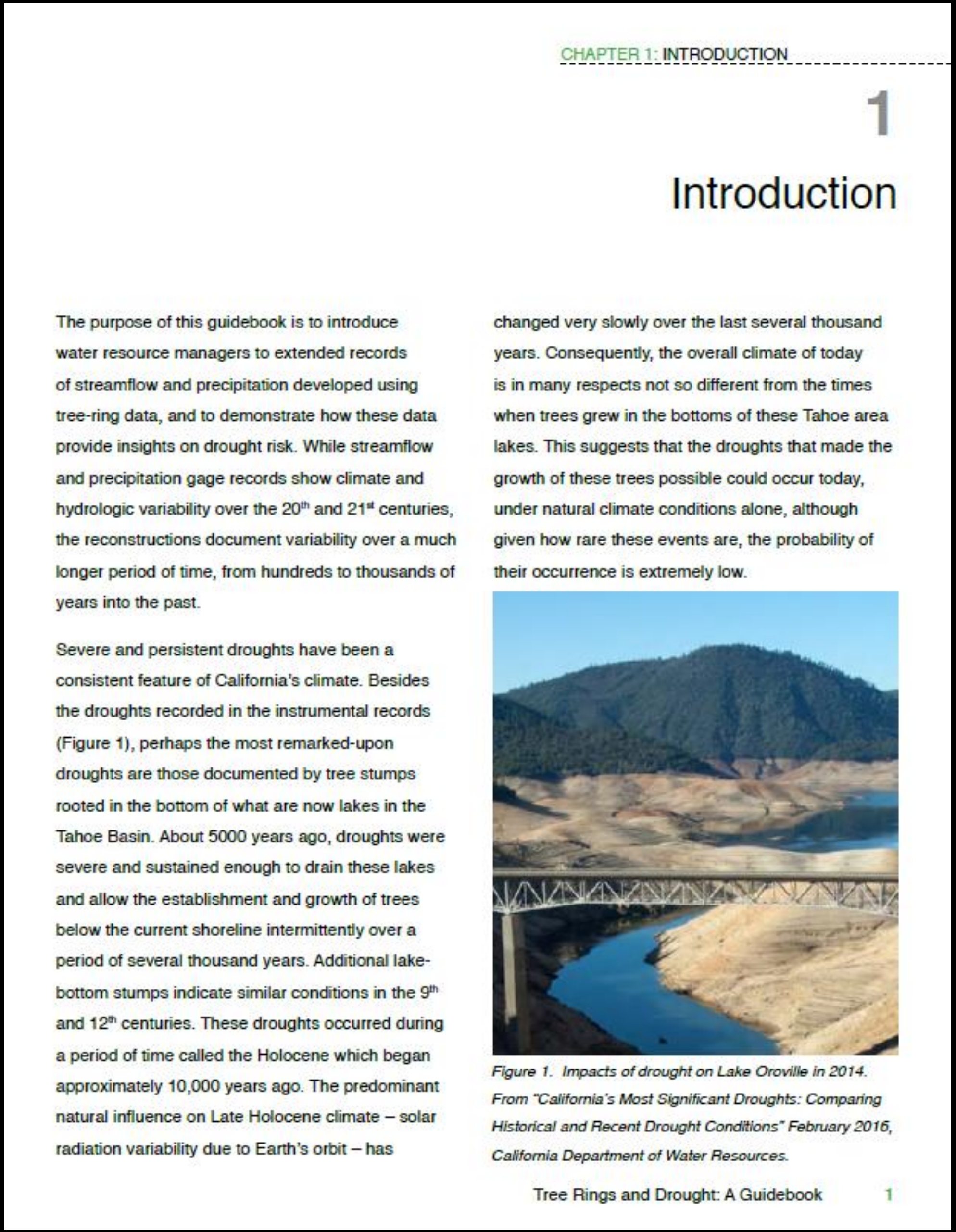
TreeFlow: Streamflow reconstructions from tree rings



Using Tree-Ring Records for Understanding Droughts in a Long-Term Context: A Guidebook

Connie Woodhouse, David Meko, Erica Bigio





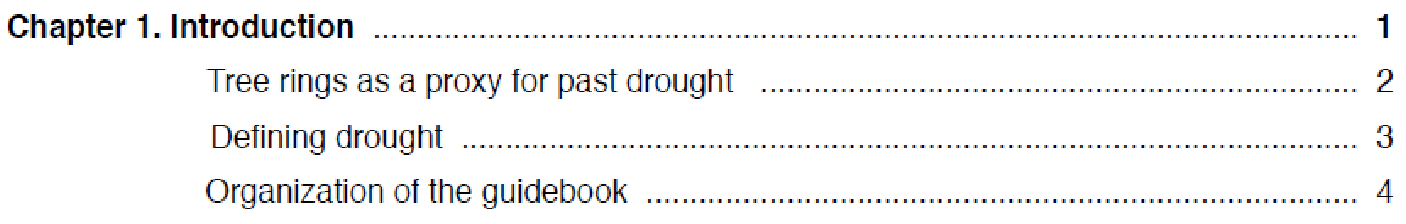
1

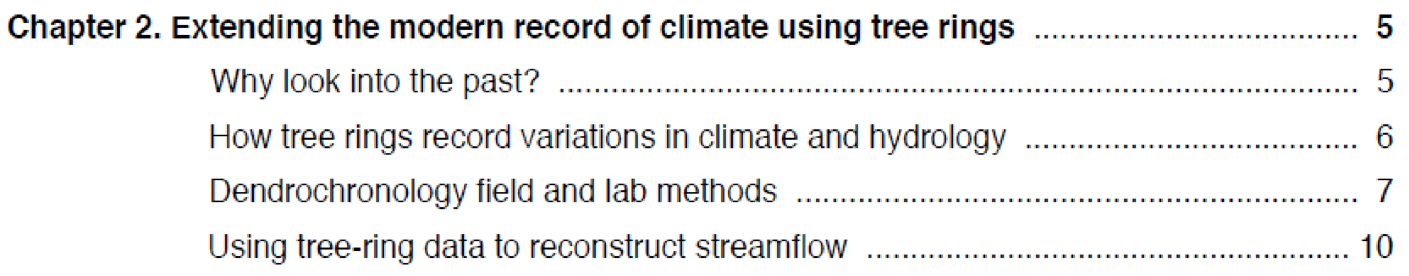
Introduction

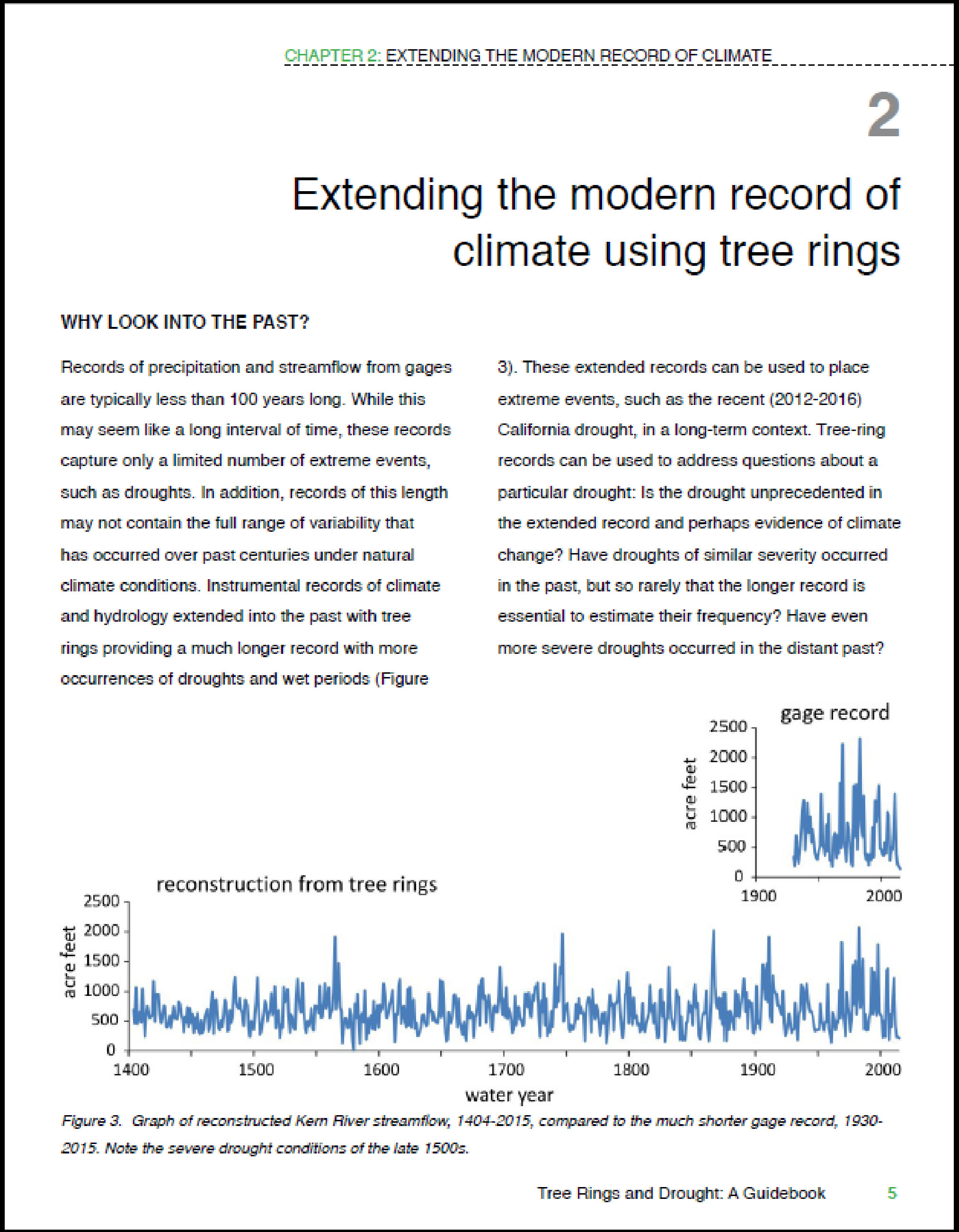
The purpose of this guidebook is to introduce water resource managers to extended records of streamflow and precipitation developed using tree-ring data, and to demonstrate how these data provide insights on drought risk. While streamflow and precipitation gage records show climate and hydrologic variability over the 20th and 21st centuries, the reconstructions document variability over a much longer period of time, from hundreds to thousands of years into the past.

Severe and persistent droughts have been a consistent feature of California's climate. Besides the droughts recorded in the instrumental records (Figure 1), perhaps the most remarked-upon droughts are those documented by tree stumps rooted in the bottom of what are now lakes in the Tahoe Basin. About 5000 years ago, droughts were severe and sustained enough to drain these lakes and allow the establishment and growth of trees below the current shoreline intermittently over a period of several thousand years. Additional lake-bottom stumps indicate similar conditions in the 9th and 12th centuries. These droughts occurred during a period of time called the Holocene which began approximately 10,000 years ago. The predominant natural influence on Late Holocene climate – solar radiation variability due to Earth's orbit – has changed very slowly over the last several thousand years. Consequently, the overall climate of today is in many respects not so different from the times when trees grew in the bottoms of these Tahoe area lakes. This suggests that the droughts that made the growth of these trees possible could occur today, under natural climate conditions alone, although given how rare these events are, the probability of their occurrence is extremely low.

Figure 1. Impacts of drought on Lake Oroville in 2014. From "California's Most Significant Droughts: Comparing Historical and Recent Drought Conditions" February 2016, California Department of Water Resources.







