University of Nevada, Reno

Tree Rings and the Truckee River:
Our Past, Our Future, and George Hardman

A thesis submitted in partial fulfillment of
the requirements of the degree of
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by

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requirements for the degree of

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ABSTRACT

The Truckee River Basin, located on the Nevada-California border, is an area of extreme hydrologic variability. It can be subject to both prolonged multi-decadal droughts and devastating floods; however, due to the brief instrumental record, the full range of this variability and its potential cyclicity is limited. As tree rings have been shown to be well suited as proxies for annual streamflow, this study revisits the first tree-ring reconstruction of Truckee River runoff, Hardman and Reil (1936), from the perspective of both physical and historical geography.

In the same way that local water managers are concerned with the current post-2000 drought, George Hardman and Orvis Reil developed their paper to address questions surrounding their contemporary drought. This study is more than just an extension of their work but in fact a replication. Hardman and Reil's original tree cores from the 1930s were preserved University of Nevada, Reno Special Collections and Archives and thereby integrated into this new research. Using modern though parallel techniques, these cores along with newly sampled material were measured and processed to develop new tree-ring chronologies for three of Hardman and Reil's study sites. These were then incorporated into a new Truckee River streamflow reconstruction extending from 1491 to 2003. This represents an over 400-year extension of the instrumental record and provides new insights into the basin's natural variability. In addition to evidence of extended droughts and extreme high streamflow years, this reconstruction shows a marked hydroclimatic shift centered around 1850. Previously, the Truckee River experienced decadal to multi-decadal higher than average streamflow periods; since then, those periods have been decreasing in length until as we experience today merely 2 to 4 consecutive years of high flow. Whether

this represents fundamental shift in the area to a new climatic regime remains unclear. However, as global temperatures continue to rise, fewer long-term high streamflow episodes may have lasting impacts on water availability in the basin and raises the question further of whether the post-2000 drought is a new megadrought or a sign of aridification.

Additionally, this study examines George Hardman's relationship with dendrohydrology both before and after his 1936 publication. It explored how Hardman, a water manager, learned the techniques of a dendrochronologist, which unfortunately remains unclear. Using bibliometrics, the legacy of Hardman and Reil (1936) was assessed and shows its influence on the subdiscipline to only be growing.

Dedicated to

Jasmine Harris

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INTRODUCTION

George Hardman's and Orvis E. Reil's 1936 study reconstructing Truckee River runoff from tree rings is a perfect synthesis of both physical and history geography. Trees, or more specifically their annual rings, contain a record of the environmental past, whereas historical documents (e.g., correspondence) contain records of the human past. Hardman and Reil (1936) was one of the first studies to examine how tree rings could be used to reconstruct river runoff, being also the first to collect tree cores specifically for that purpose, and thereby represented a fundamental shift in the field of dendrohydrology. This thesis addresses both of these aspects through the development of a new Truckee River streamflow reconstruction and examining George Hardman's relationship with dendrohydrology both before and after his landmark study.

Here I address three research questions:

1. How will creating a new Truckee River streamflow reconstruction using modern dendrochronological techniques build upon and expand the findings from George Hardman's and Orvis Reil's original 1936 study?
2. How did George Hardman, a water manager, learn the contemporary techniques of dendrochronology?
3. What was George Hardman's lasting impact on the field of dendrohydrology?

To address these research aims, new tree-ring chronologies were developed based upon Hardman's study sites using both newly obtained samples and cores from the original study (Max C. Fleischmann College of Agriculture. Agricultural Experiment Station, (1935-1936); Figure 1). These were then incorporated into a stepwise linear regression model, resulting in a new 500-year reconstruction of Truckee River naturalized streamflow. The second involved using occupational forensics and archival research to gain an understanding of whom Hardman interacted with and tracing potential sources for knowledge of dendrochronology during the 1930s. By bridging the gap between tree-ring studies in the application/policy realm with that of the academic, Hardman created a lasting change in how tree-ring hydrologic research was conducted and, in some ways, contributed to its founding as a subdiscipline of dendrochronology, something I further explored using citation analysis.

Figure 1: Tree-core samples from the Hardman and Reil (1936) study (Max C. Fleischmann College of Agriculture. Agricultural Experiment Station, 1935-1936). Photo: A. Csank.

The Western United States is an arid to semi-arid environment, and thus the presence or absence of water is key to the development and sustainability of Indigenous and Euro-American habitation in the region. In response to an expanding population, the late 1800s and early 1900s saw a large increase in irrigation and reclamation projects along the Truckee River, much of it locally spurred by the Newlands Reclamation Act of 1902 (MacDonnell, 1999). Resource managers, including Hardman, became increasingly concerned with drought and water supply, but they encountered a difficulty in assessing long-term hydrologic variability: their precipitation and river gauge data only covered five (or fewer) decades. In a 1935 *Civil Engineering* publication, Lynn Crandall, a Snake River watermaster in Idaho and contemporary of Hardman, noted with extreme dissatisfaction the limitations of available streamflow data (Crandall, 1935). Thus, there was very little empirical understanding of the natural variability of these watersheds, and so the ability to plan for and adapt to different water availability scenarios was hindered.

A.E. Douglass, who codified the study of tree rings into a formal scientific discipline, published "The Secret of the Southwest Solved by Talkative Tree Rings" (1929) in National Geographic, thereby pushing dendrochronology into the public's eye, and piquing the curiosity of many who might never have gained an interest in tree-ring research (Douglass, 1920-1956). His publication, I would argue, was the fundamental turning point in dendrochronology's existence as a scientific field. Because of it, water/resource managers like Hardman now had an avenue for gaining their desired long-term climatic data: tree rings.

George Hardman was born in 1890, giving him enough time to become a prominent figure in the beginnings of Nevadan irrigation management and conservation. He grew up in eastern Oregon and eventually earned a Master's degree from Oregon Agricultural College (currently Oregon State College). After this he began working with the University of Nevada Agricultural Experiment Station, firstly as an agronomist, then later as an instructor and researcher (Hardman, 1968). His work generally specialized in irrigation and soils (e.g., Bixby and Hardman, 1928; Hardman, 1944; Hardman and Mason, 1949; Hardman, 1968). In 1934 he began his tree-ring study, publishing in 1936, and from there he joined the US Soil Conservation Service (Hardman, 1968). Eventually he became Nevada's first state conservationist, then moved on to being the assistant director of the Nevada Department of Conservation and Natural Resources, a position he occupied until his retirement (Hardman, 1968; Area Deaths: George H. Hardman, 1975). His career spanned a wide variety of projects and interests, but for this study, his brief time practicing dendrochronology stands as most significant.

Hardman, in addition to his general role as a researcher, was an irrigation engineer and had geared his study to address water shortages caused by the 1920s/1930s drought. He too recognized the value of having longer streamflow records and their necessity in gauging variability and climatic shifts (Hardman and Reil, 1936). As current climate change causes water availability to become an increasingly important issue, gaining knowledge of past climate can assist in planning for future droughts (Meko and Woodhouse, 2005; Meko et al., 2012; Malevich et al., 2013). Tree rings provide a valuable proxy for this information. Tree-ring site chronologies from Hardman and Reil (1936) have not been updated since the 1930s, nor has an updated Truckee River reconstruction been developed since that time. Revisiting and updating their findings has increasing value. With the use of modern dendrochronological techniques and an additional 85 years of river gauge data, this new reconstruction provides a more statistically robust understanding of how streamflow has varied in the past and an opportunity to corroborate Hardman and Reil (1936), which continues to be cited today.

Like all dendrochronology, this research began with the trees themselves, or in my particular case, pieces of them. Tucked away in University of Nevada, Reno Special Collections and Archives, Hardman's original tree-core samples lay forgotten for decades until they were stumbled upon and brought back into the attention of the scientific community. In an endeavor to extend their stories, new cores were taken from three of the original study's sites. Having the benefit of eighty-five years of dendrochronological advances and instrumental data, this thesis presents the opportunity to corroborate Hardman's findings and to further our understanding of the natural variability of Truckee River streamflow.

Though streamflow reconstructions are now commonplace (e.g., Woodhouse et al., 2006; Griffin, 2007; Meko et al., 2012), in the 1930s such studies were only beginning to formally address the questions of what trees could tell us about past hydroclimates. Hardman and Reil (1936) was a revolutionary step forward and created a lasting link between streamflow reconstructions and water management. Here I create a new tree-ring streamflow reconstruction of the Truckee River, and explore Hardman's relationship with dendrochronology both before and after his pivotal study.

CHAPTER 1:

TRUCKEE RIVER STREAMFLOW RECONSTRUCTION USING TREE RINGS

INTRODUCTION

In the arid parts of the Western United States, water is a vital component for the region's development and sustainability. Some of the region's earliest laws focus on its supply and utilization (Hardman and Reil, 1936), making water also an intrinsic part of the area's culture. Throughout the 21st century, the arid West has been anomalously dry compared to earlier centuries (e.g., Williams et al., 2015), with the period from 2000 to 2018 being the driest 19-year period since the 1500s (Williams et al., 2020). Water supplies in this already water-limited region are therefore undergoing increasing stress, and as global temperatures continue to rise, water managers are increasingly concerned with future water availability (Stakhiv, 2011). Understanding long-term streamflow trends, especially their range of natural variability, can assist in planning for these future contingencies and aid in effective resource management (Meko and Woodhouse, 2005; Meko et al., 2012; Malevich et al., 2013). However, instrumental data for streamflow and precipitation in this area are often limited, consisting of few records earlier than 1900, and so our ability to gauge a hydrologic system's extremes and long-term patterns is inhibited. Thus, water managers are increasingly turning to climatological proxy data to extend hydrologic records and assess past (and therefore future) water availability scenarios, thereby allowing for more informed planning decisions (e.g., Woodhouse and Lukas, 2006; Rice et al., 2009; Meko et al., 2012; Woodhouse et al., 2016).

