An 828 Year Streamflow Reconstruction for the Jordan River Drainage Basin of Northern Utah

Bryan P. Tikalsky
Brigham Young University - Provo

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AN 828 YEAR STREAMFLOW RECONSTRUCTION FOR
THE JORDAN RIVER DRAINAGE BASIN
OF NORTHERN UTAH

by

Bryan Tikalsky

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment for the degree of

Master of Science

Department of Geography
Brigham Young University
July 2007
This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

Matthew F. Bekker, Chair

Mark Jackson

Renee Gluch
As chair of the candidate's committee, I have read the thesis of Bryan Tikalsky in its final form and have found that (1) its format, citations, and bibliographical style are consistent and acceptable and fulfill university and department style requirements; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the graduate committee and is ready for submission to the university library.

Matthew F. Bekker
Chair, Graduate Committee

Accepted for the Department

Matthew Shumway
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Accepted for the College

David B. Magleby
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ABSTRACT

AN 878 YEAR STREAMFLOW RECONSTRUCTION
FOR THE JORDAN RIVER DRAINAGE BASIN
OF NORTHERN UTAH

Bryan Tikalsky
Department of Geography
Master of Science

Mountain water resources are essential to those living along the Salt Lake City urban corridor. Water resource planners base their policy on twentieth century climate conditions and streamflow records. Often these records only account for a small amount of the natural variability in streamflow and climate. By utilizing dendrochronology this study seeks to better understand variability of streamflow in the Jordan River Drainage Basin over the last 828 years. A GIS model was used to identify potential sampling sites where tree growth would be sensitive to climate and factors affecting stream run-off. Over eighty samples from ancient limber pine (Pinus flexilis) and Douglas-fir (Pseudotsuga menziesii) were obtained to perform the reconstruction. Results indicate significant correlation between tree growth and streamflow. A multiple linear regression model created with tree-ring width as the predictor of October - March American Fork
River streamflow explained 51.7% of streamflow variance. Analysis of the reconstruction indicates that present records do not adequately represent potential streamflow variability, and several droughts of greater severity and length occurred before the instrumental period.

Keywords: Climatology, Water Resources, Dendrochronology, Wasatch Mountains, Utah, Streamflow
ACKNOWLEDGMENTS

First and foremost I would like to thank my advisor Dr. Matt Bekker. I am grateful he encouraged me to pursue graduate work and gave me the chance to take on this project. His instruction, guidance, support, and advice made this study possible. I would like to thank my graduate committee members Dr. Mark Jackson and Dr. Renee Gluch for their feedback and valuable GIS and Remote Sensing instruction. Ben Bright deserves recognition for his help collecting tree samples and for his many hours of lab work dating and measuring tree-rings. Thanks to Dane McQuarrie, Jess Clark, Dan Bentley, Bob Sivert, and Joe Dixon for their help with site selection and data collection. I especially thank my wife, Emilee, for her love, encouragement, and continual confidence that I could finish this project.
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Chapter 1 – Introduction

Residents of Utah’s urban Wasatch Front, stretching approximately from Ogden to the north and Provo to the south, rely heavily on the precipitation that falls in the Wasatch Mountains and makes its way to lower valleys through several streams and rivers. Industry and agriculture in the region place heavy demand on water resources. Current instrumental measurements of streamflow provide a very limited view of annual changes in streamflow over the long-term. Water resource planners are, therefore, forced to create policy based on the limited amount of streamflow data available. This can be problematic if estimates of streamflow variability, obtained from 20th Century streamflow records, are higher than actual long-term streamflow variability. If planners are able to access streamflow records representing variability over many centuries, they can better prepare for future droughts and extended low-flow periods.

Through the science of dendrochronology this research provides an 828 year streamflow reconstruction for the Jordan River Drainage Basin (JRDB). The reconstruction is examined in context of increasing water demand due to urban and suburban growth along the Wasatch Front. The reconstruction serves as a valuable resource for water resource managers and those interested in moisture availability in the JRDB.

Dendrochronology is the science that uses tree-rings dated to their exact year of formation to analyze temporal and spatial patterns of processes in the physical and cultural sciences. More specific to this research project, dendroclimatology is the study
of earth’s climate via tree-ring analysis (Fritts, 1976; Stokes and Smiley, 1996). In order to better understand earth’s past climate, many scientists have turned to analysis of ice cores, pollen samples, and tree-rings to carry out their research. Though tree-rings do not allow scientists to extend the climatic record back as far as other proxy methods, tree-ring research offers the distinct advantage of recording an annual climatic signal. Some consider tree-rings as the only proxy that satisfies all of the requirements for a climatic reconstruction (UDWR, 2007).

The Wasatch Mountains are an excellent location to obtain ancient tree samples useful for understanding the region’s paleoclimate and changes in water availability. Ancient limber pine and Douglas-fir, some having lived more than a millennium, inhabit high elevation sites within the Wasatch that are characterized by steep slopes and high winds. At sites such as these, on the fringe of the tree’s comfort zone, change in tree growth is likely to be most affected by climatic variation.

Researchers have successfully utilized limber pine and Douglas-fir to perform climatic reconstructions in Wyoming and other regions throughout the west. Many have discovered that limber pine’s growth is related to changes in both temperature and precipitation (Gray, Jackson, & Bentacourt, 2004; Case & MacDonald, 1995). I hypothesized that the growth of trees dwelling in these harsh Wasatch environments was limited primarily by climatic conditions derived from different combinations of temperature and precipitation.

Samples from these trees, both living and dead, were obtained from two sites: Big Flat Ridge (BFR) which is located on the south side of Alta Ski Resort in American Fork Canyon, and Cascade (CSC) which is located on the south slope of Cascade Mountain
above Rock Canyon near Provo, Utah (Figure 1-1). Once samples were obtained from these sites statistical techniques were utilized to examine the relationship between tree growth and streamflow, and to analyze the differences between modern streamflow records and proxy records based on tree growth. This analysis puts JRDB drought events such as the dustbowl of the 1930s and high-flow years such as those in the early 1980s within a context of the last 878 years rather than only the 20th Century.