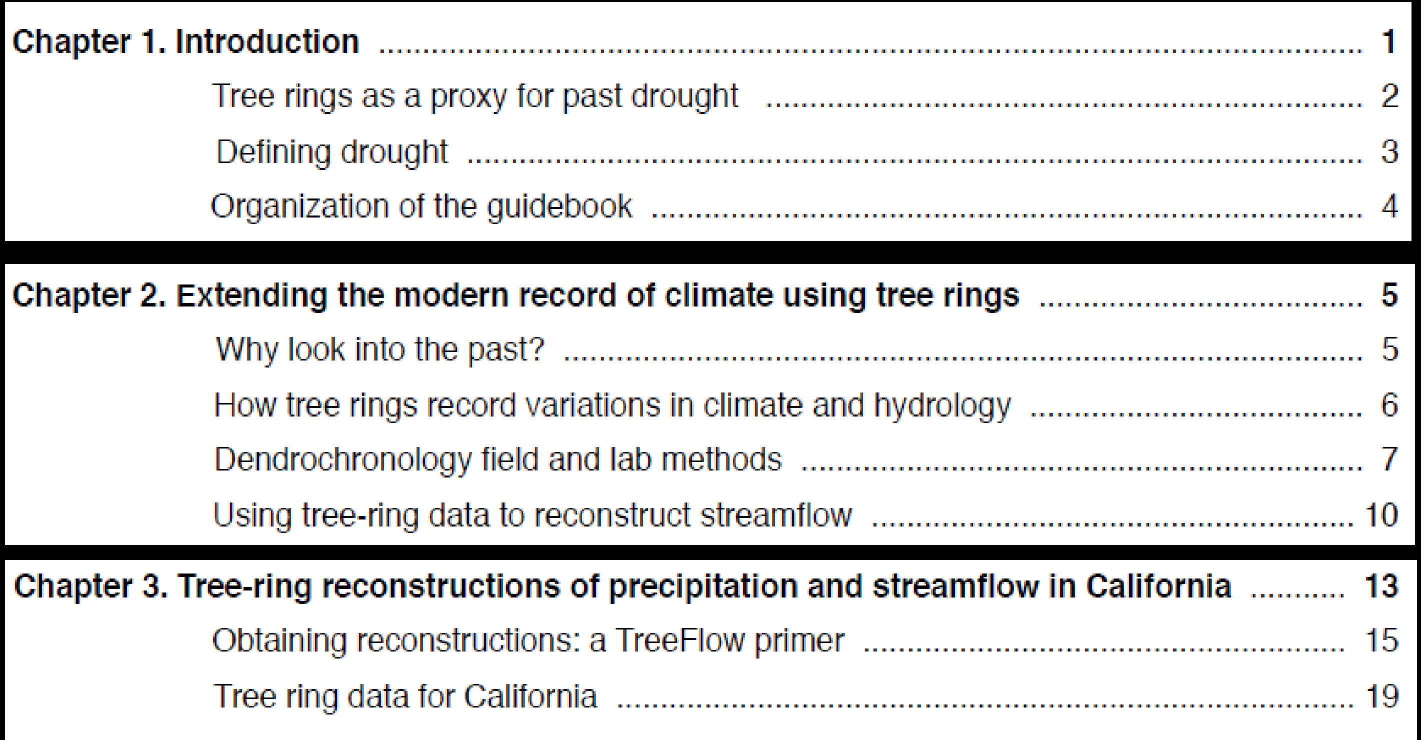
2

Extending the modern record of climate using tree rings

WHY LOOK INTO THE PAST?

Records of precipitation and streamflow from gages are typically less than 100 years long. While this may seem like a long interval of time, these records capture only a limited number of extreme events, such as droughts. In addition, records of this length may not contain the full range of variability that has occurred over past centuries under natural climate conditions. Instrumental records of climate and hydrology extended into the past with tree rings providing a much longer record with more occurrences of droughts and wet periods (Figure 3). These extended records can be used to place extreme events, such as the recent (2012-2016) California drought, in a long-term context. Tree-ring records can be used to address questions about a particular drought: Is the drought unprecedented in the extended record and perhaps evidence of climate change? Have droughts of similar severity occurred in the past, but so rarely that the longer record is essential to estimate their frequency? Have even more severe droughts occurred in the distant past?

Figure 3. Graph of reconstructed Kern River streamflow, 1404-2015, compared to the much shorter gage record, 1930-2015. Note the severe drought conditions of the late 1500s.



3

Tree-ring reconstructions of precipitation and streamflow in California

In California, the main runoff-producing parts of the state are in the north, while the largest proportion of the population is in the south, and main agricultural areas are in the central and southern parts of the state. The most important sources of surface water for much of the state are the Sacramento and San Joaquin River watersheds, and infrastructure has been developed to convey these water resources to the south via the State Water Project's California Aqueduct. Southern California has municipal and industrial water needs, along with significant agricultural water use that result in a demand for water that far exceeds the supply from local sources. Consequently, southern California relies on three major surface water sources from outside the region

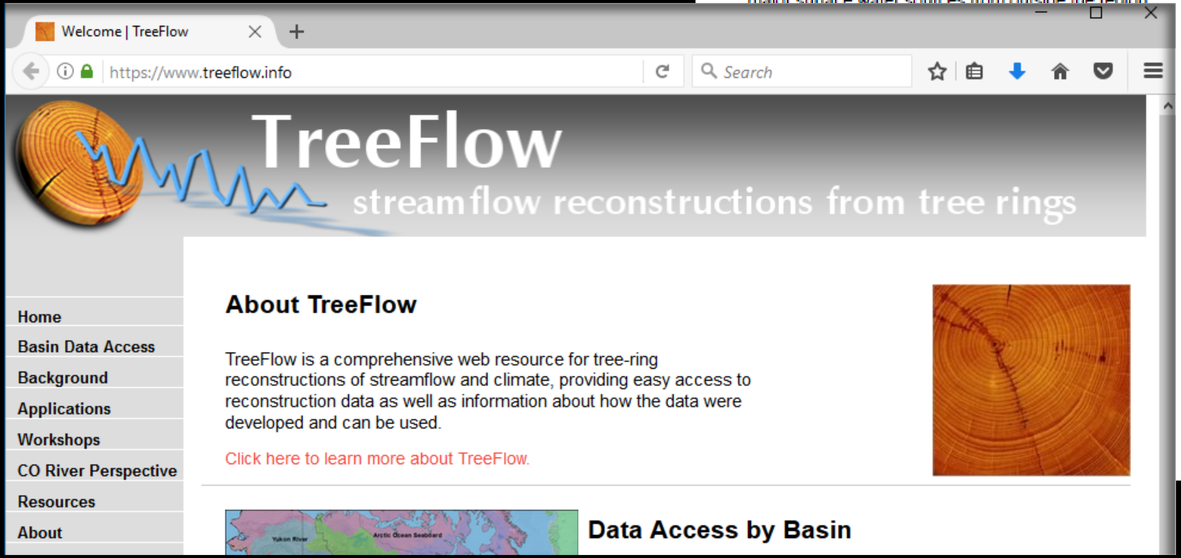
Sacramento River watershed:
- Sacramento River above Bend Bridge
- Feather River inflow to Lake Oroville
- American River inflow to Lake Folsom
- Yuba River at Smartville
- Sacramento River index

Klamath watershed (not in California, but water resources are diverted into California):
- Klamath River at Keno
- Trinity River at Lewiston

San Joaquin River watershed:
- San Joaquin River at Millerton
- Stanislaus River inflow to New Melones Lake
- Tuolumne River inflow to New Don Pedro Reservoir
- Merced River inflow to Lake McClure
- San Joaquin River index

Southern California/Sierra Nevada watersheds:
- Arroyo Seco, near Pasadena, in the Los Angeles River basin
- Santa Ana River near Mentone
- Kern River below Lake Isabella, draining the southern Sierra Nevada

Southern California (water year precipitation):
- Ojai, in the coastal region near Santa Barbara
- San Gabriel Dam, in the San Gabriel River basin
- Lake Arrowhead, near the Mojave River headwaters
- Cuyamaca, east of San Diego

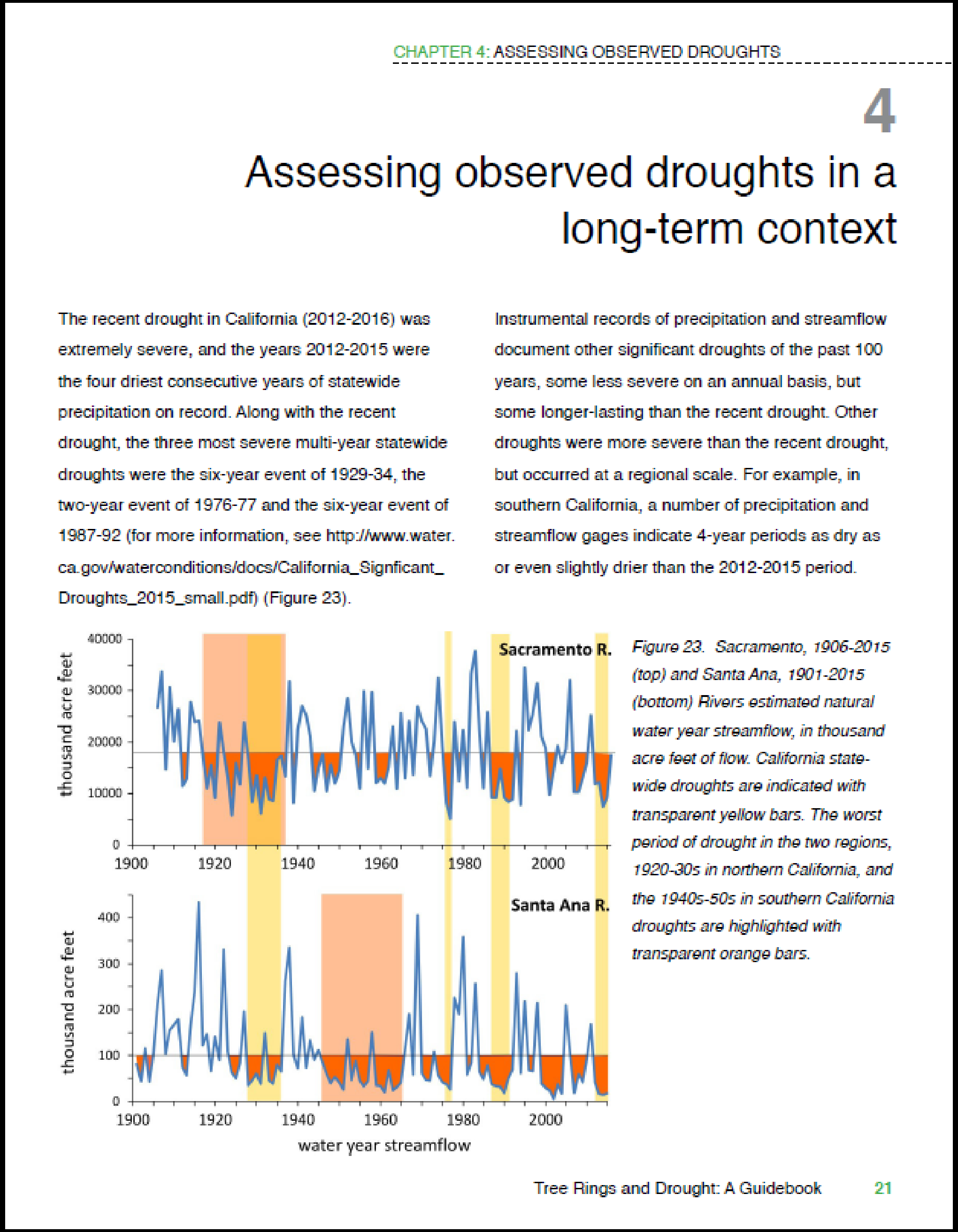


About TreeFlow

TreeFlow is a comprehensive web resource for tree-ring reconstructions of streamflow and climate, providing easy access to reconstruction data as well as information about how the data were developed and can be used.