The Truckee River flows across the Nevada-California border from Lake Tahoe, where it serves as its sole outlet, to Pyramid Lake and supplies water to the region's municipalities, agriculture, industry, and recreational activities. It serves a population of more than 400,000 (U.S. Department of the Interior Bureau of Reclamation, 2016), and the area has seen a burgeoning increase in development in recent decades, adding further concerns over water availability. Instrumental streamflow data for the Truckee River extend back to 1906 at the earliest (Farad gauge). Tree-ring studies have been conducted for several Eastern Sierra Nevada river basins (Saito et al., 2015; Biondi and Meko, 2019); however, there currently exists no streamflow reconstruction specific to the Truckee River more recent than the 1930s.

The last twenty years have been anomalously dry (Williams et al., 2020), raising concerns over water scarcity and thereby spurring a need for a deeper understanding of the natural variability of Truckee River streamflow, which this study's updated reconstruction seeks to address. So too was the impetus for the first Truckee River reconstruction. The 1920s and 1930s were also considered to be anomalously dry, and local water and resource managers were also apprehensive about water supplies (Hardman, 1968). Their climatic records were even more limited than ours, and so in 1936 Hardman and Reil published a study to address these concerns. Their research correlated tree rings with river runoff and was designed specifically from the perspective of aiding in water management planning.

Hardman and Reil (1936) was truly a revolutionary study. Not only was it one of the earliest papers to use tree rings for a streamflow reconstruction, it was conducted entirely from start to finish by Hardman and Reil. They collected their own samples and crossdated them themselves, rather than sending them to A.E. Douglass for processing as was a common practice of the time. They developed their own reconstruction, which despite differing methodologies, has may overlapping findings with this study's Truckee River reconstruction. They practiced dendrochronology in a time when its applications were just beginning to be explored, and Hardman and Reil (1936) linked the academic science of tree rings to water management planning, thereby creating a fundamental shift in dendrohydrology.

However, as would be expected of such an early study, their techniques did not entirely conform with current dendrochronological practices. For example, they used visual crossdating (in a manner similar though different from skeleton plotting) which was not statistically verified as it would be now through programs such as COFECHA (Holmes, 1983), and their detrending approach, which involved standardizing against mean annual growth, did not fully address the age/growth trend in tree-ring widths (Hardman and Reil, 1936). These methods and the brief instrumental record (30 years) available at the time, limit the full reliability of their reconstruction and its applications. The addition of 85 years of gauge data and modern techniques lends a degree of precision not previously available and increases this reconstruction's utility for local water managers.

Here we develop an updated streamflow reconstruction of the Truckee River using modern dendrochronological techniques. We developed three tree-ring chronologies from Hardman and Reil's study sites: Hirschdale, Hunter Creek, and Roberts Creek (Supplemental Figure 1). Unlike most updated chronologies, we include the original study's tree cores, which we remeasured and crossdated (Max C. Fleischmann College of Agriculture. Agricultural Experiment Station, (1935-1936); Figure 1), as well as resampled material, allowing for a distinct advantage in replicating and building upon the first

Truckee River reconstruction. Our reconstruction examines the hydroclimate of the Truckee River over a 500-year period and highlights the variability of this system which can assist water management decisions, leading to benefits for the local communities and stakeholders as climate change continues to make water availability an increasing concern.

METHODS

Study Area:

The Truckee River runs 169 km with an elevation change of 740 m, and its basin encompasses approximately 7,925 km^2 (Horton, 1997; Figure 2). Its source is primarily Lake Tahoe (located on the Nevada-California border) but also includes inflows from Donner Lake, Prosser Creek Reservoir, and Boca Reservoir, as well as minor area streams. It terminates in Pyramid Lake, Nevada and has a major diversion for agricultural use at Derby Dam. The largest municipalities which rely on the Truckee River are Reno, NV and Sparks, NV.

Snowmelt is the primary source of water for this river, and so its flow is mostly determined by previous season snowpack. Peak flow is through April to June (Supplemental Figure 2). Precipitation varies widely across the basin, from 176 cm at its headwaters to 13 cm at its terminus (U.S. Department of the Interior Bureau of Reclamation, 2016), and its peak months are December through March. This precipitation can fluctuate widely from year to year, subjecting the area to both floods and periods of drought.

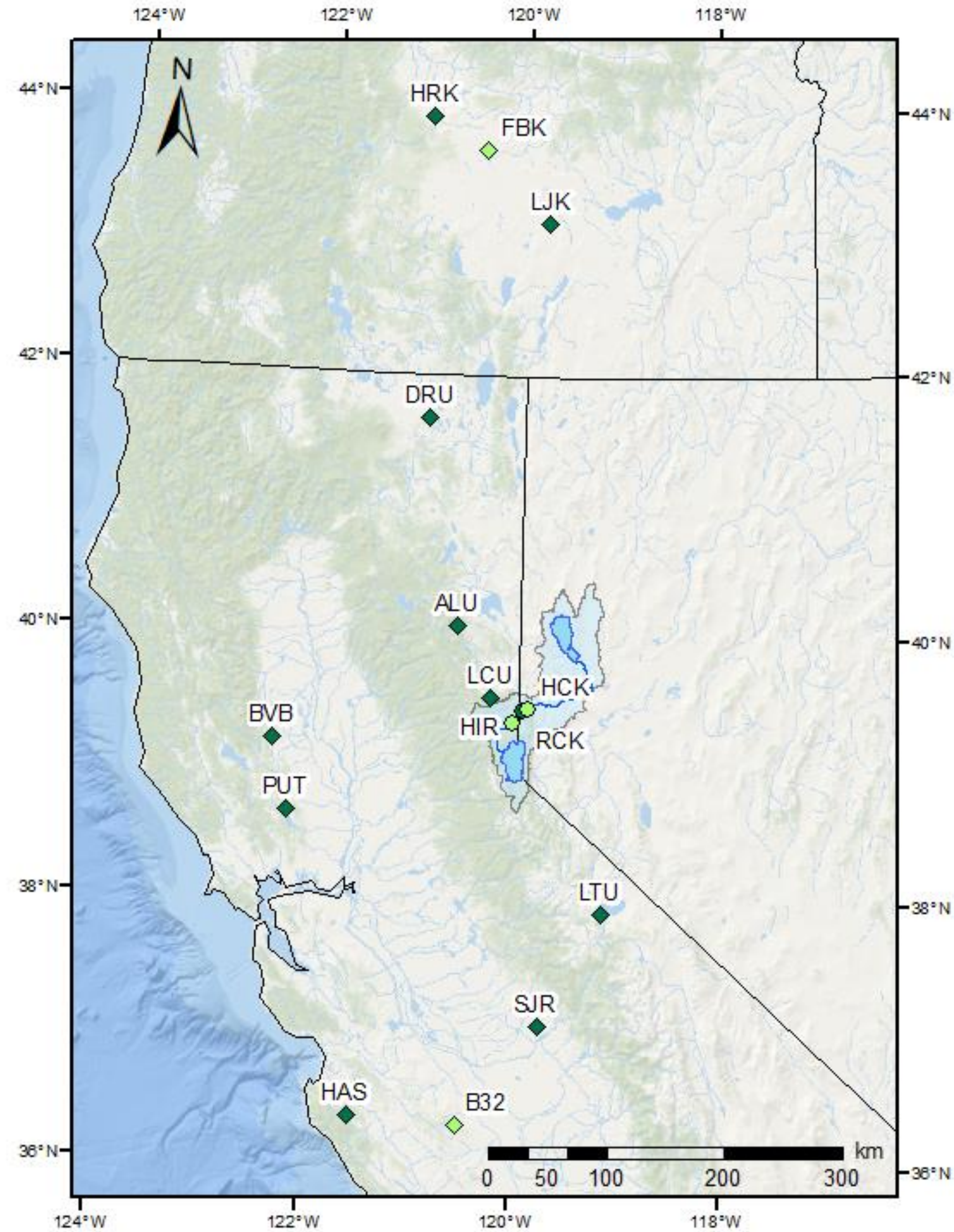

Figure 2: Locations of tree-ring sites (diamonds = ITRDB sites; circles = sites developed in this study). Light green indicates chronologies used in this reconstruction. Light blue indicates extent of the Truckee River Basin. (Service layer credit: Esri, Garmin, GEBCO, NOAA NGDC, and other contributors).

Streamflow Data:

A single gauge was selected as the basis for this reconstruction: Farad (39°25'41" N, 120°01'59" W) located on the Nevada-California border. Situated at the transition for the informally defined Upper and Lower Truckee River Basins, this gauge is particularly appropriate as it is downstream from the primary inflows, but upstream of the major municipal areas. Even more appropriately, this was the station used in the original Hardman and Reil (1936) study (referred to as "State line" (verified by Hardman and Venstrom (1941))). The river has, however, experienced extensive hydrologic modification and development upstream (e.g., the building of dams and reservoirs), thus, naturalized streamflow data were obtained from the California Data Exchange Center (California Data Exchange Center, 2020). This record also has the distinct advantage of having monthly resolution and the longest instrumental period of the Truckee River gauges (1906-2021). These were then converted to water year annual flow (WY) (previous October to current September) for reconstruction purposes.

Tree-Ring Chronologies:

Three new chronologies, consisting of new collections and the original Hardman and Reil (1936) material, were developed for this reconstruction: Hirschdale (HIR), Hunter Creek (HCK), and Roberts Creek (RCK). The approximate locations of the updated collections were determined from the Hardman and Reil (1936) study (Supplemental Figure 1), and all lie within the Truckee River Basin (TRB). A fourth study area was part of the original study (Sierraville); however, as only one original core remains and its precise location was unclear, it was decided to not resample this site; fortunately, there was a chronology available from the International Tree-Ring Databank (IRTDB) located in close proximity to the Sierraville site (Lemon Canyon Update, LCU (Malevich, et al. (2013)).