Reconstructions performed at other sites in the intermountain west have made significant discoveries. Reconstruction of Colorado River flows at Lee’s Ferry, for example, found that water allocation between states relying on the Colorado River was decided during a time of abnormally high river flow (Stockton & Jacoby, 1976). The study was recently confirmed and updated (Woodhouse & Gray, 2006). This discovery could have serious implications because as demand for Colorado River water increases, future low-flows may not be adequate enough to meet the population’s needs.

Because of regional differences in climate, results obtained in one place cannot be assumed to apply in another. With the exception of a study performed to investigate the position of a winter air mass boundary in the west that indicated that the Great Salt Lake Basin’s climate differed from surrounding regions (Woodhouse & Kay, 1990), little is known about the paleoclimate of the JRDB. Therefore, this study serves the important purpose of fulfilling the need to understand paleostreamflow in the JRDB by extending the instrumental record back to the year 1178. In short I attempt to discover if streamflow variation in the JRDB has been accurately portrayed by 20th Century records. I also compare the JRDB reconstruction with streamflow and climatic reconstructions from neighboring regions.
Figure 1-1: Map of Jordan River Drainage Basin
This study relates to Geography because it attempts to better understand environmental patterns over space and time that directly influence human development. In the American West surface water is a precious resource. A shortage can lead to an inability to cope with the environment and consequences of drought such as crop failure, lack of water supply, and wild fire. Thus, the information provided by this thesis can give direction to appropriate decisions that will enhance the ability of Wasatch Front residents to effectively utilize their water resources during times of both drought and plenty.
Chapter 2 – Background

Description of the Jordan River Drainage Basin

Demands on water resources and their management in the JRDB are complex. Because this research attempts to reconstruct streamflow for the JRDB, it is important to have an understanding of the region’s cultural and physical geography. The JRDB stretches along the Wasatch Front extending from Salt Lake City to Nephi and is unique in Utah because it serves such a large urban population. The JRDB covers all of Utah and Salt Lake counties and parts of four other counties (Figure 2-1).

The Salt Lake County portion of the basin, transected by the Jordan River, is known as the lower portion of the basin. The Utah Lake portion to the south, which feeds the Jordan River, is known as the upper portion of the basin. The size and location of the population centers within this drainage make the distribution of surface water the most complex in the state. On average approximately 86% of the flow of the Jordan River is utilized before it reaches the Great Salt Lake (UDWR, 1997a). Both the necessity to use Jordan River water for irrigation and the size of the urban population dependent on JRDB water illustrate the importance of this natural resource. There is intrinsic value in the further understanding of natural variability in JRDB streamflow.

The upper portion of the basin includes all of the tributaries to Utah Lake, which is the primary destination of all streams and rivers in the upper basin. The Provo and Spanish Fork Rivers are the two largest tributaries to Utah Lake. Other streams that drain into Utah Lake include the American Fork River, Hobble Creek, Dry Creek, and Beer Creek.
Figure 2-1: Map of JRDB Showing Upper and Lower Basin
Describing the Provo River helps illustrate how the importance of surface water in the region has driven resource managers to modify its flow and the flow of nearly every stream within the JRDB. The Provo River, the main tributary to Utah Lake, has its headwaters high in the western end of the Uinta Mountains where elevations exceed 3,350 meters. Here glacial tarns catch the high amounts of precipitation that fall primarily in the winter months. Between its headwaters and destination at Utah Lake, the two largest dams on the Provo River form two large reservoirs, Jordanelle Reservoir and Deer Creek Reservoir. Each serves agricultural, urban, and recreational purposes for the region. The Provo River drains an area just over 650 square miles, and the majority of the drainage consists of areas that are lightly inhabited consisting of mountainous and forested land. Because of the high demand for surface water in the JRDB water is imported from surrounding basins to the Provo River.

*The American Fork River*

The main sample site for this study was located within American Fork Canyon (Figure 2-2), and I chose to reconstruct streamflow for the American Fork River, which drains American Fork Canyon. This river empties into the northeastern portion of Utah Lake, and has its headwaters in the high terrain of the Wasatch Mountains. Though it drains a much smaller area compared to that of the Spanish Fork and Provo Rivers, the headwaters of the American Fork River are similar. Elevations exceed 3,350 meters, and glacial tarns such as Pittsburg and Silver Lake are present. Precipitation levels at these
Figure 2-2: Map of American Fork Canyon
high elevations are some of the highest in the state. The highest mountain peaks average more than 1,270 centimeters of snow per year. Successful streamflow reconstructions were also carried out for the Spanish Fork and Jordan Rivers.

The streamflow record for the American Fork River is affected by two small reservoirs. The smaller of the two is Tibble Fork Reservoir. Tibble Fork Reservoir, built in 1966, can hold a maximum volume of 259 acre feet and has a mean depth of only 3.4 feet. Its total shoreline is just 1,536 meters (Figure 2-3). Tibble Fork Reservoir is located at the point in the canyon where glaciers once extended furthest south (Utah Division of Water Quality [UDWQ], n.d.). It dams only the north fork of the stream; the south fork of the stream flows unimpeded. Because of its small size, the effect of this reservoir on streamflow records is likely very minimal, especially compared to the other larger rivers in the basin where much bigger reservoirs are located.

Figure 2-3: Picture of Tibble Fork Reservoir
Source: (UDWQ, n.d.)
Also located within American Fork Canyon is Silver Lake Flat Reservoir (Figure 2-4). With a total capacity of 1,040 acre feet it holds approximately four times as much water as Tibble Fork Reservoir. Silver Lake Flat Reservoir covers 44 surface acres and was built in 1971. The reservoir dams only one tributary of the north fork of the American Fork River. Because of its size this reservoir likely does have a small effect on streamflow data. However, it is minimal compared to the other rivers in the basin with good streamflow records, many of which have major dams and reservoirs. Correlation analysis was used to examine the reservoirs' effect on streamflow both before and after their construction.

Figure 2-4: Picture of Silver Lake Flat Reservoir
Source: Merrill Webb
Other JRDB Streams

Exiting the north end of Utah Lake, the 44-mile-long Jordan River passes through Salt Lake County and eventually empties into the Great Salt Lake. It is Utah Lake’s only outlet. Several major streams draining the Wasatch Mountains enter the Jordan River in Salt Lake County including City Creek, Emigration Creek, Parley’s Creek, Mill Creek, Big Cottonwood Creek, and Little Cottonwood Creek. Other small intermittent streams flow into the river from the Wasatch and Oquirrh Mountains. The aforementioned streams furnish more than 97% of the surface water that flows into the Jordan River in the Salt Lake Valley (the lower portion of the basin). The Wasatch Mountain watersheds provide much of the municipal water supply (UDWR, 1997a).