Click here to learn more about TreeFlow.

Data Access by Basin



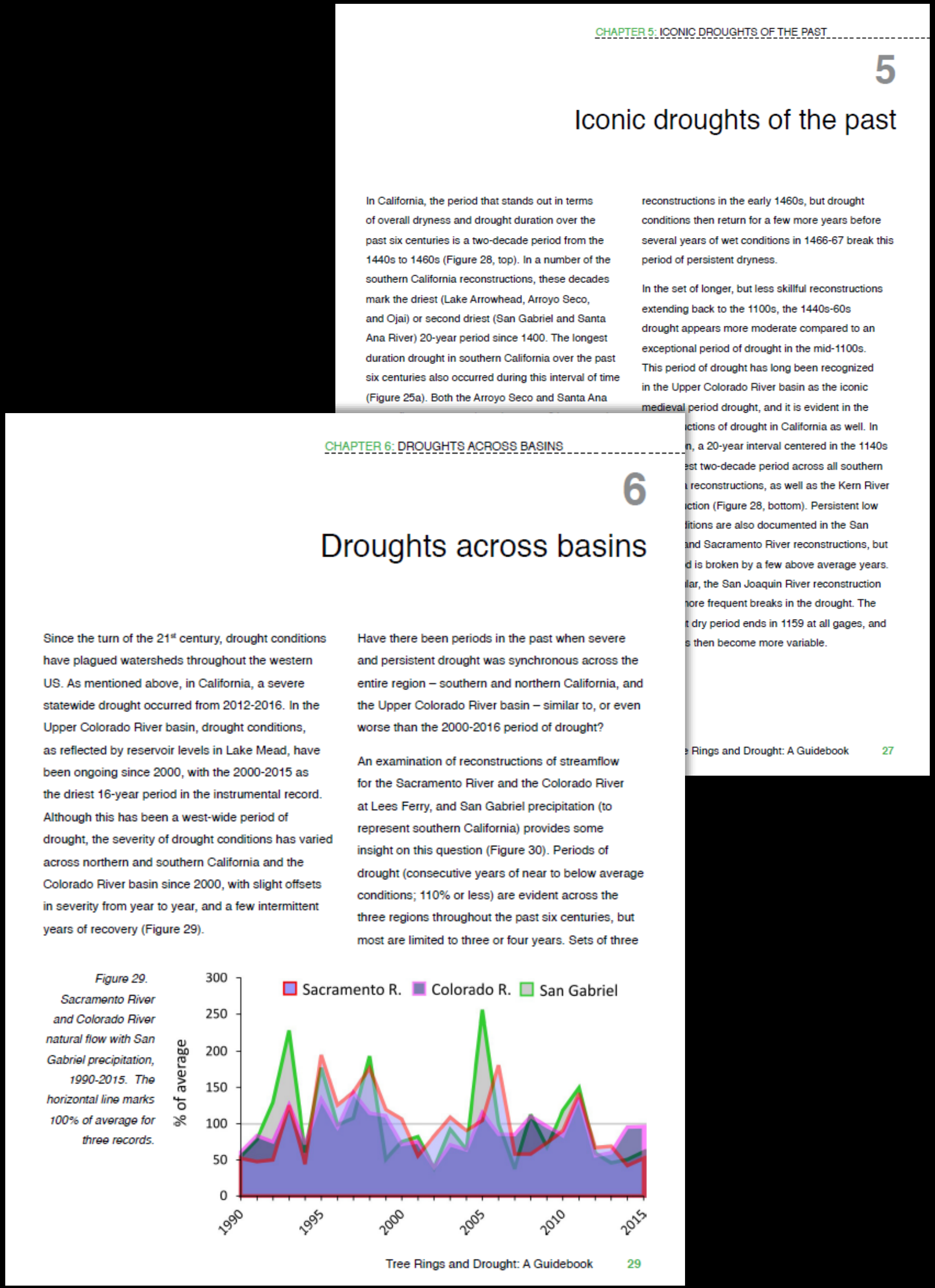
4

Assessing observed droughts in a long-term context

The recent drought in California (2012-2016) was extremely severe, and the years 2012-2015 were the four driest consecutive years of statewide precipitation on record. Along with the recent drought, the three most severe multi-year statewide droughts were the six-year event of 1929-34, the two-year event of 1976-77 and the six-year event of 1987-92 (for more information, see http://www.water.ca.gov/waterconditions/docs/California_Signficant_Droughts_2015_small.pdf) (Figure 23).

Instrumental records of precipitation and streamflow document other significant droughts of the past 100 years, some less severe on an annual basis, but some longer-lasting than the recent drought. Other droughts were more severe than the recent drought, but occurred at a regional scale. For example, in southern California, a number of precipitation and streamflow gages indicate 4-year periods as dry as or even slightly drier than the 2012-2015 period.

Figure 23. Sacramento, 1906-2015 (top) and Santa Ana, 1901-2015 (bottom) Rivers estimated natural water year streamflow, in thousand acre feet of flow. California state-wide droughts are indicated with transparent yellow bars. The worst period of drought in the two regions, 1920-30s in northern California, and the 1940s-50s in southern California droughts are highlighted with transparent orange bars.



CHAPTER 5: ICONIC DROUGHTS OF THE PAST

5

Iconic droughts of the past

In California, the period that stands out in terms of overall dryness and drought duration over the past six centuries is a two-decade period from the 1440s to 1460s (Figure 28, top). In a number of the southern California reconstructions, these decades mark the driest (Lake Arrowhead, Arroyo Seco, and Ojai) or second driest (San Gabriel and Santa Ana River) 20-year period since 1400. The longest duration drought in southern California over the past six centuries also occurred during this interval of time (Figure 25a). Both the Arroyo Seco and Santa Ana

reconstructions in the early 1460s, but drought conditions then return for a few more years before several years of wet conditions in 1466-67 break this period of persistent dryness.

In the set of longer, but less skillful reconstructions extending back to the 1100s, the 1440s-60s drought appears more moderate compared to an exceptional period of drought in the mid-1100s. This period of drought has long been recognized in the Upper Colorado River basin as the iconic medieval period drought, and it is evident in the
ctions of drought in California as well. In
n, a 20-year interval centered in the 1140s
est two-decade period across all southern
reconstructions, as well as the Kern River
ction (Figure 28, bottom). Persistent low
litions are also documented in the San
and Sacramento River reconstructions, but
d is broken by a few above average years.
lar, the San Joaquin River reconstruction
ore frequent breaks in the drought. The
t dry period ends in 1159 at all gages, and
s then become more variable.

e Rings and Drought: A Guidebook 27

CHAPTER 6: DROUGHTS ACROSS BASINS

6

Droughts across basins

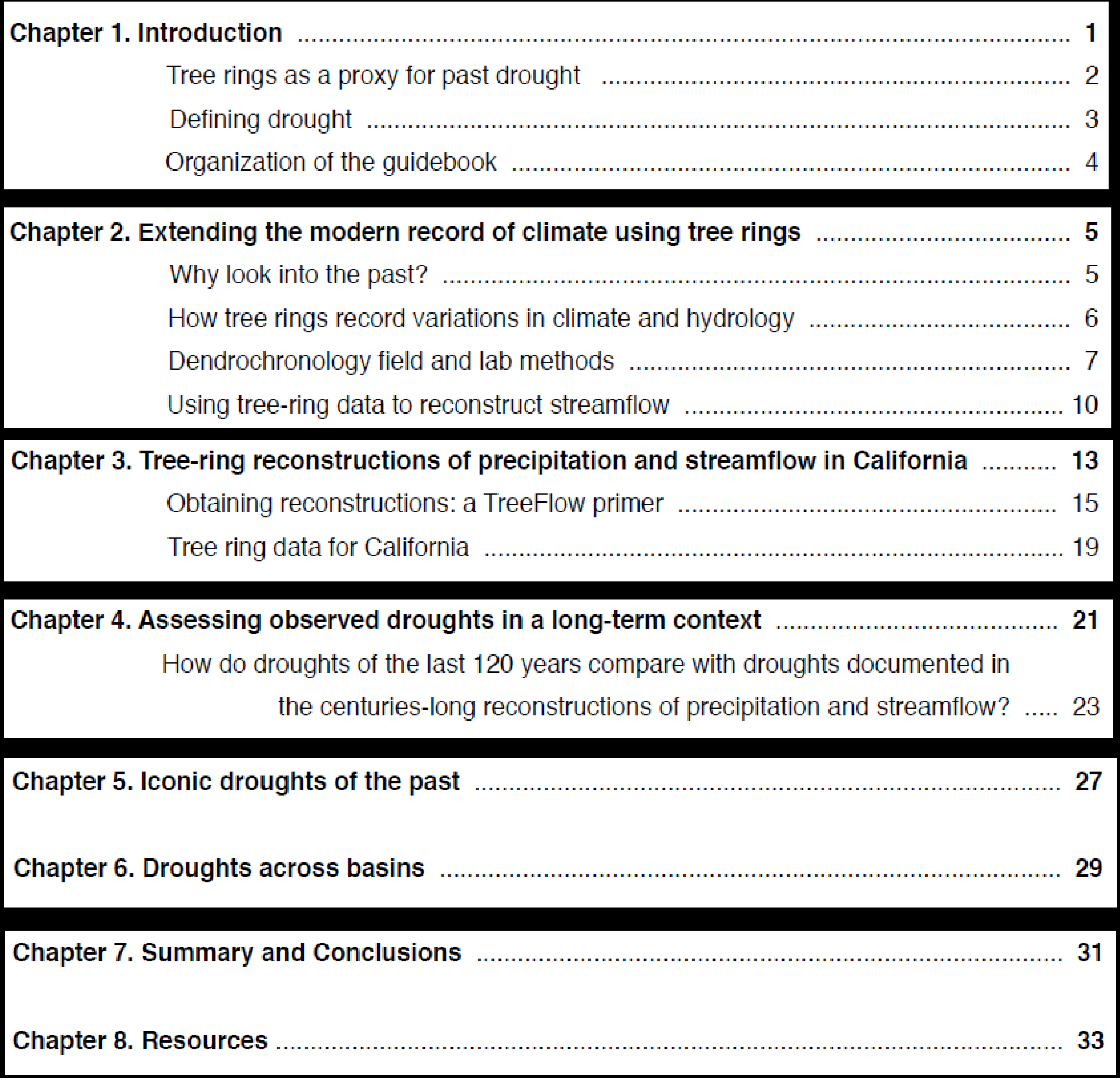
Since the turn of the 21^{st} century, drought conditions have plagued watersheds throughout the western US. As mentioned above, in California, a severe statewide drought occurred from 2012-2016. In the Upper Colorado River basin, drought conditions, as reflected by reservoir levels in Lake Mead, have been ongoing since 2000, with the 2000-2015 as the driest 16-year period in the instrumental record. Although this has been a west-wide period of drought, the severity of drought conditions has varied across northern and southern California and the Colorado River basin since 2000, with slight offsets in severity from year to year, and a few intermittent years of recovery (Figure 29).