During 2019 and 2020, tree cores were taken from Jeffrey pine (*Pinus jeffreyii*) trees at all three sites, then prepared and visually crossdated using standardized techniques established by Stokes and Smiley (1968). Annual ring widths of the new samples and the original 1930s tree cores were measured using a combination of scanned images with cooRecorder (Larsson, 2017) and a Velmex measuring bench utilizing J2X (Voortech). Crossdating accuracy was then checked using COFECHA (Holmes, 1983), as well as the R Studio coding package dplR and xDateR (Bunn, 2008; Bunn, 2010). The resulting series include: 27 new cores and 27 original cores for Hirschdale (HIR); 27 new cores and 8 original cores for Hunter Creek (HCK); and 27 new cores and 36 original cores for Roberts Creek (RCK).

As also noted by Hardman and Reil (1936), tree's responses to environmental factors (and therefore growth rates) can vary with age (Speer, 2010); thus detrending is used to remove these age-related trends (Fritts, 1976). In order to preserve long-term and low-frequency variability, the ring-width series were detrended using a modified negative exponential with a 50% frequency-response cutoff at 67% the length of the series length (Cook et al., 1990). Tukey's biweight robust mean was then used to combine the cores into a single chronology for each site (Cook and Kairiukstis, 1990). For consistency of analysis, these detrending and averaging methods were applied to all chronologies used in the reconstruction.

All tree-ring width series within a 500 km radius of the Farad gauge were obtained from the International Tree-Ring Data Bank (ITRDB). They were then screened by series intercorrelation (nothing below r=0.5), by end date (none earlier than 2003), and by start date (none later than 1600). Using the above method, these series were detrended and then correlated against monthly Farad gauge data. Any chronology with a p-value > 0.05 was removed (Woodhouse et al., 2006). This resulted in twelve additional chronologies to be considered for the reconstruction (Figure 2, Table 1).

ITRDB Site	**Series**		**Species**	**Time Period (CE)**	**Source**
CA647*	B32	Wright Mountain	QUDG	1409-2003	Griffin, (2006)
CA649	BVB	Bear Valley Buttes	QUDG	1546-2004	Stahle et al., (2013)
CA657	HAS	Hastings Reservation	QUDG	1460-2004	Stahle et al., (2013)
CA663	PUT	Putah Creek, Lake Berryessa	QUDG	1534-2004	Stahle et al., (2013)
CA664	SJR	San Joaquin Experimental Range	QUDG	1557-2004	Stahle et al., (2013)
CA674	ALU	Antelope Lake Update	PIPO	1450-2010	Malevich et al., (2013)
CA676	DRU	Dalton Reservoir Update	PIPO	1357-2010	Malevich et al., (2013)
CA677	LCU	Lemon Canyon Update	PIJE	1415-2010	Malevich et al., (2013)
CA678	LTU	Log Cabin Mine/Tioga Pass Update	PIJE	1304-2010	Malevich et al., (2013)
*	HCK	Hunter Creek	PIJE	1491-2019	This study
*	HIR	Hirschdale	PIJE	1268-2018	This study
OR093*	FBK	Frederick Butte Update	JUOC	870-2010	Malevich et al., (2013)
OR094	HRK	Horse Ridge Update	JUOC	830-2010	Malevich et al., (2013)
OR095	LJK	Little Juniper Mountain Update	JUOC	1337-2010	Malevich et al., (2013)
	RCK	Roberts Creek	PIJE	1398-2019	This study

Table 1: Tree-ring chronologies used in the predictor pool for streamflow reconstruction. Species: blue oak (QUDG, *Quercus douglasii*), ponderosa pine (PIPO, *Pinus ponderosa*), Jeffrey pine (PIJE, *Pinus jeffreyi*), Western juniper (JUOC, *Juniperus occidentalis*). * indicates chronologies incorporated into streamflow reconstruction.

Streamflow Reconstruction:

A stepwise multiple linear regression with a predictor pool of 15 was used to reconstruct Truckee River streamflow. Farad water-year gauge data were divided into two periods (1907-1954 and 1954-2003), and the regressions were run both forward and backward on each set of years to determine the model with the lowest Akaike Information Criterion (Akaike, 1974). However, the best fit models for each period differed in their numbers of chronologies, so it was decided to create simplified linear regression models using just the chronologies in common.

These models were then trained and cross-validated temporally. This split-period analysis allows for the tree-ring reconstruction to be calibrated against half of the instrumental record and then validated against the other half (Lepley et al., 2020), thereby assessing the stability and quality of the models (Fritts, 1976; Cook and Kairiukstis, 1990). Once complete, the verification statistics of root mean squared error (RMSE), reduction of error (RE), and coefficient of efficiency (CE) were calculated (Jevšenak and Levanič, 2018).

RMSE is used as a measure of differences between predicted and observed values; the lower the RMSE, the better the fit of the model. RE takes the mean squared error (MSE) of the predicted values for the validation period and divides it by an MSE which uses an average of the observed data for the calibration period against the predicted values for that period; this number is then subtracted from 1 (National Research Council, 2006). An RE above zero indicates that the model exhibits greater validation skill than simply the mean of the calibration period (Fritts, 1976; Fritts et al., 1990). CE performs a similar calculation but instead with the observed average for the validation period instead (Maxwell et al., 2012); like RE, a value closer to 1 indicates higher model skill.

Truckee River streamflow was then reconstructed for the time interval common among all four chronologies using an equation derived from the model with the highest skill. Z-scores were then obtained for the entire reconstructed period and used to assess years of higher and lower streamflow relative to the mean of the reconstructed data.

RESULTS

As previously noted, the chronologies selected by the stepwise multiple linear regression as best fit differed. The early model (1907-1954) chose five chronologies: HIR, HCK, B32, DRU, and FBK. Whereas the late model (1954-2003) chose six: HIR, HCK, RCK, B32, ALU, and FBK. To avoid overfitting, the overlapping chronologies in each model were selected for use in the simplified linear regressions from which the final reconstruction was determined (Table 1). It was not unexpected that the newly developed chronology of RCK was excluded from the early model as the original Hardman and Reil (1936) study observed that Roberts Creek had the lowest correlation with Truckee River runoff.

A strong streamflow signal was detected in all models including a linear regression run using the entire instrumental period (Table 2). For the calibration period, 62% of the variance was accounted for in the early model, and 72% in the late. The verification statistics of RE and CE indicate that these are not a product of overfitting, being both large and positive (Meko et al., 2001), and further support the decision to reduce the reconstruction chronologies to the four in common. Additionally, the residuals for each model were inspected graphically, and all exhibited normality and homoscedasticity, but not autocorrelation.

Calibration			Validation				
Period	$R^2_{adjusted}$	RMSE	Period	r	RE	CE	RMSE
1907-1954	0.6156	104784.9	1954-2003	0.7473	0.4536	0.4501	163891.7
1954-2003	0.7183	112304.2	1907-1954	0.7685	0.5457	0.5411	119587.4
1907-2003	0.6633	113819.6					

Table 2: Verification statistics for simplified linear regression models using four chronologies (HIR, HCK, B32, and FBK). Period is in water years.

A closer examination of 1907-2003 reveal that the reconstructed values track closely to the observed (Figure 3). There are some areas which show a marked undervaluation: 1911, the 1930s, 1955, 1961, and 1982-1983; and some a noted overvaluation especially in the early 1940s. The R^2 for the 1907-2003 period between the modeled and instrumental data is 0.665, which indicates slightly less skill when using the late model. However, a closer look at observed versus reconstructed values (Figure 4) demonstrates the strong correlation and supports the validity of the reconstruction.

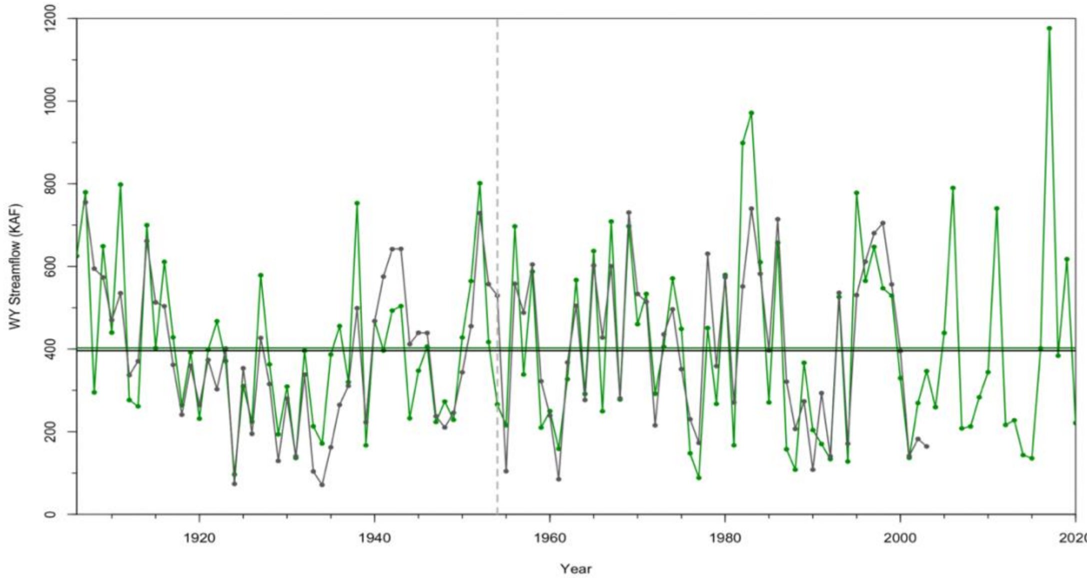

Figure 3: Reconstructed streamflow data (grey; mean = 396.0 thousand acre-feet (KAF) (black)) with instrumental data (green; mean = 402.6 KAF (dark green)) spanning 1907-2020. Dashed line = dividing year for validation/calibration (1954).