Flows on these streams correlate highly with streamflow on the American Fork River and the other reconstructed rivers (Table 2-1). The high correlations between the American Fork River and streams in the lower basin are likely due to the fact that the American Fork River’s drainage shares the boundary that separates the lower basin from the upper basin. Therefore, climate conditions likely differ very little between the two.

Water is such a special commodity in the JRDB that it is imported from two other basins (Figure 2-5). The Provo-Weber canal transfers water from the Weber Basin to the JRDB, and the Duchesne Tunnel transports water from the Uinta Basin to the JRDB. Water also enters from the Uinta Basin via Syar Tunnel, which transports water from Strawberry Reservoir (UDWR, 1997b). Imported water from the Duchesne tunnel and Strawberry Reservoir would have eventually made its way to the Colorado River. It is interesting to note that though the Wasatch Front metropolitan area is not usually brought up when discussing the southwestern United States’ dependence on Colorado River
Table 2-1: Streamflow / Climate Correlation Matrix

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*Correlations significant at the 0.05 level (two-tailed).

W = Water Year
Figure 2-5: Map of Streams / Dams / and Imports in Upper JRDB
water; water diverted from the Uinta Basin to the JRDB would have eventually made its way to the Colorado River.

**JRDB Climate**

Due to the significant difference in elevation throughout the JRDB and its location away from the moderating effects of the ocean, the regional climate varies widely and experiences large diurnal and seasonal temperature swings. Elevations range from as low as approximately 4,200 feet where the Jordan River enters the Great Salt Lake and 11,928 feet at the summit of Mt. Nebo in Juab County. On high mountain peaks where basin headwaters are located, precipitation can reach up to 60 inches (Figure 2-6). These mountainous areas experience long cold winters and short cool summers. They act to remove precipitation from passing storms. Without these high elevation catchments, the Salt Lake City metropolitan area would not exist as it does now.

The lower valleys where the majority of the population is located have more moderate climates and are considered semi-arid. Average precipitation ranges from 12 to 16 inches per year at valley locations. Temperatures have ranged from -30° F in the winter to 110° F during the summer. Throughout the growing season from May to September precipitation generally ranges from about 5- 6 inches, but the crop water requirement can be as high as 20 – 30 inches (UDWR, 1997a). The discrepancy between growing season precipitation and crop water requirement further demonstrates the reliance of JRDB residents on surface water flows.

Most of JRDB surface water originates from mountain snowpack that accumulates during the winter months leading to high streamflow when the majority of snow melts during spring and early summer. Average yearly temperatures in the basin
Figure 2-6: Map of JRDB Annual Precipitation
range from 38° F to 52° F. Average monthly high temperatures can be found as high as 93° F in July and as low as 3° F in February. Portions of mountain precipitation are absorbed into the soil and bedrock and serve to charge the valley groundwater reservoir (UDWR, 1997a).

**JRDB Topography**

The JRDB is bound to the north by the Great Salt Lake and to the west by the Oquirrh Mountains. The Oquirrh range from nine to ten thousand feet in elevation. The East Tintic Mountains also form part of the western border. The eastern border is formed by the Wasatch and Uinta Mountains. The Wasatch and Uinta Mountains are part of the Middle Rocky Mountain Province. The Wasatch Mountains and Wasatch Plateau form the southern boundary of the basin.

The valley portions of the JRDB once served as the bottom of Lake Bonneville during pluvial periods toward the end of the last Ice Age. Presently the mountain sections of the basin intercept moisture from Pacific storms that move with the westerly winds. The orographic precipitation that falls is the main source of surface water for the basin. The main valley floors have elevations from 4,500 to 6,500 ft., and the headwaters to the basin can be found at elevations in excess of 11,000 feet (UDWR, 1997a; UDWR, 1997b).

**Land Ownership / Use**

Most of the land in Salt Lake and Utah Counties, especially in the valleys, is privately owned (Figure 2-7). The U.S. Forest Service owns and oversees much of the mountainous areas of the basin. The state owns portions of the beds of all navigable
streams within the basin. For further information pertaining to Land Ownership and Administration, see Table 2-2.

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<td>State</td>
<td>267,500</td>
</tr>
<tr>
<td>Federal</td>
<td>953,600</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2,460,300</strong></td>
</tr>
</tbody>
</table>

Source: (UDWR, 1997a; UDWR, 1997b)

Table 2-2: JRDB Landownership Numbers

The mountainous areas, reservoirs, and lakes of the JRDB are subjected to high amounts of recreational use. The canyons of the Wasatch Mountains and the upper reaches of the Provo River, accessible by the Mirror Lake Highway, are subjected to the highest amount of use. The most popular activities include but are not limited to: fishing, hiking, camping, rock-climbing, boating, water skiing, and world class snow skiing (UDWR, 1997a; 1997b). Not only do private, state, and federal landowners have interest in JRDB surface water, its recreational value should not be underestimated. Severe drought would have major economic consequences on the recreational industry and those that rely on it. Figure 2-8 further illustrates the multiple demands for surface water in JRDB valley locations.

Demographics and Economics of the Basin

Growth in the JRDB continues at a steady rate. It has been estimated that between the years 1994 and 2020 the population in the upper basin (Utah Lake Portion)
Figure 2-7: Map of JRDB Land Ownership
Figure 2-8: Map of JRDB Surface Water Usage
would change from 318,020 to 569,803; an increase of 79 percent. In the lower basin much of the small amount of remaining agricultural land continues to quickly be sold to developers in the housing market. The population in Salt Lake County alone is expected to reach more than 1,300,000 by the year 2020, and possibly 2.36 million by 2050. It is also worth noting that new communities have been proposed and recently developed, and their growth has been steady (UDWR, 1997a; 1997b). This continued growth will put increasing strains on the need for surface water, and an increased understanding of streamflow variability will become more valuable with time.