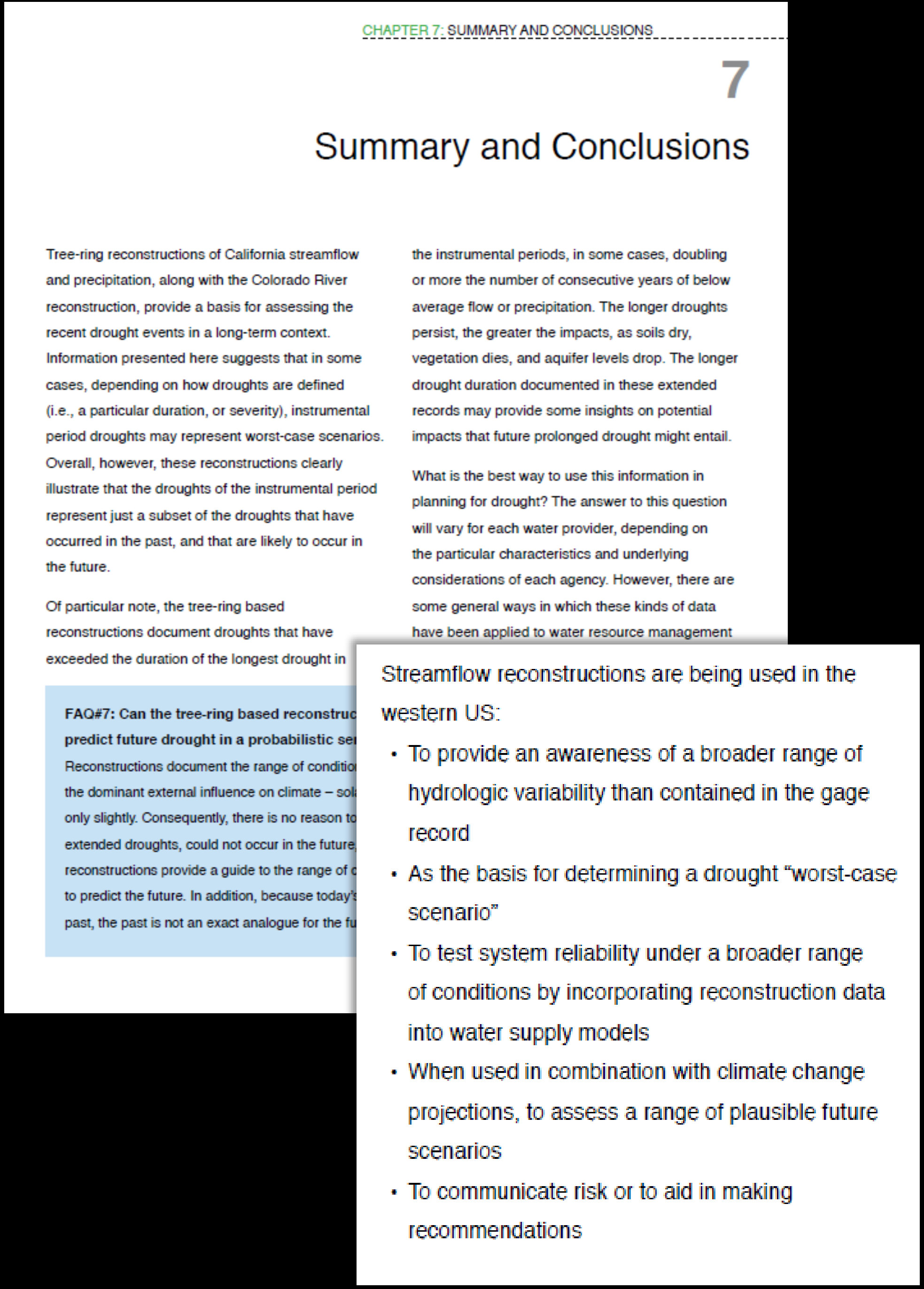
Have there been periods in the past when severe and persistent drought was synchronous across the entire region – southern and northern California, and the Upper Colorado River basin – similar to, or even worse than the 2000-2016 period of drought?

An examination of reconstructions of streamflow for the Sacramento River and the Colorado River at Lees Ferry, and San Gabriel precipitation (to represent southern California) provides some insight on this question (Figure 30). Periods of drought (consecutive years of near to below average conditions; 110% or less) are evident across the three regions throughout the past six centuries, but most are limited to three or four years. Sets of three

Figure 29. Sacramento River and Colorado River natural flow with San Gabriel precipitation, 1990-2015. The horizontal line marks 100% of average for three records.

Tree Rings and Drought: A Guidebook 29





CHAPTER 7: SUMMARY AND CONCLUSIONS

7

Summary and Conclusions

Tree-ring reconstructions of California streamflow and precipitation, along with the Colorado River reconstruction, provide a basis for assessing the recent drought events in a long-term context. Information presented here suggests that in some cases, depending on how droughts are defined (i.e., a particular duration, or severity), instrumental period droughts may represent worst-case scenarios. Overall, however, these reconstructions clearly illustrate that the droughts of the instrumental period represent just a subset of the droughts that have occurred in the past, and that are likely to occur in the future.

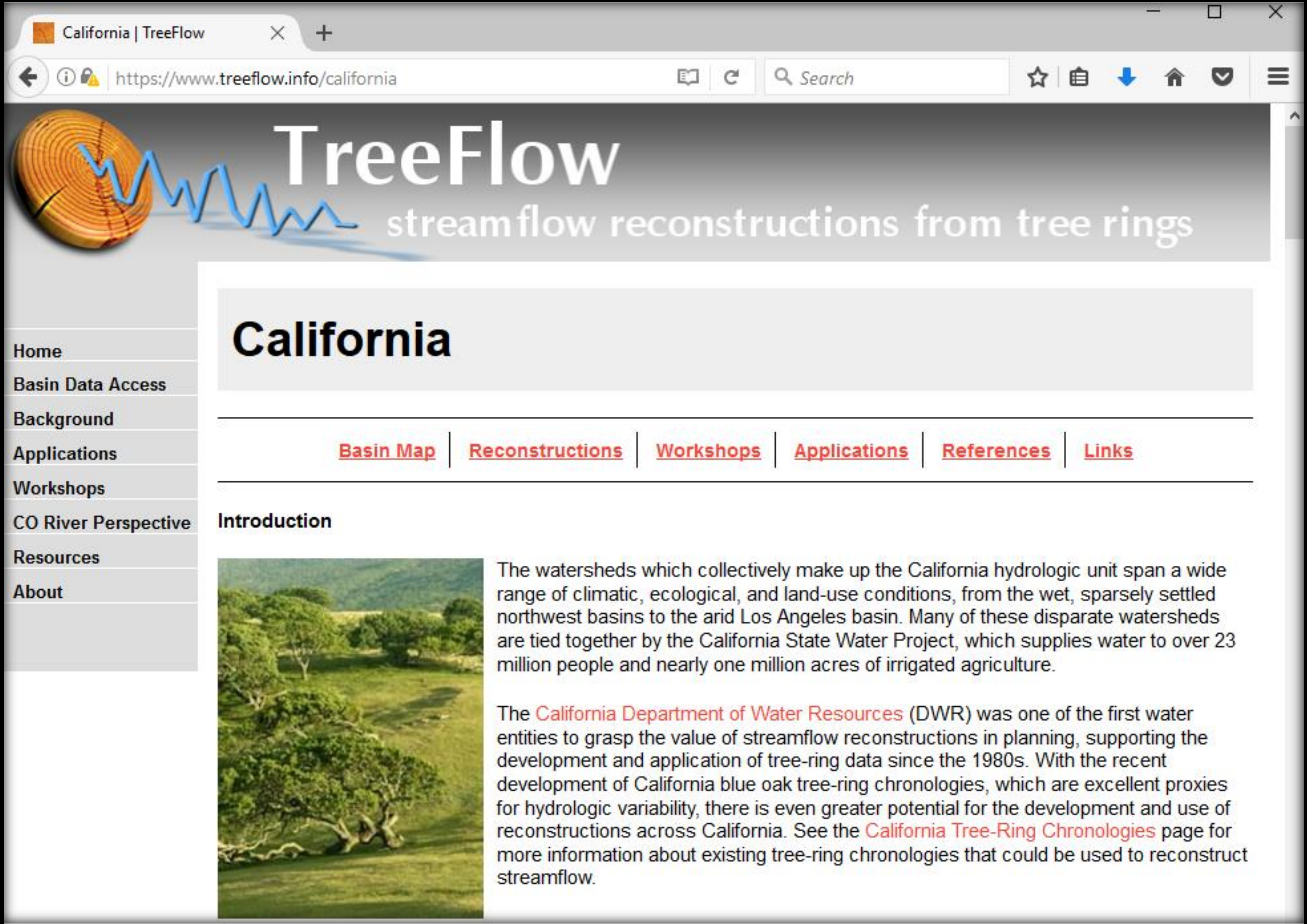
Of particular note, the tree-ring based reconstructions document droughts that have exceeded the duration of the longest drought in the instrumental periods, in some cases, doubling or more the number of consecutive years of below average flow or precipitation. The longer droughts persist, the greater the impacts, as soils dry, vegetation dies, and aquifer levels drop. The longer drought duration documented in these extended records may provide some insights on potential impacts that future prolonged drought might entail.

What is the best way to use this information in planning for drought? The answer to this question will vary for each water provider, depending on the particular characteristics and underlying considerations of each agency. However, there are some general ways in which these kinds of data have been applied to water resource management

FAQ#7: Can the tree-ring based reconstruc
predict future drought in a probabilistic se
Reconstructions document the range of conditio
the dominant external influence on climate – sol
only slightly. Consequently, there is no reason to
extended droughts, could not occur in the future
reconstructions provide a guide to the range of c
to predict the future. In addition, because today'
past, the past is not an exact analogue for the fu

Streamflow reconstructions are being used in the western US:

- To provide an awareness of a broader range of hydrologic variability than contained in the gage record
- As the basis for determining a drought "worst-case scenario"
- To test system reliability under a broader range of conditions by incorporating reconstruction data into water supply models
- When used in combination with climate change projections, to assess a range of plausible future scenarios
- To communicate risk or to aid in making recommendations