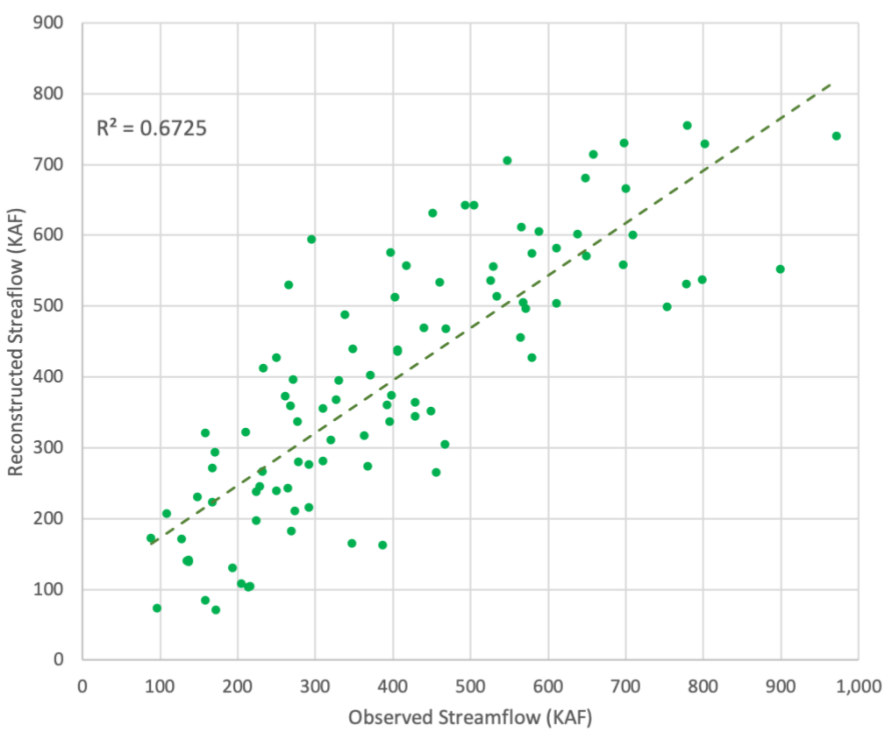

Figure 4: Correlation plot between reconstructed and instrumental data for 1907-2003 including trendline.

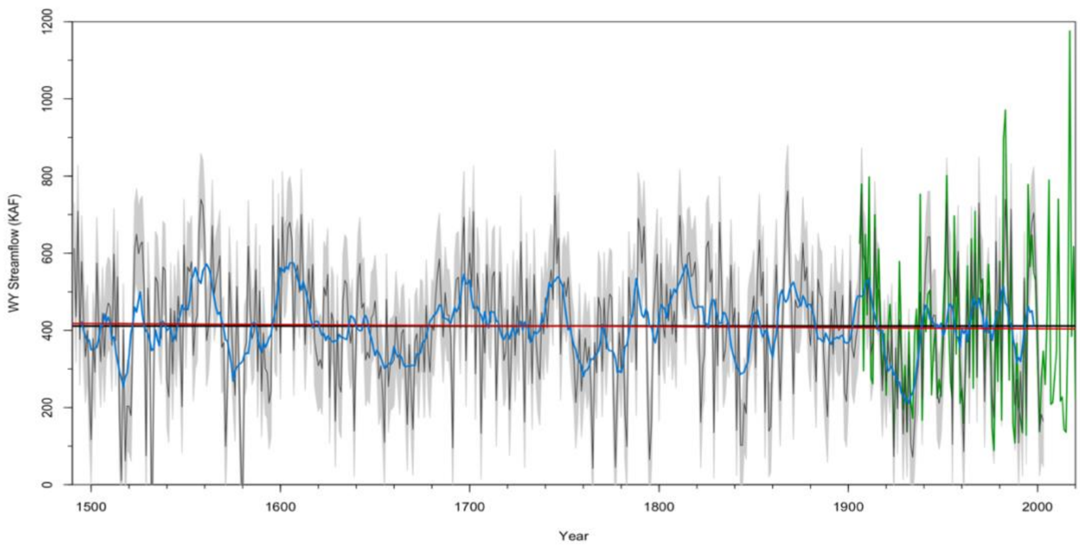

Figure 5: Truckee River streamflow reconstruction spanning 1491-2003 (dark grey) with a 10-year moving average (dark blue). Mean (411.3 KAF, black), and trendline (red) also indicated. Instrumental record in green.

Based upon these correlation and validation statistics, the late period model was decided upon, creating a Truckee River streamflow reconstruction spanning 1491-2003 (Figure 5). This represents an over 400-year extension of the instrumental record, and interestingly there are no periods in the 400-year record paralleling the 1917-1937 drought period in terms of the combination of length (20 years) and severity (65.9% of normal from the instrumental period reconstructed values (1907-2003)). 1651-1679 exhibit a similar prolonged dry period but without the same magnitude (81.8% of normal and punctuated by several high flow years). The most intensive low streamflow period for the reconstruction is 1515-1522 (8 years with 51.5% below normal streamflow, though it was 23.6% higher than the mean for the 10 lowest reconstructed years from 1917-1937). The well-documented late 1500s megadrought of western North America (e.g., Woodhouse and Overpeck, 1998; Meko and Woodhouse, 2005; Stahle et al., 2007) is also captured in this reconstruction, and for the TRB extends from 1569 to 1595. The lowest reconstructed individual years were 1516, 1532, and 1580 (the latter two of which reconstructed as negative streamflow, indicating that there was likely no measurable flow in the Truckee River during those years). 1745, 1868, and 1907 were the highest reconstructed years. Though 1907 is within the instrumental period (and a noted flood year), previous centuries have extended high streamflow periods that have no analogue in the 20th century. Notable high streamflow periods include 1549-1568, 1596-1617, 1738-1753, and 1801-1821.

To further support the reliability of this reconstruction, flood events from the historical records of the area were examined and also track closely with high streamflow years of the reconstruction. The flood of 1861-1862, as well as the several years of drought conditions preceding it, were both captured in this reconstruction and the findings of Lepley et al. (2020) on Sierra Nevada snowpack. Noted as a major flood year by Hardman and Venstrom (1941), the 1868 has a higher reconstructed streamflow value than 1862 (761,670.1 acre-feet versus 569,822.6 acre-feet) (Figure 5) and was also present in the neighboring Carson River Basin (U.S. Geological Survey Nevada Water Science Center, 2013). The 1906-1907 flood and 1950 "Thanksgiving Flood" track quite closely between the observed and reconstructed streamflow values. 1955, noted for being an exceptionally large flood spanning both Carson and Truckee River Basins (NevadaFloods.org, 2019; U.S. Geological Survey Nevada Water Science Center, 2013), is underestimated in the reconstruction; however, as this flood was driven by a localized rain-on-snow, this undervaluation is understandable as less snowmelt would be available during a tree's growing season (Moore and McKendry, 1996; Harpold, 2016). Interestingly, another rain-on-snow driven flood, 1997, shows an overestimation of streamflow. Beyond the historical records, there are several years of very high streamflow (potentially indicative of flooding): 1493, 1558, 1559, 1611, 1702, and 1745.

To develop a more in-depth understanding of the long-term variability between high and low streamflow episodes, z-scores were examined for the full reconstruction period (Figure 6). In simple terms, they indicate how far above and below the mean a data point is which thereby makes them appropriate for assessing the magnitude and duration of such streamflow episodes. Years of low streamflow extremes show a far greater magnitude than years of high extremes. With the exception of 1651-1679, 1754-1767, and 1917-1937; low streamflow periods tend to be very short in duration compared to higher flow periods. These latter periods not only have a longer duration; they also show a longer consistency of flow.

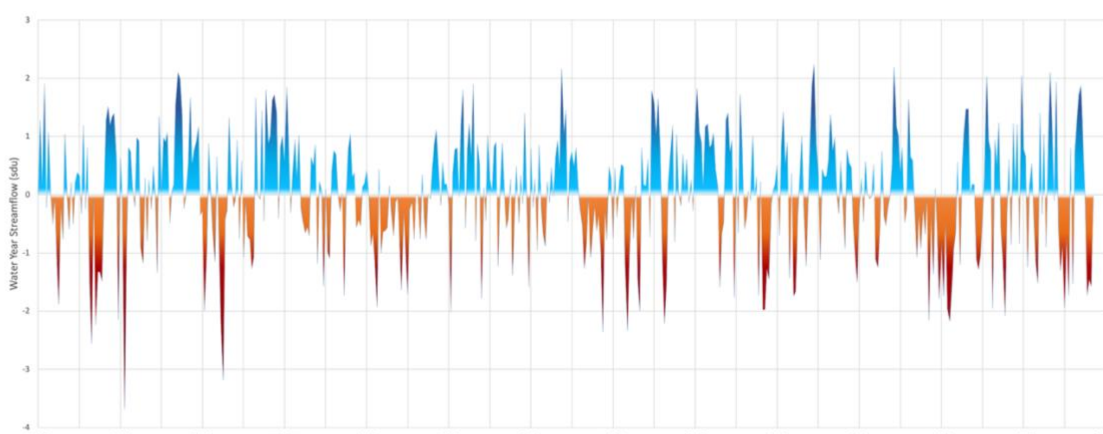

Figure 6: Plot of reconstruction z-scores for 1491-2003. Water Year Streamflow in standard deviation units (sdu). Blue shading indicates periods of higher streamflow; red shading indicates periods of lower streamflow.

DISCUSSION

The Truckee River streamflow reconstruction we developed in this study presents a 400-year extension of the instrumental record (Figure 5) and indicates that the region has been prone to extended higher and lower streamflow periods. Additionally it well captures instances of both extreme high- and low-flow events (e.g., floods), based upon the instrumental and historical records, which in turn lends credence to the magnitude of similar years within the reconstruction itself.