The basin's water supply is used mainly for agricultural, municipal, and industrial purposes. In the Salt Lake County portion of the basin, the need for agricultural irrigation is being replaced by a greater need for municipal water supply. The large population puts considerable strain on the water supply; and as mentioned previously, water is imported from bordering drainage basins. Because of continued growth and water demand, the Utah Division of Water Resources has stressed the need for conservation and water education. See Figure 2-9 for annual streamflow and diversions within the upper portion (Utah Lake) of the basin.

This description of the JRDB brings to light the many sources of demand for surface water within the basin. It is likely that continued growth within the basin will put further strains on surface water resources. The aim of this thesis to provide a greater expanse of time to observe streamflow variability will undoubtedly contribute to the increased effectiveness of water resource planning. This information will be especially valuable as growth within the basin continues at a rapid pace.
Figure 2-9: Map of Upper JRDB Streamflow and Diversions
Use of Dendrochronology for Utah State Water Resource Planning

In a recent publication by the Utah Division of Water Resources, *Drought in Utah: Learning from the Past – Preparing for the Future* (UDWR, 2007), the use of dendrochronology as a planning tool was highlighted. Because a reconstruction of moisture conditions had not been carried out for the JRDB at the time of the report's release, the planners were forced to use reconstructions performed for surrounding regions in order to assess the potential for longer and more severe droughts in Utah's future. Planners chose the Palmer Drought Severity Index (PDSI) (Alley, 1984) as the drought index used to identify major droughts in Utah. They readily admit that the current instrumental record's max length of 111 years does not provide a complete picture of drought and moisture variability. In order to obtain a better view of drought variability, they turn to proxies such as tree-rings.

The authors pointed out that research indicates that prolonged dry periods have occurred in greater frequency before the twentieth century than times when instrumental records are available. Water resource planners also admit that based on tree-ring proxies the possibility of a decade-long or longer drought in Utah is very possible (UDWR, 2007). The streamflow reconstruction for the JRDB carried out for this research confirmed that severe and sustained droughts have occurred several times in the JRDB in the last 828 years. It also indicated that the high-flow period of the early 1980s was an extremely rare event.

In order to assess possible future drought conditions in Utah, water resource planners specifically referred to a PDSI reconstruction for the Eastern Uinta Mountains that was based on tree-ring data (Gray, Jackson, & Betancourt, 2004). Though it is likely
that larger spatial scale droughts influenced both the Eastern Uinta Mountains and the Wasatch Front, it is probable that local droughts affecting Eastern Utah did not affect the JRDB and vice versa. Further analysis of this possibility is located in the discussion section of this thesis. Woodhouse (2001) argued that local droughts on the Colorado Front Range may be overlooked as a major stress to water supplies in the Front Range. This research project will provide water resource planners with a drought perspective that includes the effects of both local and regional droughts. It will allow resource planners to utilize proxy records that apply specifically to the JRDB and, therefore, allow for more detailed planning.
Chapter 3 – Literature Review

Relevant Tree-Ring Reconstructions

Dendrochronology has a long history of being utilized to understand past variation in earth’s climate, and strides continue to be made in using tree-rings to understand variability in the earth’s atmosphere. The science has a global presence and has been especially successful in the mid-latitudes where trees are most likely to respond to annual limitations on growth (Briffa, 2000).

Aside from its many uses as a proxy for climatic and fire reconstructions (Bekker, 2001; Grissino-Mayer, 2000), dendrochronology has proven useful for reconstruction of past streamflow and hydrologic variability (Loaiciga, Haston, & Michaelsen, 1993). Depending on its location and species, a tree’s growth often depends on those same factors that influence streamflow, namely precipitation and evapotranspiration. Therefore, tree growth can serve as an effective proxy of ancient streamflow variability (Woodhouse, 2001). Many streamflow reconstructions have been carried out within the United States. For example Cleaveland (2000) created a 963-year summer streamflow reconstruction for the White River in Arkansas using baldcypress trees.

Closer to the JRDB, streamflow reconstructions have been successfully carried out for several streams and rivers in the Western United States. These reconstructions have effectively placed streamflow variability for each region within a more expansive context. The closest reconstruction to the Salt Lake urban corridor and the JRDB was carried out by Carson & Munroe (2005). They reconstructed streamflow for Ashley Creek on the southern slopes of the Uinta Mountains. One significant discovery of this
research was that the years 1898 – 1945 contained an overabundance of extremely large flows and relatively few small flows. This compares favorably with the results of the JRDB study which also found the 20th century to be a time of relatively high-flows compared to previous centuries.

Woodhouse (2001) reconstructed streamflow for the Colorado Front Range, mountains that also play a pivotal role in providing water resources to a large swath of urban development similar to that of the Wasatch Front. From Boulder to the north, and Colorado Springs to the south, the Colorado Front Range is one of the fastest growing populations in the U.S. Woodhouse discovered that 20th century streamflow variability may not represent the actual variation of streamflow in the region and possible worst-case scenario droughts. She also concluded that 20th century records for the Colorado Front Range may not do an adequate job of showing low-frequency variations in climate that could impact water resources differently than high-frequency changes in streamflow; the latter of which can often be mitigated by reservoir storage. Woodhouse also points out that vulnerability to extreme hydrologic events will increase with increasing population, a point that certainly applies also to the development occurring in the JRDB.

In the Western United States surface water demands vary greatly. Some regions are more susceptible to surface water fluctuations than others. The Upper Gila River Basin in southeastern Arizona and southwestern New Mexico is an example of a region that is comparatively more vulnerable to changes in surface water availability. Here the available amount of surface water is inadequate for current demand. A reconstruction was attempted for this region to improve water resource planning (Meko & Graybill, 1995). This study indicated that the gauge record appeared suitable for representing
extremes in both high and low-flows when compared to the extended tree-ring record. This differs notably from the discovery made by Woodhouse on the Colorado Front Range and serves as a case in point for the necessity to perform reconstructions for each individual region. Even though the streamflow records appeared to adequately represent extremes in high and low-flows for this region, the reconstruction is still valuable. This is because its extended length, compared to modern records, can do a better job at showing low frequency changes in streamflow variability.

Case and MacDonald (2003) reconstructed streamflow for three Canadian prairie rivers. The rivers are important for both agricultural and urban uses. It was discovered that the worst case scenario drought found from the years 900 – 1300 fell considerably outside the region’s current ability to effectively deal with such an event. It is important that those living along the Wasatch Front are aware of possible drought scenarios such as the one discovered by Case and MacDonald. This will allow residents to adequately prepare for the occurrence of such events.