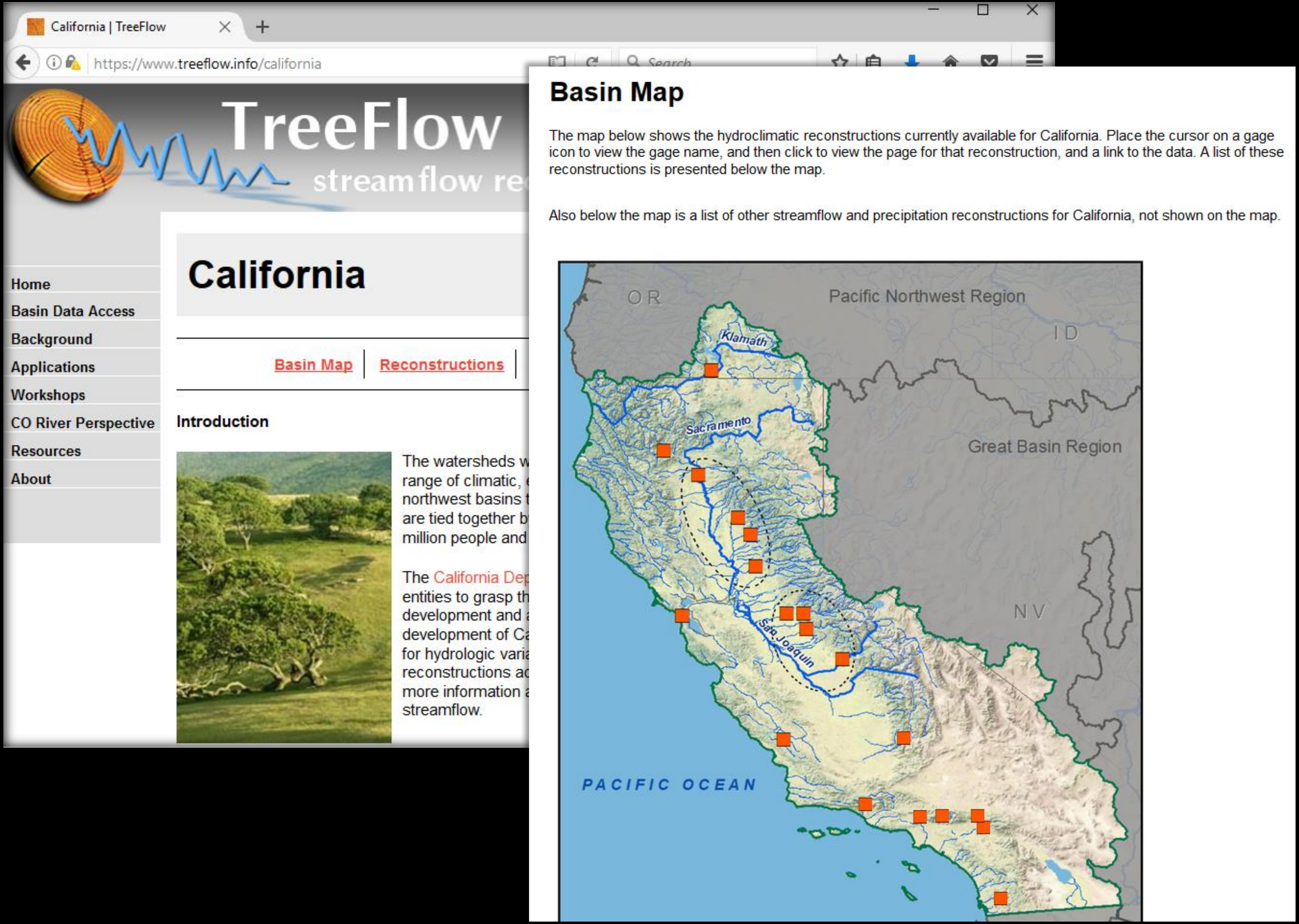


California

Introduction

The watersheds which collectively make up the California hydrologic unit span a wide range of climatic, ecological, and land-use conditions, from the wet, sparsely settled northwest basins to the arid Los Angeles basin. Many of these disparate watersheds are tied together by the California State Water Project, which supplies water to over 23 million people and nearly one million acres of irrigated agriculture.

The California Department of Water Resources (DWR) was one of the first water entities to grasp the value of streamflow reconstructions in planning, supporting the development and application of tree-ring data since the 1980s. With the recent development of California blue oak tree-ring chronologies, which are excellent proxies for hydrologic variability, there is even greater potential for the development and use of reconstructions across California. See the California Tree-Ring Chronologies page for more information about existing tree-ring chronologies that could be used to reconstruct streamflow.



California

Introduction

The watersheds w
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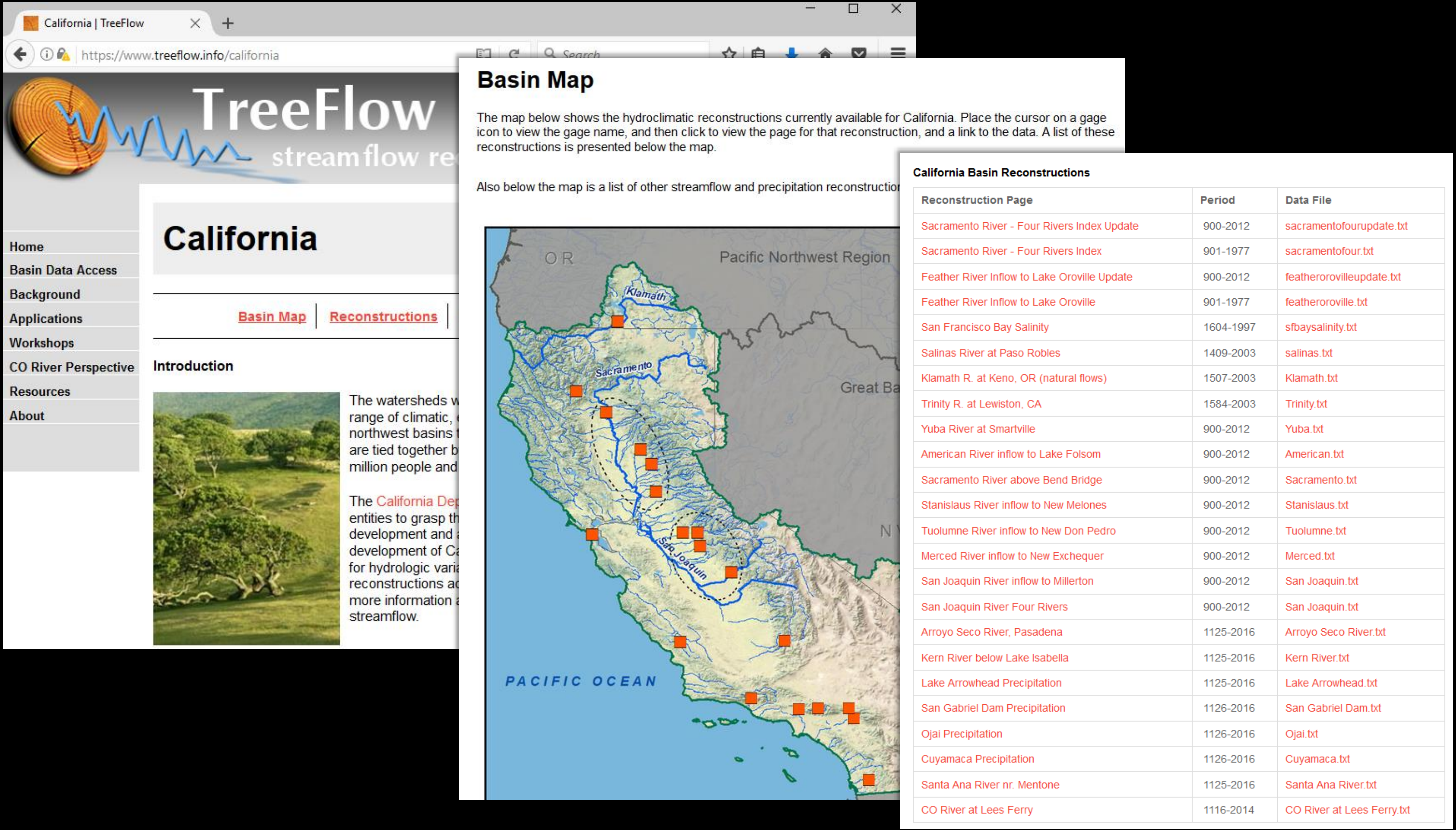
streamflow.

Basin Map

The map below shows the hydroclimatic reconstructions currently available for California. Place the cursor on a gage icon to view the gage name, and then click to view the page for that reconstruction, and a link to the data. A list of these reconstructions is presented below the map.

Also below the map is a list of other streamflow and precipitation reconstructions for California, not shown on the map.



California

Basin Map | Reconstructions

Introduction

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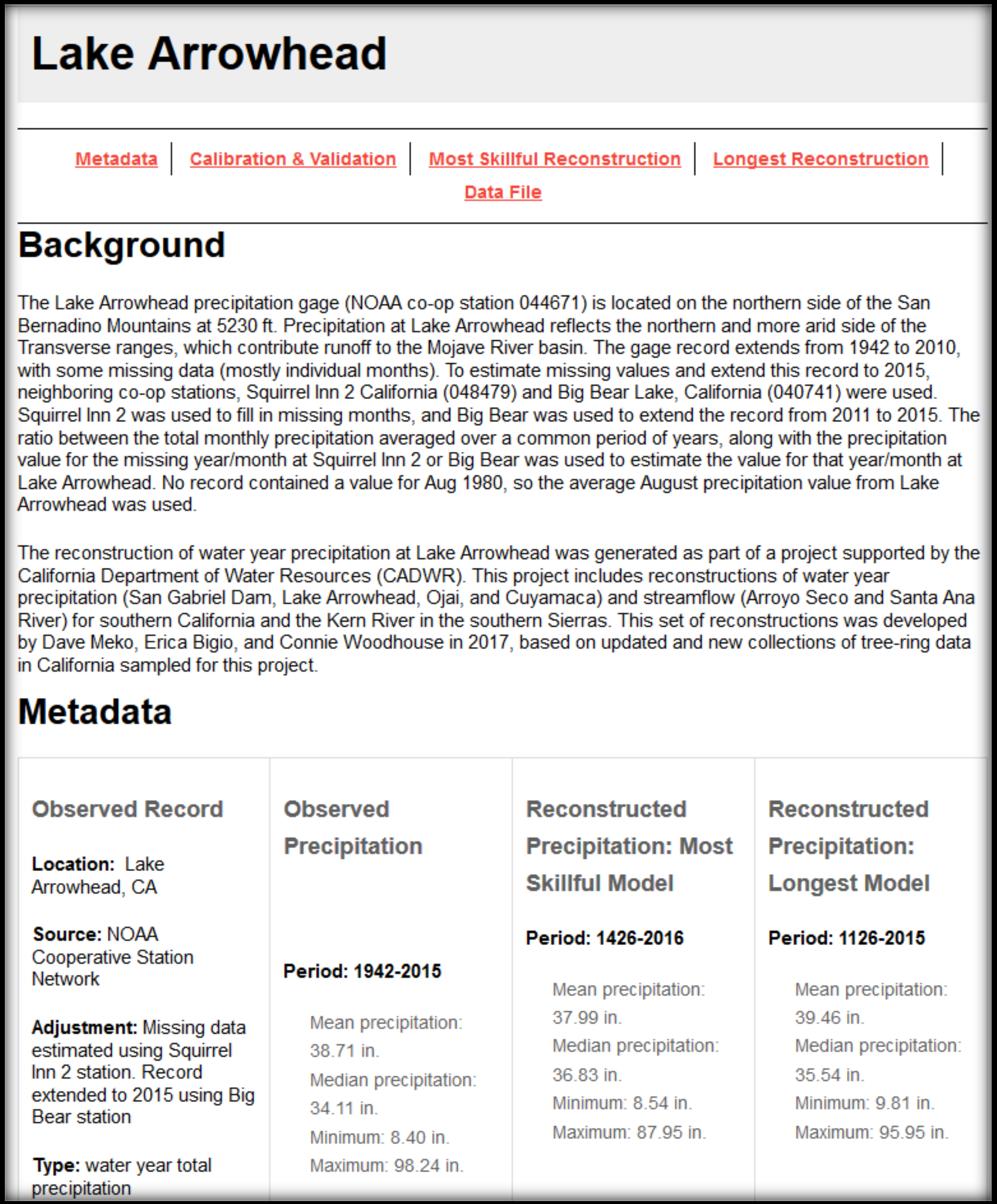
California Basin Reconstructions