As Hardman and Reil (1936) used differing techniques to construct their chronologies and based most of their findings upon tree-growth curves produced using 3- and 5-year moving averages (which may miss some of the nuance of year-to-year variation), there are difficulties in directly comparing their findings to this study's statistical reconstruction. Interestingly, there appears to be a fair amount of agreement between the two. Firstly, their study and this both conclude that the 1917-1937 drought (for them 1918-1935) was the most severe, with Hardman and Reil estimating it to be the worst of the past 200 if not 600 years. Secondly, both studies indicate 1742-1753 had above average streamflow. Thirdly, Hardman and Reil (1936) also indicated that the years between 1755 and 1870 were exceptionally dry with the exception of two wet periods centered around 1790 and 1810 (Hardman and Reil, 1936), which fits roughly with our identification of a high streamflow periods of 1789-1793 and 1797-1821; however, our reconstruction does show more irregularity between briefer high- and low-flow episodes. They noted that 1875-1915 had values consistently above their mean and was likely the longest period of sustained higher flow since 1630; however, this does not entirely match our reconstruction which shows a more even balance of mixed high- and low-flow years

(21 above and 19 below). Additionally, 1692-1753 and 1797-1839 exhibit similar continual high flow with a comparable ratio of low-flow years to Hardman and Reil (1936). Hardman continued his examination of Truckee River runoff in a follow-up study (Hardman and Venstrom, 1941) by analyzing lake levels of its terminus lakes: Pyramid Lake and Winnemucca Lake (now nonexistent). Using photographs, historical accounts, and US Bureau of Reclamation records, they estimated lake levels and in turn used them as a proxy for Truckee River streamflow from 1839 to 1939. They reached similar conclusions to the tree-ring study, such as 1860-1917 being generally a period of higher precipitation/streamflow (Hardman and Venstrom, 1941). Consistent across Hardman's studies and this reconstruction was the 1840s regional drought which also occurred in the Sacramento, Walker, and Carson River Basins (Meko et al., 2001; Saito et al., 2015; Biondi and Meko, 2019) as well as at Lee's Ferry on the Colorado River (Woodhouse et al., 2006). The late 1500s megadrought (discussed below) too was present. An area of disagreement was centered around 1890. Hardman and Reil (1936) indicated this was a period of generally well above average streamflow, while Hardman and Venstrom (1941) showed it as a period of typically lower flow punctuated by two drastically higher years (1890 and 1893). Our reconstruction more closely reflects the latter paper's findings; however, the high-streamflow years show an undervaluation inconsistent with the instrumental records used in their study, which may potentially be due to carryover effects in the tree's physiology from the preceding drier years. Though there is general agreement between Hardman's original studies and this reconstruction, even the small disagreement emphasizes the importance of examining previous research to corroborate their and current

findings and verifying that the reconstructed values are in fact consistent with what is actually occurring within the watershed.

In a parallel concern of this study with the post-2000 drought, a major impetus behind Hardman and Reil's 1936 study was to assess whether their current drought was part of the natural variability of the area's hydroclimate:

> "While there may be some doubt about the date of some of the major climatic changes which have taken place in western Nevada, the droughts of the past few years have given intimate and painful evidence of recent variations in moisture supply which, while they may be of short duration, are disastrous to all interests dependent on irrigation." (Hardman and Reil, 1936)

Interestingly, in both this reconstruction and the instrumental record, the 1917-1937 drought is the most dire via a combination of consecutive dry years and extremely below average streamflow. There have been longer periods of low streamflow (e.g. 1651-1679, 28 years) (something also observed in Hardman and Reil (1936)) and episodes of even lower flow (e.g., 1515-1522, approximately 204,190 acre-feet/year per this reconstruction); however, Hardman and Reil's drought did in fact have the statistically highest severity (Supplemental Figure 3). In defining a drought as consecutive years below a standard deviation unit of -1 (Woodhouse and Pederson, 2018), 1515-1522 had 6 out of 8 years that qualify as drought (75%). Scaling this up to the same temporal extent as the 1917-1937 drought, it would have required 15 years to exhibit the comparable magnitude of severity. The 1651-1679 drought (6 years out of 28, 21.4%) when scaled down would entail 4.3 years. Neither of these periods exhibit the same relative size as the 1917-1937 drought with its 7 out of 20 years with below -1 sdu (35%). Additionally, 1934 has been previously recognized as the worst North American drought year for the last millennium based upon the Palmer Drought Severity Index (Cook et al., 2014) and prior to 2014 as the driest year in California since 1900 (Griffin and Anchukaitis, 2014). For the TRB, 1934 reconstructed as the 9th lowest (16th based upon Farad gauge data from 1907 to 2020; California Data Exchange Center, 2020), as well as the lowest for that drought, lending further support to its being the worst drought for the entire reconstruction period. That such a period could reoccur should be a concern for local water managers as we saw no evidence it may not. Additionally if it were, water usage and demand in the TRB have grown dramatically since the 1930s, thereby lessening the potential effectiveness of using similar mitigation strategies from that era to assist in the future. A further concern are rising global temperatures. Recent modeling studies of the Colorado River Basin have shown marked decreases in streamflow under various warming scenarios for droughts from 1900 onward (Udall and Overpeck, 2017; Woodhouse et al., 2021), indicating that temperature can play a major role in the severity of a drought period. Hence, the possibility of an ongoing drought and its magnitude as driven by higher temperatures both represent challenges in planning that water managers should be aware of, especially as increasing climate change's influence on future water availability remains uncertain.

The late 1500s megadrought is a well-known climate event in Western North America and has been studied extensively via tree-ring reconstructions (e.g., Woodhouse and Overpeck, 1998; Meko and Woodhouse, 2005; Stahle et al., 2007). Per this reconstruction, it spanned from 1569-1595 and an average streamflow of 84.2% of normal (based upon the reconstructed mean for 1907-2003) for the TRB. Though regional in scale, this wasn't precisely a 30-year period of extended drought but rather a series of very intense droughts broken up by single years of higher streamflow (Meko and Woodhouse, 2005), a pattern also exhibited in the TRB for this period. The most extreme year of this megadrought is 1580 (reconstructed as negative streamflow), and all of this study's newly developed chronologies had either missing or micro-rings for this year, a finding consistent with many trees within the Sacramento River Basin (Meko et al., 2001). Knowing that a megadrought has occurred within the TRB raises the question of whether another may happen in the future. There has been increasing amount of literature studying the post-2000 drought in western North America in comparison to Medieval megadroughts and if it is unprecedented due to rising global temperatures (e.g., Martin et al., 2020; Overpeck and Udall, 2020; Williams et al., 2020). Streamflow in this basin has seen a marked shift since 2000 with increasing drought-like conditions punctuated by 1-2 year events of higher than average streamflow (Supplemental Figure 4). Notably this does follow a similar pattern as the 1500s megadrought; however, because of the influence of anthropogenic climate change, it remains unclear as to whether the TRB is in fact undergoing a megadrought (which may end) or aridification (which may not end). The latter is especially concerning for water management as it would represent a fundamental shift in hydroclimate, and planning strategies could no longer rely on the past stationarity of the watershed's natural variability (Milly et al., 2008).

To further compound these uncertainties, starting around 1850 there is a marked shift away from decadal to multi-decadal high streamflow periods. Since that time, these episodes have gradually reduced in length: going from 8 years (1872-1879) to 6 years (1906-1911), and finally to 2-4 years since the 1930s (Figure 6). While not necessarily undergoing the same decline in high streamflow episodes, California has been experiencing an increasing frequency in the rapid change between extremely wet and dry years (Swain et al., 2018), which in turn indicates briefer durations of these periods. Whether this is a new feature for the nearby TRB is unclear; however, we see no evidence for this in the 500 years covered by our reconstruction. There is the possibility that this trend could be related to the increased burning of fossil fuels resulting from the Industrial Revolution, though such a hypothesis would require further study. This movement away from longer high streamflow periods could contribute to future water scarcity. With reduced water abundance, municipalities and other consumers will rely more heavily on reservoirs and aquifers for their water, which will in turn undergo decreases themselves due to a reduction in source water. This may also force water managers to rely more heavily on single-year high streamflow events (e.g., floods and atmospheric rivers) to replenish reservoirs, a practice with its own myriad of challenges and economic risks (Dettinger, 2013); Corringham et al., (2019); Rhoades et al., 2020), and difficult to plan for as these events do not have a predictable pattern of occurrence.

The pattern of decadal to multi-decadal high streamflow periods punctuated by generally brief low-flow years is especially apparent in the 1600s and 1700s. These centuries track quite closely the reconstruction of the nearby Sacramento River (Meko et al., 2001), and though they have different yearly streamflow volumes (in part because of the rain shadow effect as these rivers are on opposite sides of the Sierra Nevada, and the Sacramento River Basin is much larger than the TRB), their correlation lends further support to the validity of this reconstruction. This may also indicate that Sacramento River streamflow could be used to assess long-term trends (though not magnitude) in the Truckee River, which is particularly useful as Meko et al.'s reconstruction extends to CE 869.

Despite these longer high streamflow periods, extended droughts did still occur, notably 1651-1679 and 1754-1767. This may suggest that even with the streamflow pattern shift around 1850 such long-term droughts are likely to reoccur in the future and need to be considered in future water management planning.