Perhaps the most significant streamflow reconstruction ever carried out was performed to estimate ancient flows on the Colorado River. The breakthrough discovery of this research was that water resources in the upper Colorado River Basin had been allocated during a time of particularly high discharge, and future flows would likely not meet the criteria established for Colorado water partition (Stockton & Jacoby, 1976). This study was recently updated, and the findings of Stockton and Jacoby were reaffirmed (Woodhouse, Gray, & Meko, 2006). The reconstruction for the JRDB also indicates that overall the 20th Century has experienced higher flows compared to previous centuries.
Though not specifically performed to reconstruct streamflow for a particular region, climatic reconstructions of temperature and precipitation have been carried out in abundance throughout the intermountain west. Many of these reconstructions offer an excellent annual resolution view of moisture variability in their respective regions (Graumlich, 1993; Case & MacDonald, 1995; Gostev, Wiles, D’Arrigo, Jacoby, & Khomentovsky, 1996; Palmer & Xiong, 2004). Also of value are reconstructions that have been carried out to study changes in global climatic patterns such as the Atlantic Multidecadal Oscillation, the Pacific Decadal Oscillation, and El Niño (Gray, Graumlich, Betancourt, & Pederson, 2004c; Schongart, et al., 2004; Cook & D’Arrigo, 2001; Allan & D’Arrigo, 1999; D’Arrigo et al., 1999). Regional scale studies that integrate the use of several tree-ring chronologies to map past changes in climatic conditions such as drought have been carried out and offer valuable insights to understanding ancient changes in regional climate (Knapp, Soule, & Grissino-Mayer, 2004; Zhang, Mann, & Cook, 2004). These studies are valuable because they can be viewed to verify and compare results of streamflow in the JRDB with moisture conditions in other regions throughout the West. Other scientists will surely be able to use the JRDB reconstruction to improve regional understanding of paleoclimate.

Two precipitation reconstructions will be highlighted here. Salzer and Kipfmueller (2005) reconstructed temperature and precipitation for Northern Arizona for a span of over 1,425 years. They were able to highlight periods of extremes in precipitation and temperature. For example, they noted that warmth similar to that which occurred during the 20th Century approached, but never exceeded, 20th Century levels, and the latter half of the 1900s was the warmest period in the record. The associated
moisture accompanying this warmth has been unprecedented compared to the proxy records, and it is unlikely the warmth and moisture will continue. It was therefore concluded that those in the southern Colorado Plateau should prepare accordingly. Salzer and Kipfmueller utilized the Predicted Residual Sum of Squares (PRESS) method to verify their linear regression models used to create their reconstructions. This method was used to verify the models in this study as well.

To the north of Utah, limber pine and Douglas-fir, the same two species used in the JRDB reconstruction, were utilized to reconstruct precipitation in the Bighorn Basin of Wyoming (Gray et al., 2004). It was discovered that both single year and decadal-scale dry events were more severe before 1900. Gray also found that precipitation variability in the Bighorn Basin appeared to shift to a higher frequency mode after 1750, with 15-20 year droughts becoming rare. The climate of the 20th Century in the Bighorn Basin had been overall wetter than previous centuries. Gray was also able to connect his findings with El Niño and La Niña years, something that could be done with the JRDB reconstruction. In short, even though the last two papers discussed did not specifically reconstruct streamflow, they are still valuable resources to this project because they illustrate how to apply correct methodologies and compare changes in precipitation and moisture availability over the last eight hundred years.

Work in the Wasatch

To date, dendrochronological inquiry utilizing sites in the Wasatch Mountains is limited. Streamflow, temperature, and precipitation have not been reconstructed. Wager and Baker (2003) sampled Douglas-fir trees at Wasatch Mountain sites near Salt Lake City, and Logan, Utah in order to investigate the effects of ozone, climate, and spruce
budworm on Douglas-fir growth in the Wasatch Mountains. Woodhouse & Kay (1990) used tree samples from the Wasatch Mountains and other nearby sites to investigate spatial and temporal changes in the region’s air mass boundaries. They discovered that trees near the Great Salt Lake demonstrated a different growth pattern when compared to other trees in the region more distant from the Great Salt Lake Basin. Woodhouse & Kay called for more study in the area because new chronologies would help update older ones and would provide more depth to the spatial network that currently exists. This streamflow reconstruction for the JRDB provides some of the valuable information Woodhouse requested in her study seventeen years ago. This study is also unique because it attempts to reconstruct streamflow over eight hundred years in length, a feat rarely achieved in the Western United States.

Cautions with Tree-rings

The previously discussed studies serve as good examples of successful reconstructions similar to the one performed in this study. It is, however, important to note that even though dendroclimatolgy has a great track history of being used to reconstruct climatic variables on an annual scale, there are some cautions that should be taken when performing and analyzing a study that utilizes the methodology of dendrochronology.

One drawback to consider has come to be known among dendrochronologists as the “segment length curse” (Cook et al., 1995). Dendrochronology often involves dating tree-ring samples by matching their dates. For example, a tree that died in 1941 and lived for 200 years can be matched with a 150 year old tree that is still alive in the year 2007. This allows the record to be extended back to the year 1741 instead of only 1791. This
process is repeated again and again, until the record is extended back as far as possible. The segment length curse is the idea that the amount of low frequency variation in climate that can be extracted from a study is directly related to the length of the tree-ring segments being analyzed.

Another caution concerning tree-ring studies that should be considered is that dendroclimatology has the unique challenge of using trees, from the very complex biological world, to understand changes to the earth’s dynamic and complicated atmosphere. Because of the complexity of these two entities there is inherently noise, factors affecting tree growth that are not related to climate, that should be removed before a tree-ring based analysis is carried out. Fritts (1976) outlined the best techniques to remove noise from biological factors in order to best reconstruct desired climatic variables. One of the most effective ways to assure good results in a study utilizing tree-rings is to be very selective about which trees are sampled. Trees sampled on the fringe of their ecological niche will often be most influenced by climatic change and thus produce a more representative reconstruction of the desired variable.