Reconstruction Page	Period	Data File
Sacramento River - Four Rivers Index Update	900-2012	sacramentofourupdate.txt
Sacramento River - Four Rivers Index	901-1977	sacramentofour.txt
Feather River Inflow to Lake Oroville Update	900-2012	featherorovilleupdate.txt
Feather River Inflow to Lake Oroville	901-1977	featheroroville.txt
San Francisco Bay Salinity	1604-1997	sfbaysalinity.txt
Salinas River at Paso Robles	1409-2003	salinas.txt
Klamath R. at Keno, OR (natural flows)	1507-2003	Klamath.txt
Trinity R. at Lewiston, CA	1584-2003	Trinity.txt
Yuba River at Smartville	900-2012	Yuba.txt
American River inflow to Lake Folsom	900-2012	American.txt
Sacramento River above Bend Bridge	900-2012	Sacramento.txt
Stanislaus River inflow to New Melones	900-2012	Stanislaus.txt
Tuolumne River inflow to New Don Pedro	900-2012	Tuolumne.txt
Merced River inflow to New Exchequer	900-2012	Merced.txt
San Joaquin River inflow to Millerton	900-2012	San Joaquin.txt
San Joaquin River Four Rivers	900-2012	San Joaquin.txt
Arroyo Seco River, Pasadena	1125-2016	Arroyo Seco River.txt
Kern River below Lake Isabella	1125-2016	Kern River.txt
Lake Arrowhead Precipitation	1125-2016	Lake Arrowhead.txt
San Gabriel Dam Precipitation	1126-2016	San Gabriel Dam.txt
Ojai Precipitation	1126-2016	Ojai.txt
Cuyamaca Precipitation	1126-2016	Cuyamaca.txt
Santa Ana River nr. Mentone	1125-2016	Santa Ana River.txt
CO River at Lees Ferry	1116-2014	CO River at Lees Ferry.txt



Lake Arrowhead

Metadata | Calibration & Validation | Most Skillful Reconstruction | Longest Reconstruction | Data File

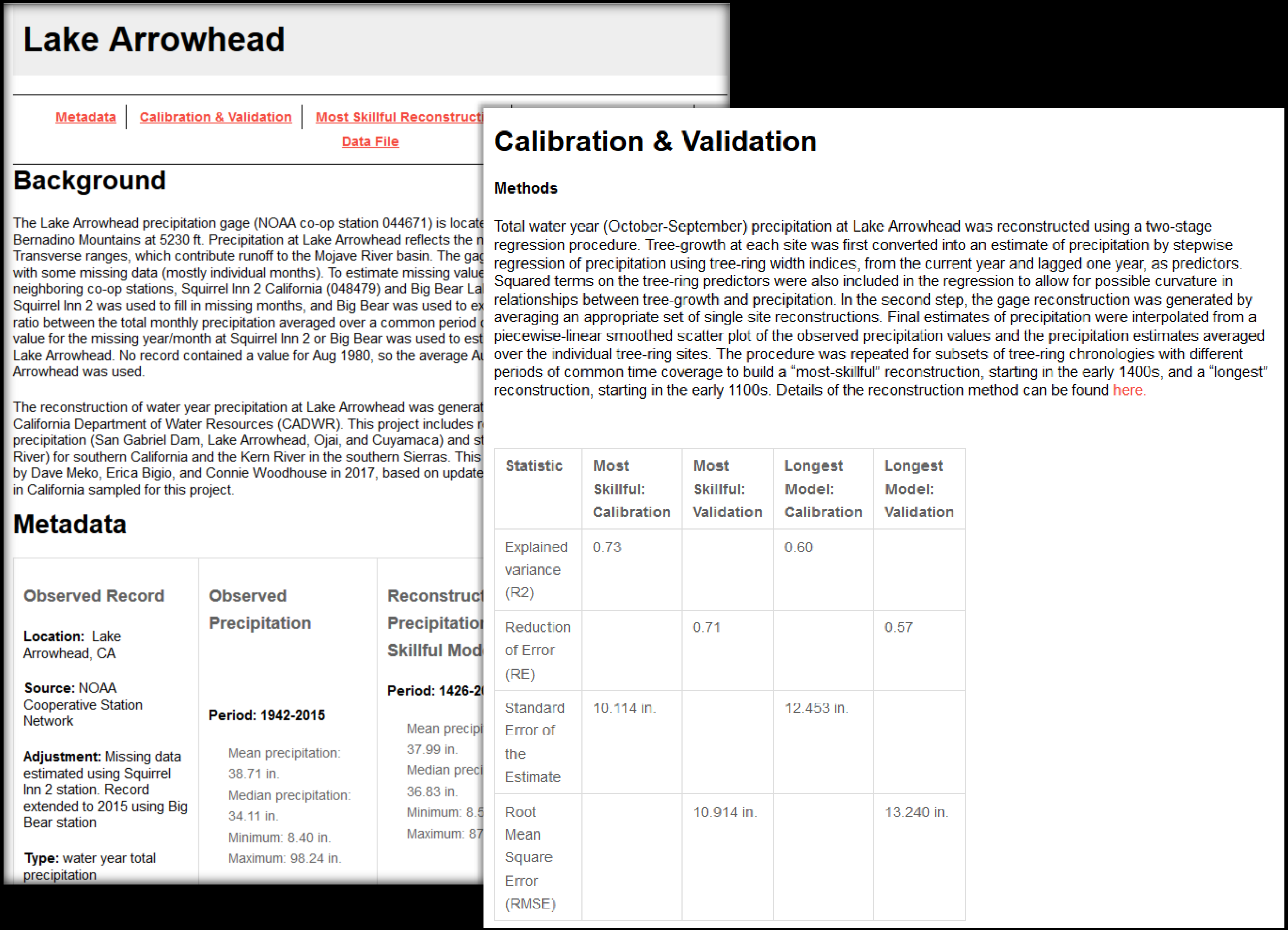
Background

The Lake Arrowhead precipitation gage (NOAA co-op station 044671) is located on the northern side of the San Bernadino Mountains at 5230 ft. Precipitation at Lake Arrowhead reflects the northern and more arid side of the Transverse ranges, which contribute runoff to the Mojave River basin. The gage record extends from 1942 to 2010, with some missing data (mostly individual months). To estimate missing values and extend this record to 2015, neighboring co-op stations, Squirrel Inn 2 California (048479) and Big Bear Lake, California (040741) were used. Squirrel Inn 2 was used to fill in missing months, and Big Bear was used to extend the record from 2011 to 2015. The ratio between the total monthly precipitation averaged over a common period of years, along with the precipitation value for the missing year/month at Squirrel Inn 2 or Big Bear was used to estimate the value for that year/month at Lake Arrowhead. No record contained a value for Aug 1980, so the average August precipitation value from Lake Arrowhead was used.

The reconstruction of water year precipitation at Lake Arrowhead was generated as part of a project supported by the California Department of Water Resources (CADWR). This project includes reconstructions of water year precipitation (San Gabriel Dam, Lake Arrowhead, Ojai, and Cuyamaca) and streamflow (Arroyo Seco and Santa Ana River) for southern California and the Kern River in the southern Sierras. This set of reconstructions was developed by Dave Meko, Erica Bigio, and Connie Woodhouse in 2017, based on updated and new collections of tree-ring data in California sampled for this project.

Metadata

Observed Record	Observed Precipitation	Reconstructed Precipitation: Most Skillful Model	Reconstructed Precipitation: Longest Model
Location: Lake Arrowhead, CA **Source:** NOAA Cooperative Station Network **Adjustment:** Missing data estimated using Squirrel Inn 2 station. Record extended to 2015 using Big Bear station **Type:** water year total precipitation	**Period: 1942-2015** Mean precipitation: 38.71 in. Median precipitation: 34.11 in. Minimum: 8.40 in. Maximum: 98.24 in.	**Period: 1426-2016** Mean precipitation: 37.99 in. Median precipitation: 36.83 in. Minimum: 8.54 in. Maximum: 87.95 in.	**Period: 1126-2015** Mean precipitation: 39.46 in. Median precipitation: 35.54 in. Minimum: 9.81 in. Maximum: 95.95 in.



Lake Arrowhead

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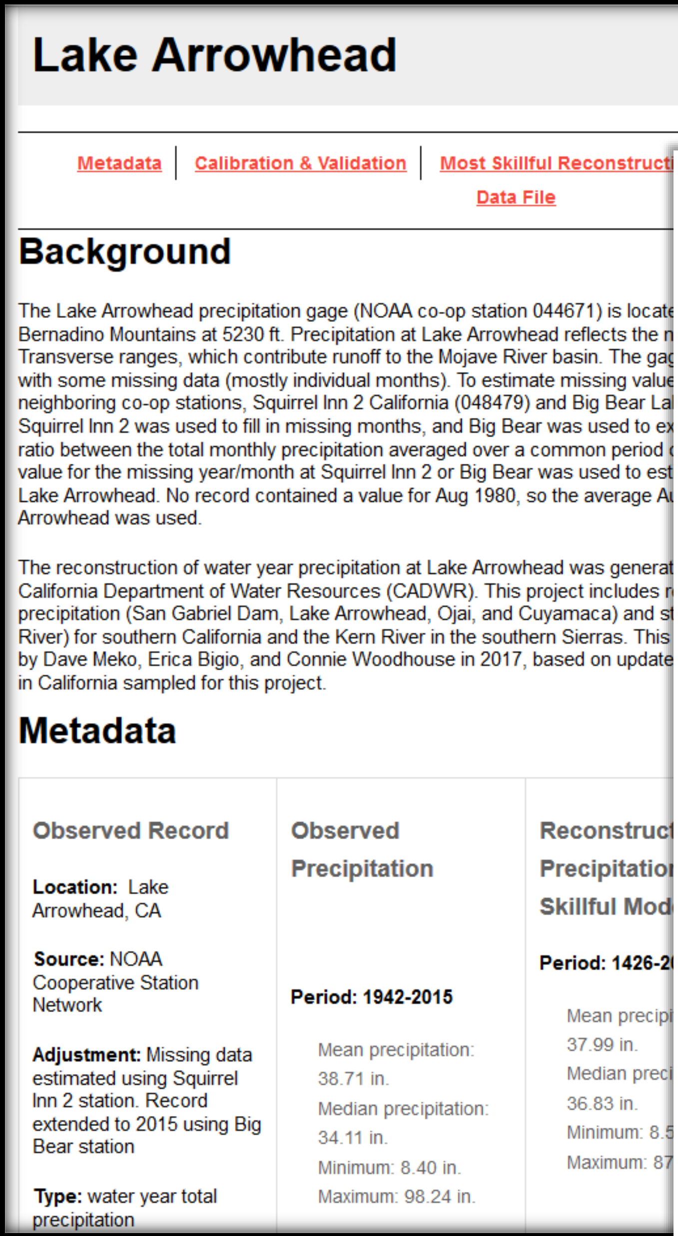
Calibration & Validation

Methods

Total water year (October-September) precipitation at Lake Arrowhead was reconstructed using a two-stage regression procedure. Tree-growth at each site was first converted into an estimate of precipitation by stepwise regression of precipitation using tree-ring width indices, from the current year and lagged one year, as predictors. Squared terms on the tree-ring predictors were also included in the regression to allow for possible curvature in relationships between tree-growth and precipitation. In the second step, the gage reconstruction was generated by averaging an appropriate set of single site reconstructions. Final estimates of precipitation were interpolated from a piecewise-linear smoothed scatter plot of the observed precipitation values and the precipitation estimates averaged over the individual tree-ring sites. The procedure was repeated for subsets of tree-ring chronologies with different periods of common time coverage to build a "most-skillful" reconstruction, starting in the early 1400s, and a "longest" reconstruction, starting in the early 1100s. Details of the reconstruction method can be found here.

Statistic	Most Skillful: Calibration	Most Skillful: Validation	Longest Model: Calibration	Longest Model: Validation
Explained variance (R2)	0.73		0.60	
Reduction of Error (RE)		0.71		0.57
Standard Error of the Estimate	10.114 in.		12.453 in.	
Root Mean Square Error (RMSE)		10.914 in.		13.240 in.