As previously noted, the Truckee River is prone not only to droughts but also seasonal floods, which in turn adds complexity from a water management standpoint as both long-term water scarcity and single-event overabundance need to be accounted for. The highest streamflow value from the reconstruction was 761,670.1 acre-feet (1868), 92% above the reconstructed mean from the instrumental period (1907-2003). 1868 was a well-known major flood and high streamflow year (Hardman and Venstrom, 1941; NevadaFloods.org, 2019); however, this reconstructed value may in fact be an underestimation. As shown in Figure 3, tree-ring reconstructions can often underestimate years of extremely high streamflow. Trees that are moisture-sensitive (such as in this study) have their annual growth dictated by how much water is present in their environment; however, even in the presence of an overabundance of water, a tree can still only grow so much in a season. Therefore underestimations in hydrologic reconstructions are to be expected but also potentially indicate the 1868 flood was of a much higher magnitude. Additionally, 1493, 1558, 1559, 1611, 1702, and 1745 (the highest reconstructed years prior to the historical record) could also have had higher streamflow, though we are currently unable to determine if these too were flood years. The 2017 water year had the highest streamflow on record (1,176,457 acre-feet; Supplemental Figure 4, Supplemental Figure 5) and was characterized as having a large flood; this event therefore may itself be outside the magnitude of past (and thereby future) high streamflow years, but further development of flood-specific tree-ring chronologies would be needed to address this question.

In addition to the uncertainty of past high flow magnitude, assessing how Truckee River streamflow is influenced by larger climate phenomena can be difficult given the basin's position within the north-south precipitation dipole of western North America (Brown and Comrie, 2004; Wise, 2010). Cool-season precipitation can manifest as a kind of seesaw between the Pacific Northwest and the American Southwest (Dettinger et al., 1998); i.e., when one area receives more precipitation, the other generally receives less, and vice versa. The boundary between these two zones, however, is spatiotemporally variable (Wise, 2010), and so how a location is affected by a mode of climatic variability such as the El Niño-Southern Oscillation (ENSO) may differ from year to year. Between 1926 and 2007, the transition latitude for 120°W had ranged from 37-42°N (Wise, 2010); the TRB extends from 38.70-40.45°N and 119.17-120.46°W (Figure 2), well within this zone of variability. Therefore, this reconstruction is unsuitable for understanding ENSO events, and water managers should be discouraged from relying on larger climate cycles as predictors for future Truckee River streamflow. To further emphasis this, a recent study indicated that cold-season precipitation in the Sierra Nevada does not follow any cyclical patterns (Williams et al., 2021).

This study was first and foremost designed as a continuation of the work by Hardman and Reil (1936). It was a replication as well as an update, both aiming to understand local drought in the context of wider climatic variability, and as such there were certain limitations in its design that may be mitigated by future research. The newly developed chronologies' locations were derived from the original runoff study

(Supplemental Figure 1); HCK and HIR did in fact prove to capture Truckee River streamflow quite well. Thus building new chronologies from even more suitable sites within and without the TRB would enhance our understanding of its streamflow variability. Updating those chronologies in the region that were eliminated due to their end-date (prior to 2003) would also be beneficial and allow for a better understanding of how trees have responded to the hydroclimatological changes of the 21st century.

CONCLUSION

In this study we developed a 500-year reconstruction of streamflow for the Truckee River, the first since 1936 and the first using modern dendrochronological techniques and technologies. It represents a 400-year extension of the instrumental record (Figure 5) and thereby provides a deeper understanding of this basin's hydrological variability. This broader picture of the range of extreme hydrologic events and occurrences of long-term high and low streamflow episodes can assist local water managers in their future planning decisions, especially as global temperatures continue to rise.

It demonstrates that extended droughts are a common periodic occurrence in previous centuries as are intensive high streamflow years and floods, both of which water managers should accommodate for in their planning strategies. The 1850s show a transition away from decadal/multi-decadal high streamflow periods which may have concerning consequences in the future as less water may be available for reservoir and groundwater recharge. The 1917-1937 drought is unique through its combination of duration and magnitude in the reconstruction as well as the instrumental record. However, more severe (but shorter) and longer (but less severe) droughts have occurred, and we have seen no evidence that they or the 1917-1937 drought may not reoccur. As global temperatures rise, the severity of such episodes would likely only increase (Udall and Overpeck, 2017; Woodhouse et al., 2021), providing additional concerns for future water policy planning scenarios. The post-2000 drought shows similarities with the late 1500s megadrought, but the extent to which is yet to be fully determined, especially under the contribution of anthropogenic warming (Williams et al., 2020). As the influence of climate change increases, future water management planning may need to develop mitigation strategies for streamflow variability beyond what has been experienced in the last five centuries.

CHAPTER 2:

GEORGE HARDMAN'S RELATIONSHIP WITH DENDROHYDROLOGY

INTRODUCTION

George Hardman took on the role of both a scientist and a water manager when he authored one of the earliest studies correlating tree rings with river runoff (Hardman and Reil, 1936). Such reconstructions are now common and well-understood in the field of dendrohydrology (e.g., Woodhouse et al., 2006; Meko et al., 2012; Malevich et al., 2013) as are their benefits to water managers (e.g., Woodhouse and Lukas, 2006; Rice et al., 2009; Woodhouse et al., 2016). However, in the 1930s, there was a disconnect between the realms of academia and application. Hardman was one of the earliest to bridge this gap, thereby creating a lasting impact on the study of tree rings and their relationship to streamflow.

Hardman was part of a larger tradition of land and water management in the Western United States in the first half of the 20th century. His career spanned a broad range of specialties from agronomist to Nevada's first state conservationist, and he participated in many of irrigation and soils projects as part of his affiliation with the University of Nevada Agricultural Experiment Station (e.g., Bixby and Hardman, 1928; Hardman, 1944; Hardman and Mason, 1949; Hardman, 1968). In the 1920s and 1930s, western Nevada had been undergoing a severe drought, and Director Samuel B. Doten, Hardman's superior at the station, had developed growing concerns over possible water shortages if the drought were to continue. So in 1934 he persuaded Hardman to do a tree-ring study on the Truckee River to address worry.

Hardman was not the first to investigate the relationship between tree rings and streamflow. Beginning in the 1870s, Jacobus Kapteyn began exploring how tree rings reflected river levels in Germany (Kapteyn, 1914). Though there had been informal studies since that time, it wasn't until after A.E. Douglass (a founder of modern dendrochronology) published "The Secret of the Southwest Solved by Talkative Tree Rings" (Douglass, 1929) that water managers and civil engineers truly began questioning of how tree rings may be applied to hydrologic planning. H.B. Lynch did a study focused exclusively in Southern California with an emphasis on rainfall, but he did include a consideration of stream runoff as well (Lynch, 1932). John Girand built upon this with an examination of tree rings in relation to the Salt River in Arizona (Girand, 1933). Hardman's friend and colleague, Sidney Harding correlated them to Lake Tahoe lake levels (Harding, 1935). Yet none of these studies truly came to the attention of academic circles until Hardman's revolutionary publication.

His time using dendrochronology was brief, merely a single study, but it laid the foundation for the next pioneers in dendrohydrology such as Edmund Schulman, a protégé of Douglass. His numerous tree-ring publications regarding precipitation and streamflow in the Western United States (e.g., Schulman, 1942; Schulman, 1945; Schulman, 1954; Schulman, 1956) firmly established the subdiscipline, and Schulman's role as academic made sure his work was cited far and wide. Not to be overlooked, Hardman's river runoff study is increasingly being cited today (Google Scholar, 2021; Figure 7). Here I conducted a preliminary examination of Hardman's direct influence on dendrohydrology; firstly, however, I explored how he, a water manager, potentially learned the techniques of a dendrochronologist.

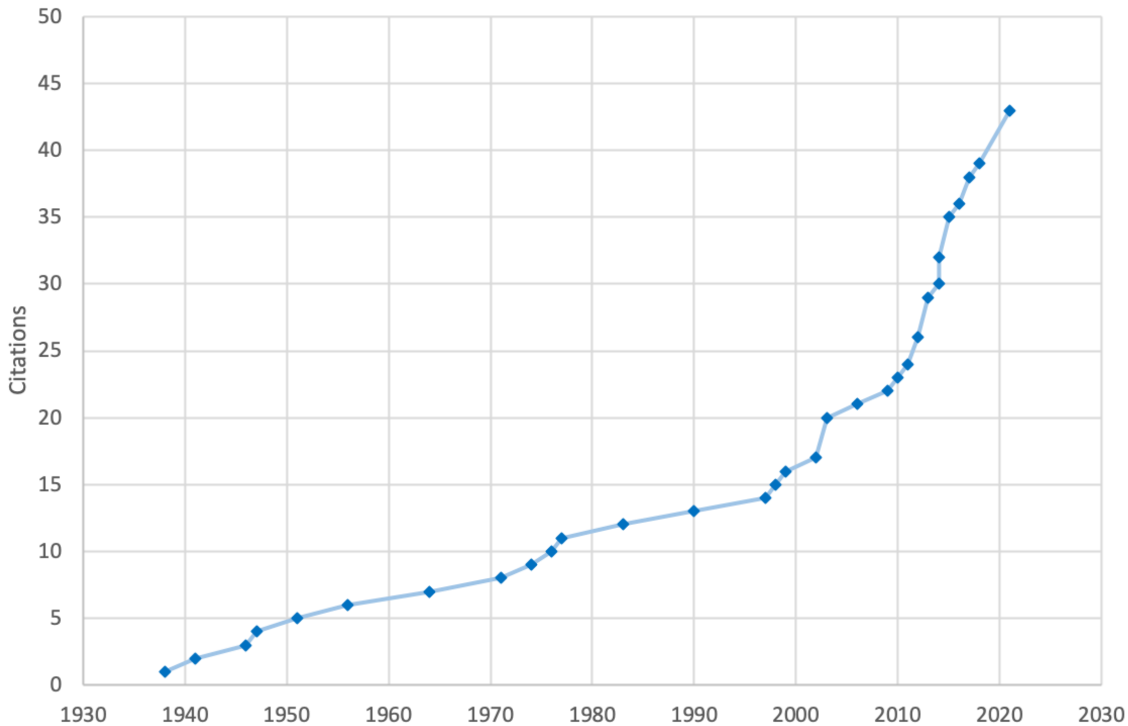

Figure 7: Plot of citations for Hardman and Reil (1936) since publication. Source: Google Scholar.