Also worth noting is the fact that tree-ring based reconstructions generally do a better job of estimating low-flows than high-flows because there is a biological limit to how much a tree can grow when there are high amounts of moisture and low evapotranspiration (Loaiciga, 1992). For the JRDB reconstruction, special care was taken in order to select appropriate sample sites and analysis techniques that will be most representative of changes in streamflow.
Dendrochronology is an established science with a standardized methodology. Because streamflow is essentially the climatic combination of precipitation and evapotranspiration, this study utilized the even more specific methodology utilized for dendroclimatology, the study of the earth’s climate using tree-rings (Fritts, 1976). Two main types of data were required in order to carry out this research. Climate and streamflow data were obtained from the United States Geological Survey (USGS) (http://waterdata.usgs.gov/nwis), the National Oceanic and Atmospheric Association (NOAA)( http://www7.ncdc.noaa.gov/CDO/CDO DivisionalSelect.jsp), and the Utah Climate Center (http://climate.usurf.usu.edu/products/data.php). Data was also retrieved by collecting samples from limber pine and Douglas-fir located in the Wasatch Mountains; trees that would respond to changes in temperature and precipitation in a matter similar to that of streamflow.

Pilot studies revealed that limber pine and Douglas-fir growing on south and west facing slopes in Rock Canyon near Provo, Utah had lived more than 500 years. In order to locate similar sites where ancient trees would exist and climate would be the principal limiting factor on tree growth, I created a Geographic Information System (GIS) model. The model used a 10-meter digital elevation model (DEM) to identify sites with slopes greater than 30 degrees, south or west facing aspect, and elevation greater than 8,500 feet (Figure 4-1). One meter National Agriculture Imagery Program (NAIP) imagery was then used to locate open tree stands at the aforementioned sites selected by the GIS model. The model was effective at predicting sites with ancient trees. Other GIS spatial
queries were performed to find sites located within a relatively close distance of trails and roads.

The model helped lead to the selection of two sites for this study: one on the south side of Cascade Peak near the top of Rock Canyon near Provo, Utah, and the other at the head of American Fork Canyon near Sunset Peak and Alta Ski Resort. Each site consisted primarily of limber pine, but Douglas-fir trees were also present. Both sites were steep with thin soil cover.

![ERDAS Site Selection Model](image)

Figure 4-1: ERDAS Site Selection Model

The sites consisted of relatively open tree stands and a large amount of remnant wood. The remnant wood is valuable because if it has been dead for hundreds of years
and it can be matched with living trees, this can thus extend the proxy record back even further. In the Wasatch Mountains the ecological niche where limber pine and Douglas-fir grow is relatively small, and due to the tree’s preference to grow near cliffs and rocky slopes, it is especially difficult to find sites that are accessible. The GIS model was especially helpful in this regard as time was saved locating sites via computer rather than through exploration.

Two sampling trips were made to the Cascade site (CSC), and three trips were made to the Big Flat Ridge (BFR) site. Sampling trips to CSC were made in June of 2006, and sampling trips to BFR were made in August and September of 2006. In order to reduce noise in the tree growth caused by non-climatic factors, an attempt was made to take at least two core samples from each tree and focus on open canopy trees. Living and dead trees were sampled. Over 30 trees were sampled at CSC, and more than sixty trees were sampled at BFR. Sampling live and dead standing trees involves the use of an increment borer, a hollow hand drill, which is used to extract a core from the tree that is approximately the width of a straw. Samples from downed trees were obtained by taking a cross section of the wood utilizing a chainsaw.

Samples were prepared for analysis using standard dendrochronological techniques (Fritts, 1976; Stokes & Smiley, 1996). Samples were dried, mounted, and then sanded in order to assure that the samples could be measured and dated. In order to date the samples correctly, each sample was skeleton plotted (Stokes & Smiley 1996). This process involves looking at each tree-ring and marking narrow strips of graph paper with a longer line to represent the narrow rings. The graph paper from one sample can then be matched up with another in order to identify patterns in tree growth and
accurately confirm the year when the tree-ring was created. Each annual ring-width for each sample was measured to the nearest millimeter and saved in digital format.

In order to assure that each sample was dated correctly the program COFECHA, used for crossdating and measurement quality control (Grissino-Mayer, 2001; Holmes, 1983), was used to verify the dating. COFECHA works by separating the sample measurements into segments and then testing each segment against a master chronology. The master chronology is simply the average ring width for each year. If a sample’s segments correlate well with the master chronology, then one can confidently assume that the sample has been dated correctly. The inter-series correlation, the correlation among the different sample making up the chronology, was .507, and 95 samples were successfully dated. The mean series length for this chronology was 354 years, indicating that the chronology could potentially do a good job representing both low and high frequency streamflow variation. Several samples did not correlate well with the master chronology and were consequently eliminated from the analysis.

Once the samples had been dated correctly, a standardized series was produced. As a tree ages, its annual growth decreases, causing a negative growth trend to appear in the tree-ring measurements. A standardized tree-ring chronology consists of the average ring-width among samples from each year with the natural growth trend removed (Figure 4-2). The program ARSTAN (Cook & Holmes, 1984), made specifically for detrending tree-ring series and chronology development, was used to fit a negative exponential curve through each series, thus removing this trend and producing a standardized ring-width measurement for each year that would be most sensitive to climatic variations (Fritts, 1976)(Figure 4-3).
Figure 4-2: BFR and CSC Standardized Tree-Ring Chronology and Sample Depth

Figure 4-3: Tree-Ring Series Detrended with Negative Exponential Curve
There are many methods utilized to remove the growth trend in trees. Choosing which method to use depends on the specific circumstances of the research project such as site dynamics and the variable being reconstructed. The negative exponential curve is one of the most conservative methods utilized to detrend tree-ring series. This method was appropriate for this study because the sites had little competition and other non-climatic factors affecting tree growth. Thus, the negative exponential curve was chosen in order to eliminate the least amount of climatic information.