Lake Arrowhead

Metadata | Calibration & Validation | Most Skillful Reconstruct

Data File

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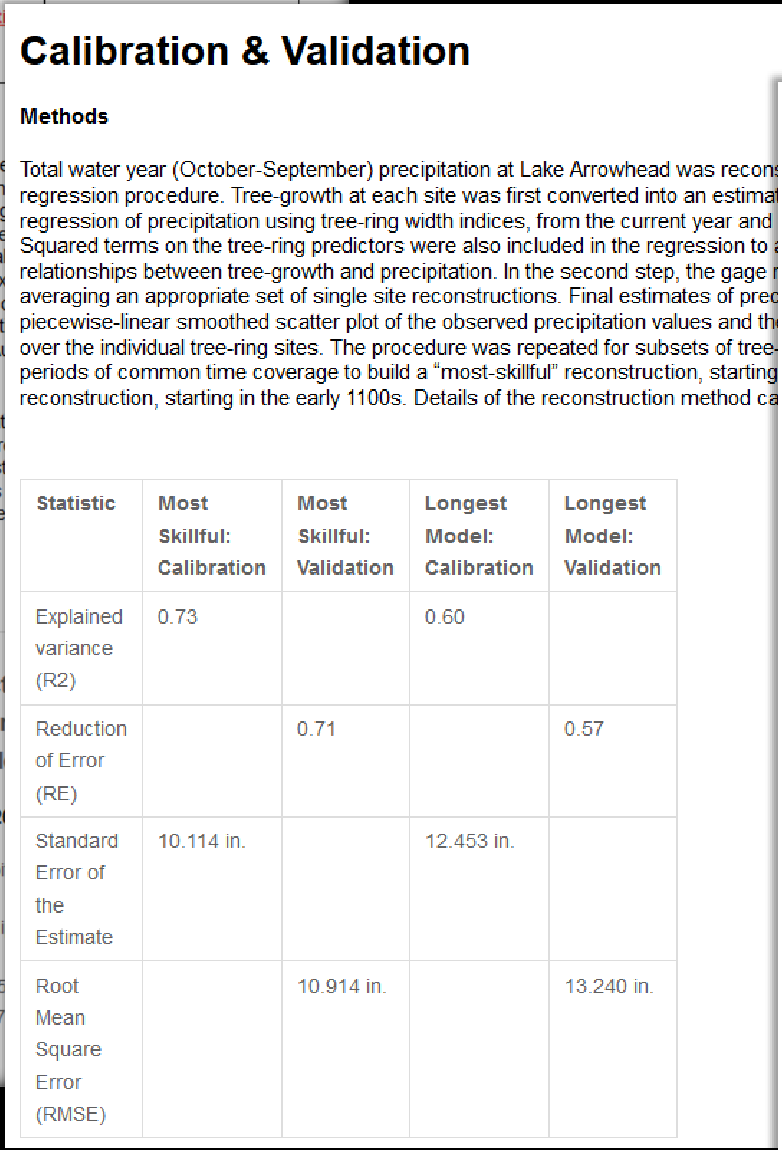

Calibration & Validation

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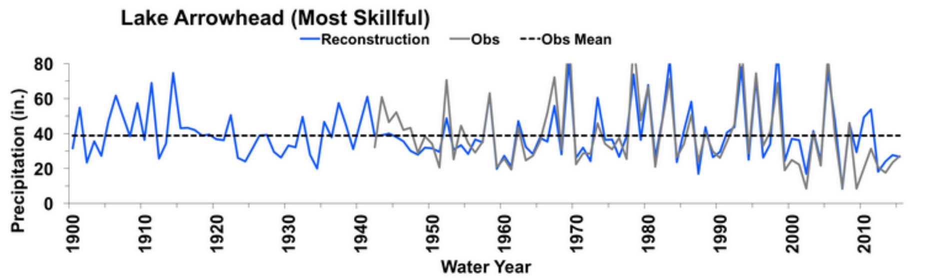


Figure 2. Observed (gray) 1942-2015, and reconstructed (blue) 1900-2016, Lake Arrowhead annual precipitation. The observed mean is illustrated by the black dashed line.

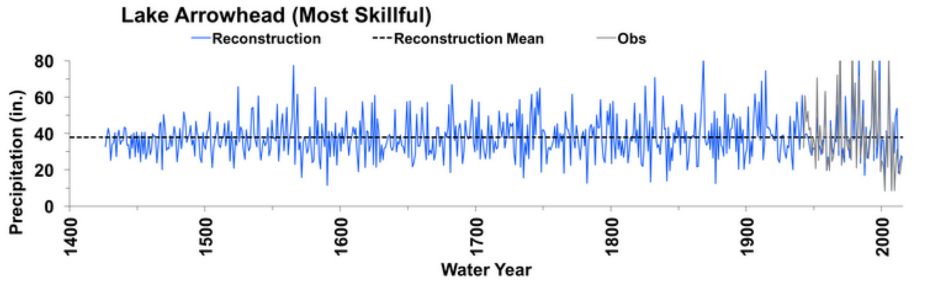
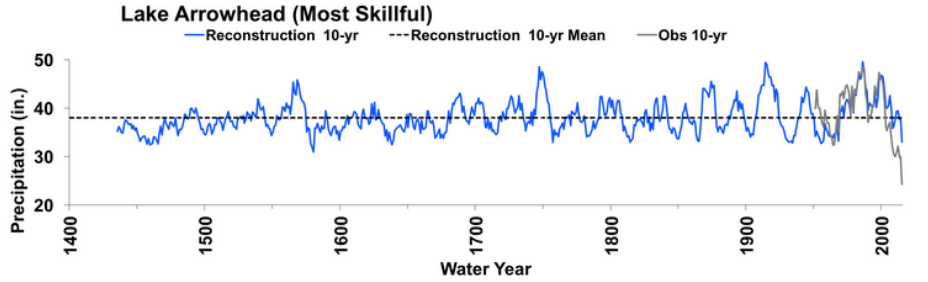


Figure 3. Reconstructed annual precipitation for Lake Arrowhead (1426-2016) is shown in blue. Observed flow is shown in gray and the long-term reconstructed mean is shown by the black dashed line.



Guidebook and Project Report:

https://www.water.ca.gov/News/News-Releases/All-News-Articles/Tree-Ring-Study-Reveals-Historical-Drought-Record-in-Southern-California

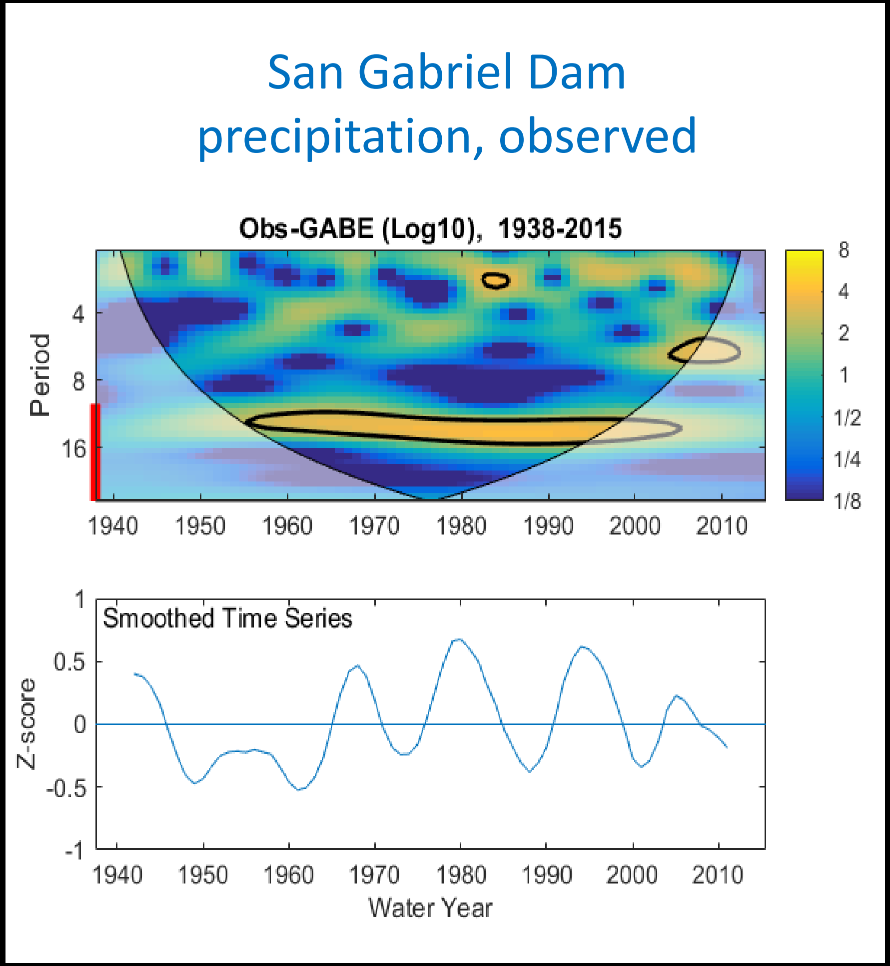
TreeFlow web site:

https://www.treeflow.info/

Questions comments, suggestions?

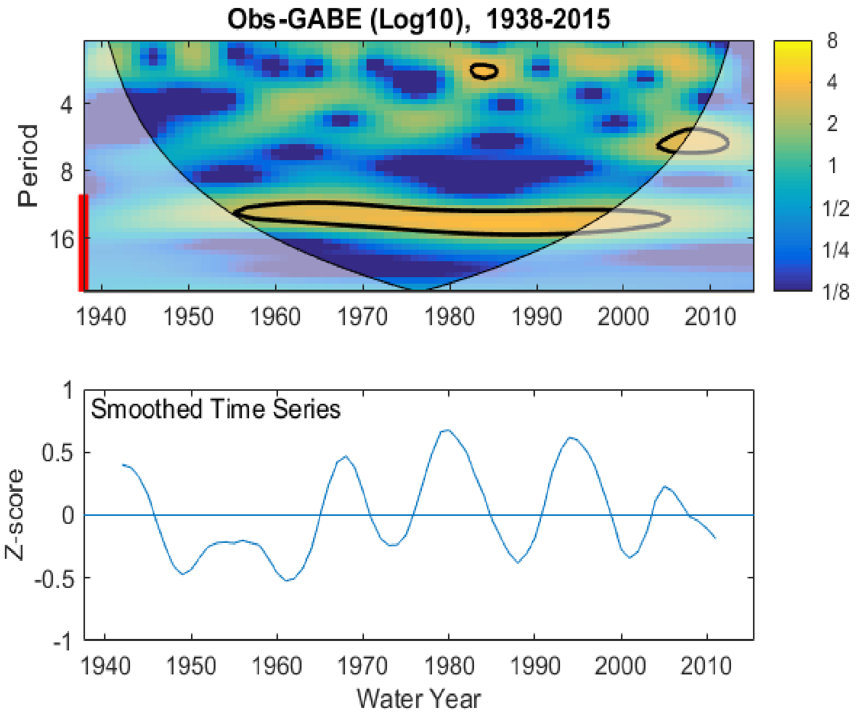
What about cycles?