METHODS

No knowledge truly develops in a vacuum; it is always built upon the methods and information developed by previous scientists. As a scientific discipline, dendrochronology was over twenty years old by the time Hardman published his paper. As Marvin Stokes and Terah Smiley had yet to write their handbook detailing the field's techniques (1968), Hardman would have needed someone to instruct him how to conduct such a study. To discover this individual, I employed occupational forensics with an emphasis on archival research.

Jane Maienschein provided a methodological framework for such in an undertaking remarkably similar to my own streamflow reconstruction (Maienschein et al., 2008). She reproduced the experiments of a past scientist but required further information for them to succeed. She applied occupational forensics to trace Ross Granville Harrison's career in the early 1900s to seek the tacit knowledge and personal connections which allowed him (and eventually her) to successfully complete his research (Maienschein et al., 2008). In the same vein, I examined Hardman's employment history, his correspondence, and a firsthand account of his time at the University of Nevada Reno (UNR) via an oral history (Hardman, 1968).

Due to his employment with the Agricultural Experiment Station and agencies like the Soil Conservation Service, UNR Special Collections and Archives has extensive material on Hardman and the projects he was involved in. This includes official correspondence, outlines for studies, travel receipts, and other documentation (Max C. Fleischmann College of Agriculture. Agricultural Experiment Station, 1932-1942 (hereto known as "AES, 1936-1942")). This correspondence in addition to that of Harding's obtained from the Water Resources Collections and Archives at the University of California Riverside (Harding, 1912-1969), and of Douglass's obtained from the University of Arizona Special Collections (Douglass, 1920-1956); provided the bulk of my primary source material through which I looked for specific references regarding tree-ring research and how Hardman may have learned dendrochronological techniques.

In determining a scientist's impact on a field, there are several potential metrics to pursue. For example, conducting personal interviews to gain insights and testimonials from that individual's colleagues/mentees; assessing how many conferences or symposia they attended and gave presentations for; and tracking the number of their publications and the awards they received. I chose to use bibliometrics via the use of citation analysis, which is a form of network analysis that instead of tracing social connections, traces connections via publications (Nicolaisen, 2007). Google Scholar has been shown to be an effective gauge of this metric (Onyancha, 2009), and so it was used as a primary source to gauge the specifics of who has referenced Hardman and Reil (1936) and in what context. While not every citation was examined in depth, this cursory overview still allowed for a general understanding of what Hardman's influence has been and what it continues to be.

RESULTS

Based on documentary evidence, Hardman most likely first became aware of dendrochronology through the suggestion from Doten (Hardman, 1968); however, how he learned dendrochronological techniques remains unclear. Doten immediately recognized Hardman's ability to take on a wide array of projects by putting him in charge of the Agricultural Experiment Station Farm and had first suggested using tree rings to study the Truckee River and assess their current drought (Hardman, 1968). Doten was an etymologist and could have learned about Douglass's work through his own research, representing a connection to dendrochronology for Hardman, but it is still unclear, and further research would be required.

Hardman used a similar measuring apparatus as Douglass, even employing the man's core-dotting practice (Hardman and Reil, 1936). Both of these imply a detailed studying of contemporary dendrochronological methods, knowledge of which had to come from somewhere. Regarding administrative documents (e.g., invoices and project outlines), none gave any hints of possible travel or collaborative endeavors that would have allowed Hardman to learn dendrochronology. There was, however, an expense sheet regarding the 1936 study which provided a list of the individuals who directly assisted him with the project, so this line of research was not entirely unfruitful. Findings from Hardman's oral history were also extremely limited: merely two paragraphs referencing the why and when the study was done (Hardman, 1968).

Correspondence between Hardman and others was somewhat sporadic in results. It was quite clear that Hardman and Harding were friends as well as colleagues, and they certainly did discuss some tree-ring research, especially in 1935 when Hardman was conducting his study (AES, 1936-1942; Harding, 1912-1969). There were tantalizing hints of phone calls and a conference they both attended in Los Angeles (the name and date of which I was unable to determine) (Harding, 1912-1969). If Harding were the person to have taught Hardman dendrochronology, then it would have occurred during these personal interactions; however, nothing is concrete. There was a letter in 1935 from Hardman to Douglass requesting feedback on his paper (AES, 1936-1942), so there at least was some connection between them. However, as no reciprocal correspondence was found, the nature of their association remains unclear.

As this is merely a cursory exploration into those citing Hardman and Reil (1936), these findings do not represent the full scope of his influence on dendrohydrology. I restricted my in-depth analysis to the most highly-cited publications as well as the most recent. Both I believe represent a preliminary overview of his historical impact and his continuing relevancy.

Per Google Scholar (2021), Hardman's paper has been cited 43 times in scientific papers and books, including 4 times in this year alone (2021) (Figure 7). Using a 100-

citations cutoff, Hardman and Reil (1936) was cited 4 times: Woodhouse and Overpeck (1998); Benson et al. (2002); Herweijer et al. (2006); and Liu et al. (2010). Of them, three focused on droughts in North America, and the fourth applied Hardman's dendrohydrological framework to a Chinese watershed. In the last five years (2017-2021), Hardman and Reil (1936) was cited 6 times: Gholami et al. (2017); Stoffel et al. (2017); Thornton (2018); Galelli et al. (2021); Gholami et al. (2021); Ruman et al. (2021); and Sun et al. (2021). Each of these focus on the Hardman's usage of dendrohydrological techniques.

CONCLUSION

It is often difficult to assess the full story and impact of a single event. In this case, the event was the publication of a study correlating tree rings to river runoff in an academic venue (Hardman and Reil, 1936), which has a history and aftermath all of its own. Hardman had never used previously tree rings for his research; he therefore needed to take an intellectual journey before that study could begin. By bridging the gap between the academic and the applicative, his study forever changed the field of dendrohydrology.

Though the first part of my inquiry remains inconclusive, there is still archival material to be examined, especially in the UNR Special Collections and Archives, and potentially other water-manager-related archives around the Western United States. While this is a question that may never be answered, merely exploring it can reveal insights into the connections of early tree-ring research in dendrohydrology and whom the key practitioners may have been outside of Douglass's tree-ring lab.

Following Hardman, dendrohydrology grew into a subfield all its own. Yet it never fully remained within the purview of academia, as water managers and policy decisionmakers continue to utilize tree-ring streamflow and hydrologic reconstructions for their projects (e.g., Stockton and Jacoby, 1976; Rice et al., 2009; Woodhouse et al., 2016). As for Hardman's influence, this preliminary overview only begins to answer that question. There remains an active interest in his research, not only through recent citations but my own Truckee River streamflow reconstruction, and only history will tell how this field will continue to evolve.

CONCLUSION

In this thesis, I used annual tree-ring widths to create a reconstruction of Truckee River naturalized streamflow, the first since the 1930s (Hardman and Reil, 1936). Additionally I performed a preliminary examination of this original study's impact on dendrochronology. My reconstruction extends the instrumental record by over 400 years and provides insights into the Truckee River Basin's long-term natural variability, which may assist in future water management policy decisions. The relevancy of George Hardman's work persists in the field of dendrohydrology as it signified an early bridge between academia and the applicative uses of tree-ring research, and is increasingly cited.

Using Hardman's original 1930s tree cores and newly sampled material, I built new tree-ring chronologies from three of his study sites. Combined with additional ITRDB chronologies, these were incorporated into a stepwise multiple linear regression to create a 500-year streamflow reconstruction for the Truckee River. The region is subject to both prolonged low streamflow periods and sharp single-year high flows, both of which are evident in the reconstruction. There is a marked turn around the 1850s in which decadal/multi-decadal high streamflow episodes no longer occur, possibly representing a fundamental shift in the basin's climate. The 1917-1937 drought was the most severe in both the reconstruction and the instrumental record, and as global temperatures continue to rise, its repetition may become an increasing concern, and one water managers should consider in their policy planning.

In addition to this reconstruction, I explored Hardman's relationship with dendrohydrology, both before and after his 1936 study. The former remains as a matter of further research, but even with preliminary work on the latter, he has a lasting legacy within the field. From the early recognition received from Schulman, a pioneer in dendrohydrology, (Douglass, 1920-1956) to an editorial examining the usage of tree-ring data for water resources management set to be published this August (Galelli et al., 2021), Hardman's influence has lasted over 85 years and in some ways is only growing with 25 citations since 2000 (Google Scholar, 2021; Figure 7).

Dendrochronology and history go hand-in-hand: one explores the story of an environment; the other, the story of people. In both we learn about the past, inform the present, and make predictions for the future. George Hardman's 1936 study provides a link between these two in the same way that it linked the academic and non-academic worlds. My research explored both of these avenues, creating an up-to-date understanding of the Truckee River and an understanding of how a water manager changed the field of dendrohydrology forever.