The “ARSTAN” chronology, often most successful at extracting the climate signal from trees, was used for this study. Compared to the basic standardized chronology, the ARSTAN chronology better represented changes in streamflow. The ARSTAN chronology is the standardized chronology with autoregressive modeling integrated into the chronology (Cook, 1985). Samples from both the BFR site and the CSC site were included in the standardized chronology. The majority of samples came from the BFR site because many of the trees from the CSC site were impossible to date due to a high amount of missing rings and other tree growth disturbances. It is normal for trees to have some missing rings, and in most cases it is relatively easy to recognize them and account for them. However, if a tree has consecutive missing rings or other disturbances that make it difficult to measure ring-width, then it is nearly impossible to correctly date them because they can not be compared with other trees.

“Twister,” at least 1,697 years old and the oldest known successfully dated limber pine tree, was discovered while sampling trees for this study. Even with the exceptional age of this one tree, the chronology utilized for the streamflow reconstruction was cut off at the year 1178. This is because subsample signal strength, “the likely detrimental effect
of decreasing sample size on chronology variance” (Meko & Graybill, 1995), indicated that before the year 1178 the sample depth was inadequate to effectively portray variability in tree growth. Several other trees, as old as or older than “Twister,” would have to be discovered to extend the record beyond 1,500 years.

In order to investigate the climatic relationship with tree growth, climate data was obtained for the Wasatch Mountains climatic division established by NOAA (Figure 4-4). When performing analysis utilizing dendroclimatology, regional climatic data has the benefit of averaging measurements from weather stations throughout a region, thus minimizing the local effects that influence measurements at only one site (Blasing, Duvick, & West, 1981; Duvick & Blasing, 1981). The regional approach is also beneficial because it makes it possible to utilize the tree-ring series in order to infer information about the entire climatic region. Correlation analysis was carried out to discover relationships between climatic variables and the tree-ring chronology. The program DENDROCLIM2002 (Biondi & Waikul, 2004) was utilized to perform this correlation based exploratory analysis.

Multiple linear regression analysis indicated that temperature and precipitation accounted for more than 60% of the variance in tree growth. Because streamflow is also a product of changes in both temperature and precipitation, it was decided that the chronology would be useful to reconstruct streamflow.

Streamflow data was obtained for several rivers and streams within the JRDB from the United States Geological Survey surface water database (http://waterdata.usgs.gov/nwis). Streamflow levels for each month of the year were compared with the values for the standardized tree-ring chronology.
Utah Climate Divisions

Legend

- Sample Sites
- JRDB Streams
- Climate Divisions
- Lakes

Annual Precipitation (Inches)
- 5 - 13
- 14 - 19
- 20 - 25
- 26 - 33
- 34 - 41
- 42 - 49
- 50 - 59
- 60 - 73

Figure 4-4: Map of Utah Climate Divisions
Once it was determined that tree growth correlated highest with streamflow it was necessary to establish which streamflows correlated best with tree growth. This too was done by evaluating correlation between tree growth and monthly flows. Stepwise multiple-linear regression was then used to construct a statistical model that would estimate streamflow for each individual river. Due to the amount of autocorrelation in both the tree-ring series and streamflow, the potential predictors for the model included the standardized chronology values for the current year, lagged one year, lagged two years, and lagged three years. Predictors were also included with the chronology moved forward one, two, and three years. This method proved effective in predicting streamflow because some of the prediction models used lagged tree growth to predict streamflow.

The models were verified using the predicted residual sum of square (PRESS) statistic. The PRESS statistic works by predicting the value based on all of the variables except the given case being predicted. These residuals can then be used to calculate the predicted R squared which indicates how much variance the model can be expected to predict given new data (Douglas, Peck, & Vining, 2006). The reduction of error statistic (Fritts, 1976) was also used to confirm the models’ ability to predict streamflow. If the models passed the verification tests, they were subsequently used to create the streamflow reconstructions. Reconstructions were also verified and analyzed by comparing them with similar studies in neighboring regions.
Chapter 5 – Results and Discussion

The American Fork River Reconstruction

Streamflow for the American Fork River was chosen for reconstruction because the principal sample site, BFR, is located within the American Fork drainage. Furthermore, compared to several streams within the Jordan River Basin, the tree-ring chronology best predicted streamflow for the American Fork River. Aside from the sample site location being within American Fork Canyon, this is likely because the only reservoirs within the canyon are very small, and do not have a major impact on streamflow records. The only diversions on the river are below the stream gauge.

At a length of 61 years, 1928-1989, the American Fork River streamflow record compares favorably with other streamflow records in the JRDB. It takes into account extremes in regional streamflow levels during the 20th century, specifically the dustbowl of the 1930s, the El Niño year of 1983, and subsequent wet years of the early and mid 1980s.

Tree growth best predicted October – March streamflow of the American Fork River. Though one might hope to be able to directly reconstruct summer streamflow or spring runoff, the October – March reconstruction adequately represents moisture conditions for the region. The high correlations between tree growth and October – March streamflow may be in part due to the effects of excess water releases from the Silver Lake Flat reservoir at the end of the growth year. Analysis of correlation between streamflow and tree growth, however, indicates that with the exception of the month of
March, the construction of these small dams has a limited effect on streamflow during these months (Table 5-1).

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</tr>
<tr>
<td>Mar</td>
<td>0.43</td>
<td>Not significant</td>
<td>Not significant</td>
</tr>
</tbody>
</table>

Table 5-1: Correlation Values between Tree growth and American Fork Streamflow over Different Time Intervals

It is more likely that October – March streamflow is best predicted by tree growth because both October – March streamflow and tree growth are the result of moisture conditions in general. For example, October – March streamflow is much less likely to exhibit the enormous discrepancies in streamflow that occur each year during the spring runoff due to a myriad of factors such as soil moisture, snowpack, and the onset of warmer temperatures, but winter streamflow does represent general moisture conditions to which the sampled trees respond.

Correlation analysis indicated that October – March streamflow is a good overall indicator of moisture conditions throughout the previous growth year. For example, October – March streamflow inversely correlated with summer temperatures, and for the month of July correlations were as low as -.57. This indicated that high temperatures promoting more evapotranspiration contributed to lower flows in the following winter months. Perhaps even more important is that PDSI values for May – September of the growth year had a positive correlation of .69 with Oct-Mar streamflow. This likely
indicates that October – March streamflow is a good indicator of overall moisture conditions during the months preceding October. October – March streamflow appears to adequately represent high-flow and drought conditions for the American Fork River portion of the drainage. Streamflow for these months also correlated highly with water year streamflow for rivers throughout the region (Table 5-2).