Variations in cyclicity over time: instrumental period

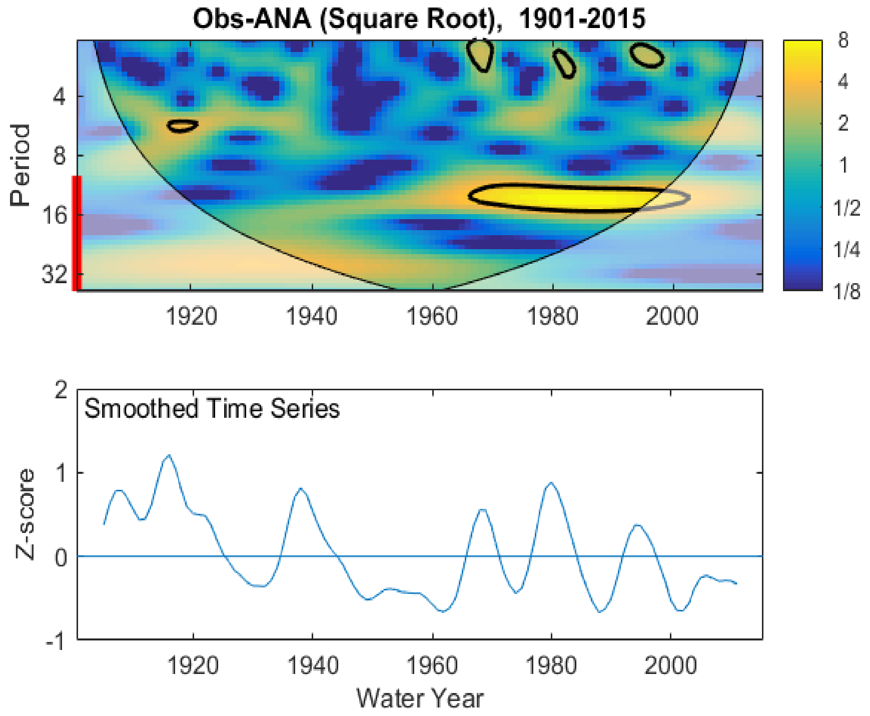


Variations in cyclicity over time: instrumental period

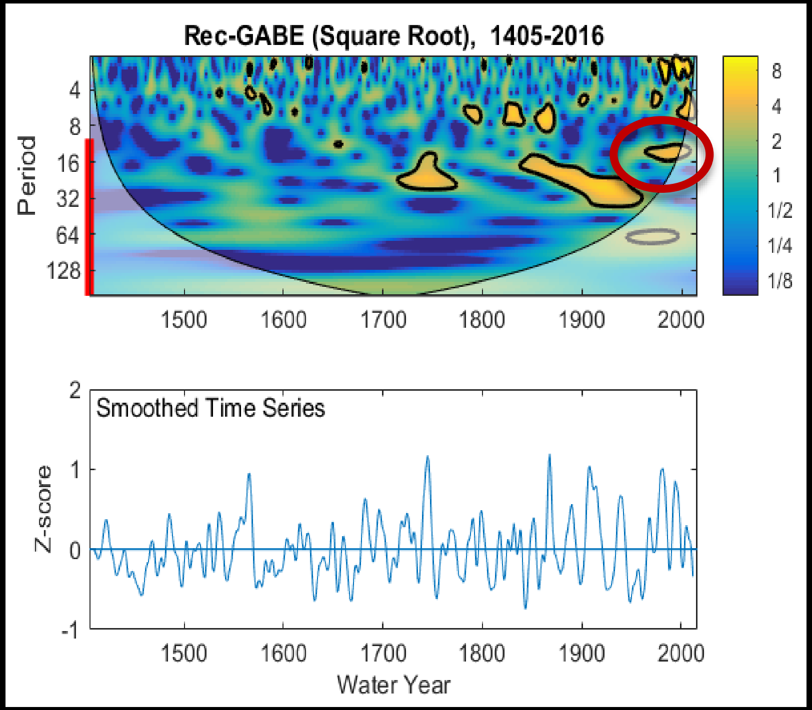
San Gabriel Dam
precipitation, observed

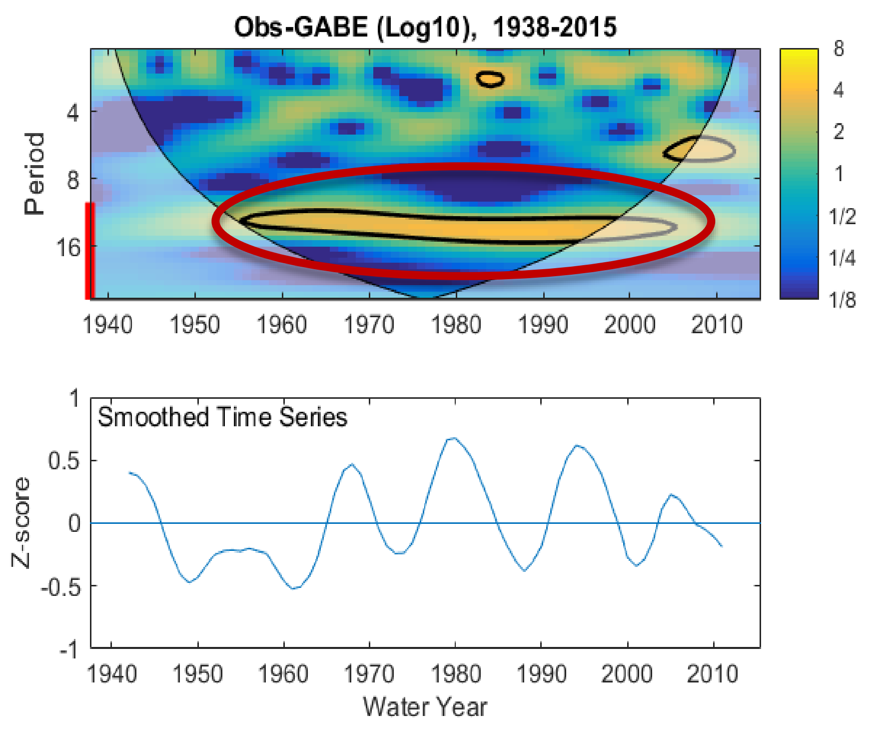


Santa Ana River flow,
observed

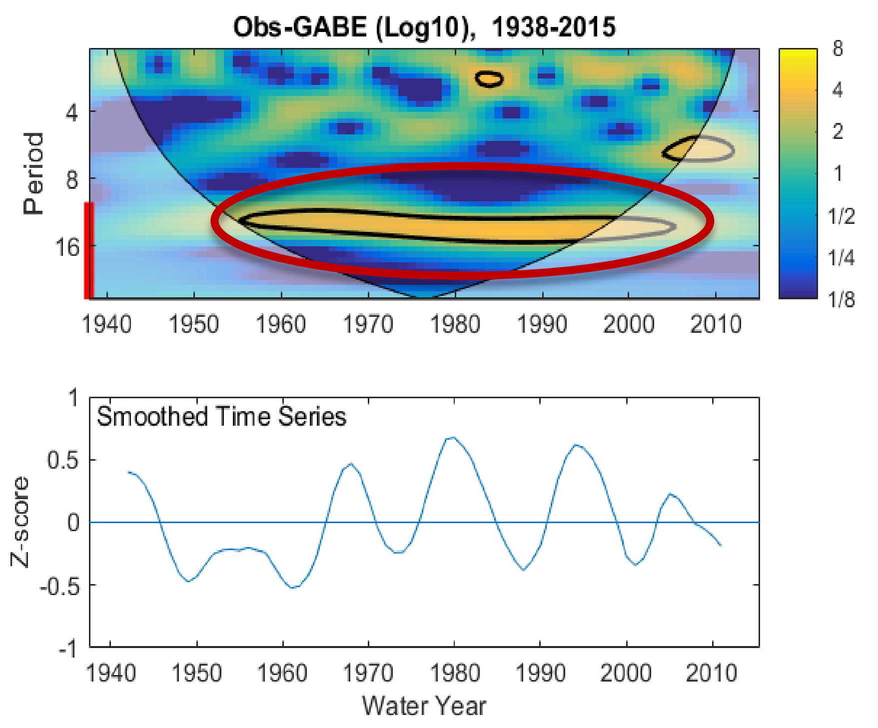


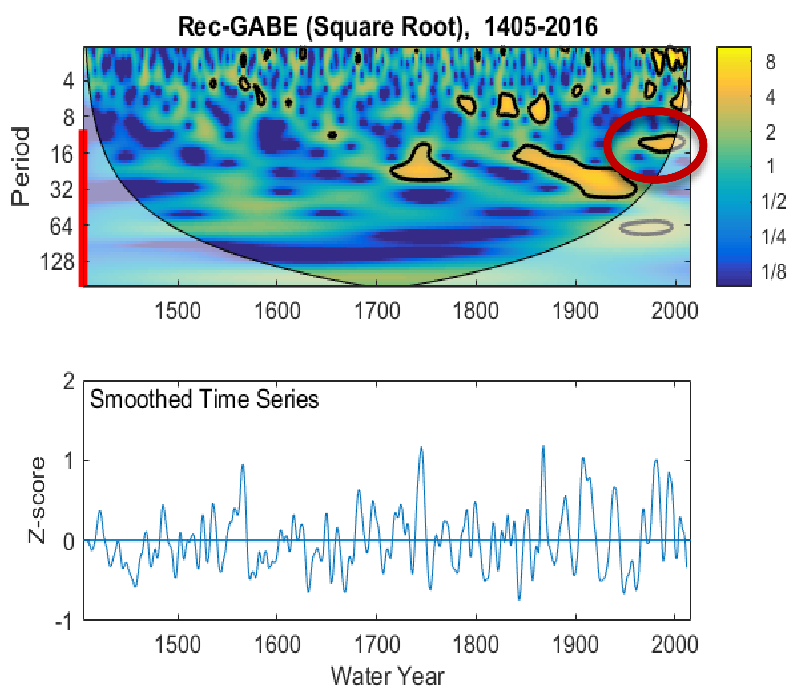
Variations in cyclicity over time: the paleo period context

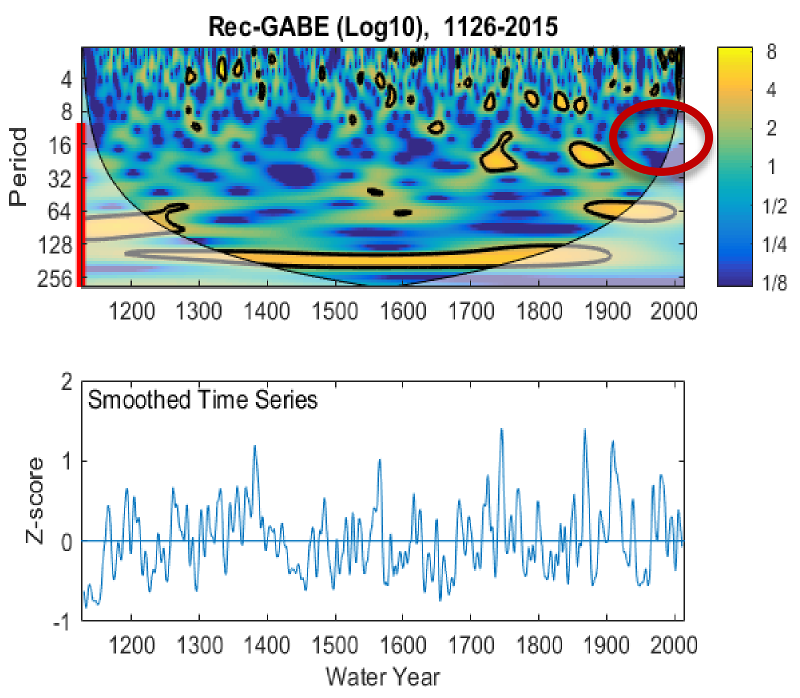




Variations in cyclicity over time: the paleo period context


Obs-GABE (Log10), 1938-2015


Rec-GABE (Square Root), 1405-2016


Rec-GABE (Log10), 1126-2015