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APPENDIX A

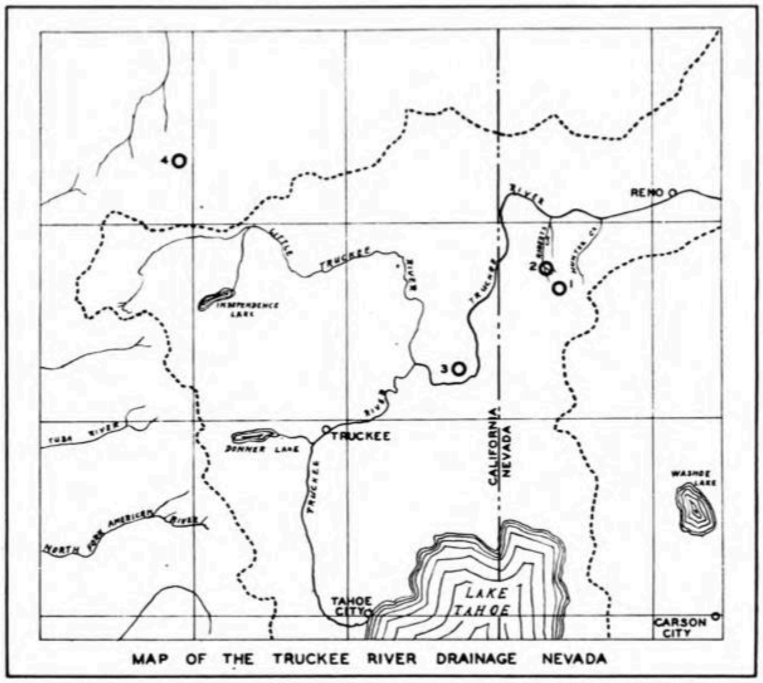
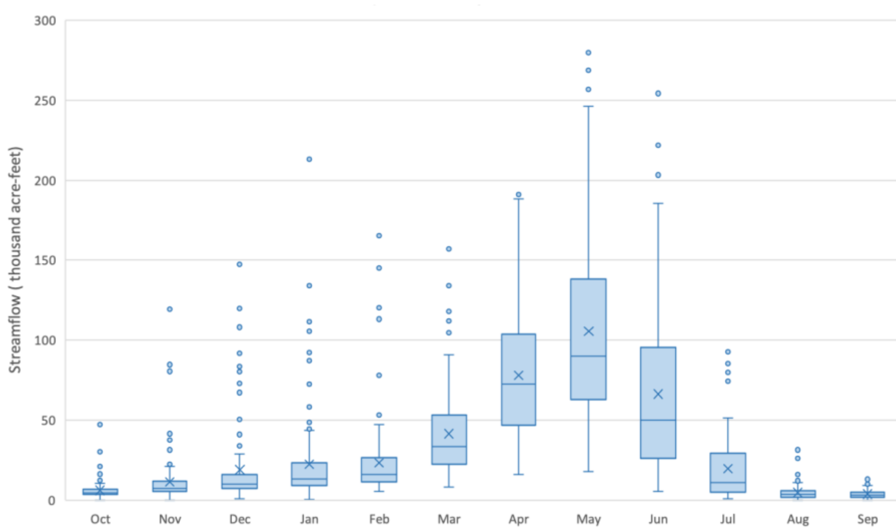


Figure 1. Map of the Truckee River Basin.

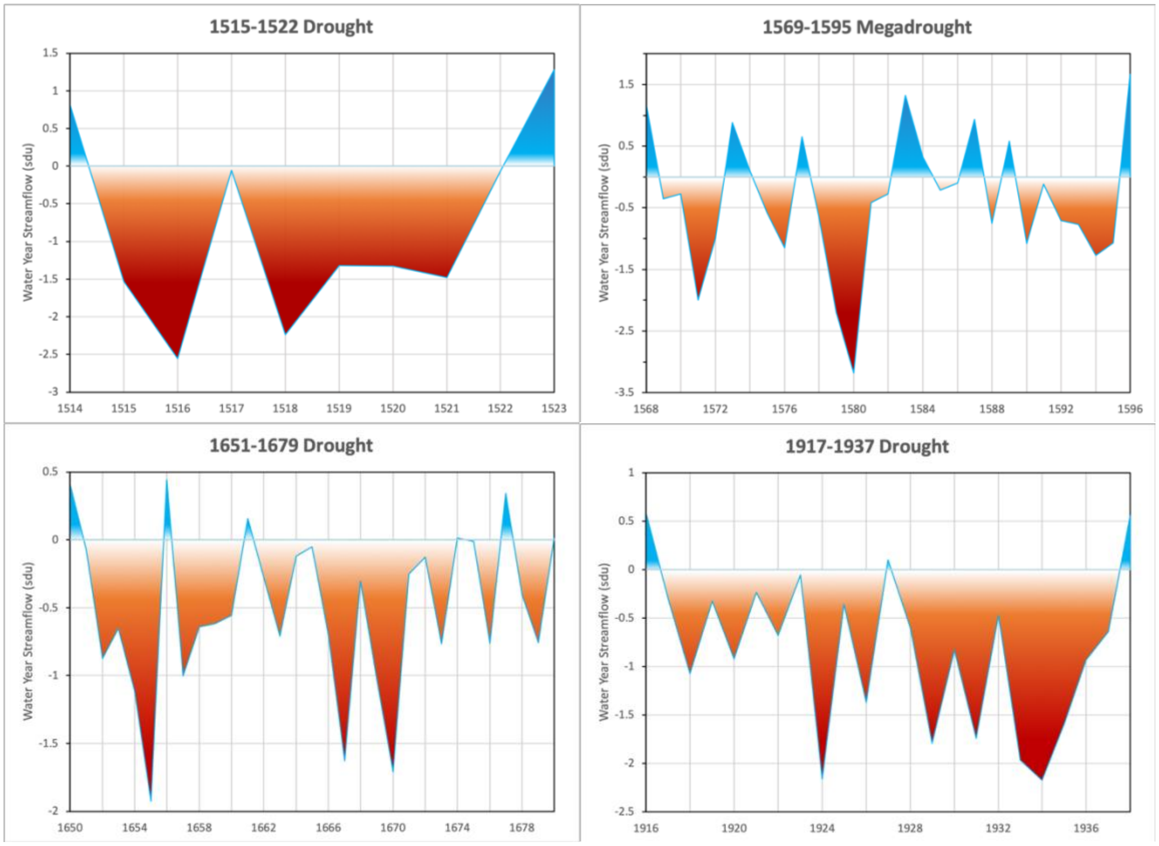
The groups of trees, indicated by circles and numbers, are as follows:

Number	Group	Elevation
1	Hunter Flat	7,500–8,500 feet
2	Roberts Creek	6,000–7,000 feet
3	Hirschdale	5,500–6,000 feet
4	Sierraville	5,500–6,000 feet

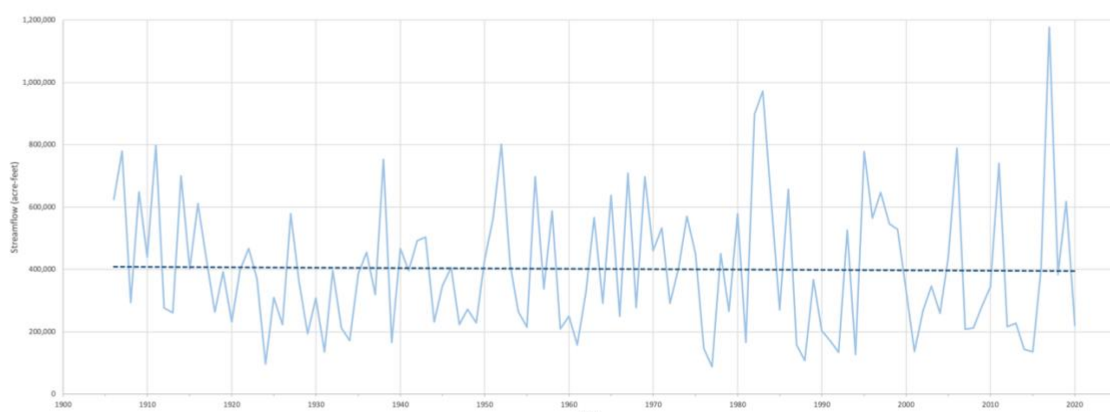
Supplemental Figure 1: Map from original Truckee River study (Hardman and Reil, 1936).



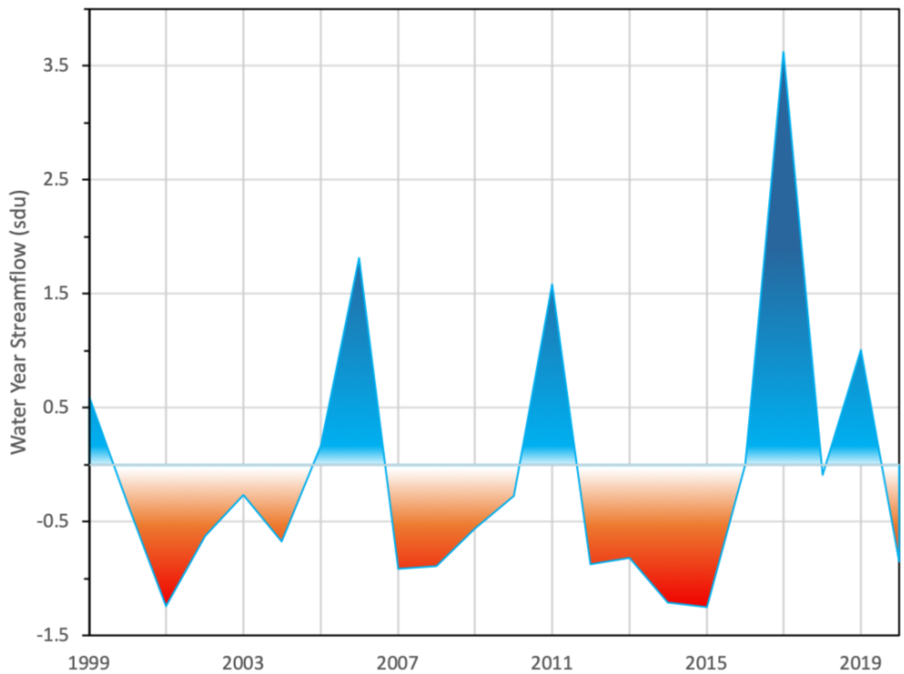
Supplemental Figure 2: Boxplots of monthly Farad gauge streamflow (October 1906-September 2020). Source: California Data Exchange Center.



Supplemental Figure 3: Z-score plots of significant droughts based upon reconstruction values and mean for the entire reconstruction (1491-2003).



Supplemental Figure 4: Truckee River Farad Station gauge data for streamflow spanning 1907-2020 including trendline.



Supplemental Figure 5: Z-score plot of post-2000 drought based upon Farad gauge data with a mean for entire instrumental period (1907-2020).