Standard techniques in dendroclimatology were utilized to reconstruct the American Fork River streamflow. Stepwise multiple linear regression was performed to predict American Fork River streamflow using standardized tree growth lagged one, two, and three years as independent variables. Tree growth plus one, two, and three years were also included in the model as potential predictors. The lagged chronology is included due to the autocorrelation in both the dependent and independent variables. For example, one year with optimal conditions for tree growth, such as high amounts of soil moisture and temperatures that lengthen the growing season, will often lead to more growth the following year. The same is true of streamflow. The effects of above average amounts of precipitation and soil moisture will often carry over to the runoff of the following year.

For the American Fork Reconstruction one predictor variable, tree growth lagged one year, was chosen as a predictor in the stepwise linear regression model. This is logical because October – March streamflow encompasses monthly data from both the previous growth year and the current growth year. If moisture conditions were optimal for growth during the summer and spring when tree growth took place, essentially defined as tree growth lagged one year, then there would likely be more winter streamflow and release from the small reservoirs.
Table 5.2: Streamflow / Climate Correlation Matrix

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</table>
The linear regression model produced explained 51.7% (Adjusted R squared) of the variance in streamflow. Though 51.7% is not as high as other streamflow reconstructions that explain up to 70% of the variance, the model compares favorably with other tree-ring studies. Case & MacDonald (2003), for example, published models that explained as little as 33% of streamflow variance.

_Other JRDB Reconstructions_

Streamflow for other rivers within the basin, including the Spanish Fork to the south and the Jordan River to the north, also correlated highly with American Fork River streamflow and therefore, reconstructions were attempted for the Jordan and Spanish Fork rivers as well. Being able to perform these other two reconstructions offers the benefit of demonstrating the tree-ring chronology’s ability to predict streamflow throughout the drainage basin.

The Jordan River is especially important because its gauge is located downstream from Utah Lake. Flow from the Jordan River at this point represents excess flows of water from Utah Lake, whose main tributaries are the Provo River, Spanish Fork River, and American Fork River. Thus it represents all flows entering the Utah Lake portion of the JRDB. The reconstruction was for the months of March – June and effectively demonstrated the ability of the tree-ring chronology to predict spring and early summer streamflow. This site on the Jordan River is less susceptible to huge swings in annual run-off variability because of the modifying effects of Utah Lake and other reservoirs located in the higher portions of the basin. This idea is confirmed by the fact that the linear regression model chose both the current year tree growth and previous year tree
growth as predictors of Jordan River streamflow. The lag time of water reaching Utah Lake and finally exiting the lake was effectively integrated into the model. This is also logical because it would take more time for Utah Lake to rise and water to reach the Jordan River compared to the tributaries entering the lake. The multiple linear regression model for the Jordan River indicated that tree growth explained 43.6% of the variance in March – June streamflow.

The reconstruction for the Jordan River actually predicts values below zero during times of intense droughts. This could be a reflection of how much water would remain in the Jordan River if such a drought were to occur if present water demands existed during that time.

The Spanish Fork River enters Utah Lake at its southeast end. It has multiple diversions and water is imported from Strawberry Reservoir which could explain why tree-rings correlate most highly with flows during the late summer (July – August) when excess water is released downstream. Through the process of stepwise linear regression, the tree-rings from the current year were chosen as the predictor for this model. The model for the Spanish Fork River explained 40.5% of the variance of July – August streamflow.

**Model Verification**

The models for the JRDB reconstruction were verified using the PRESS statistic, the correlation coefficient, the sign test, and the reduction of error (RE) statistic (Table 5-3). The PRESS statistic works by creating a set of predicted values based on all of the variables except the given case being predicted. The residuals from this model, often
referred to as deleted residuals, can then be used to calculate the predicted R squared. The predicted R squared indicates how much variance the model can be expected to predict given new data. The PRESS method is especially helpful when dealing with smaller data sets such as the streamflow records in this study, which on average span about 60 years. This is because unlike other popular verification techniques such as the split-sample method, the PRESS statistic makes it possible to use the entire dataset to calibrate the model (Douglas et al., 2006).

<table>
<thead>
<tr>
<th>Streamflow Reconstruction Regression Model Verification Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adjusted R Squared</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>American Fork River (October – March)</td>
</tr>
<tr>
<td>Jordan River (March – June)</td>
</tr>
<tr>
<td>Spanish Fork River (July – August)</td>
</tr>
</tbody>
</table>

Table 5-3: Streamflow Reconstruction Regression Model Verification Statistics

The correlation coefficient is simply the correlation between the actual streamflow values and the values predicted by the model. High correlations indicate greater model accuracy. The adjusted R squared value which indicates the percent of variance explained by the model is directly related to the correlation coefficient.

The sign test works by attempting to see if both the predicted value and actual value are greater than or less than the mean of the actual values. This test can be helpful because it can indicate whether or not the model predicts high frequency trends in the data such as a quick change from wet conditions to dry conditions. If both values are positive or both values are negative, then the prediction for that year is said to be a hit. If
one value is positive and the other negative, or vice versa, then the value for that year is said to be a miss. It is important to note that this verification technique can be misleading if the predicted and actual values are close to the mean of the actual values. In that instance it is possible for the predicted and actual values to differ in whether they are above or below the mean, but still be an accurate estimate of the actual value (Fritts, 1976).

The RE is a verification statistic developed specifically for tree-ring based reconstruction models. The possible values for the RE statistic range from +1 to negative infinity with any positive value in the RE statistic indicating that the model has skill in predicting streamflow based on the tree-ring data (Fritts, 1976). The RE statistic compares each of the estimated streamflow values with the actual streamflow values. RE equals one minus the residuals divided by the sum of squares of the differences of the actual data from the mean of the dependent dataset used for calibration. It can be written as \( RE = 1 - \left( \frac{SSR}{SSM} \right) \). If the model perfectly estimates streamflow values, then RE will be equal to one.

Figures 5-1 through 5-3 offer a visual representation of how statistical estimates compare with actual values. Comparison of the predicted values with actual streamflow values indicates that the reconstructions may do a better job reconstructing low frequency variation in streamflow compared to high frequency variation in streamflow. It is, however, helpful to reconstruct both types of variance because short-term and long-term droughts each provide unique challenges for water resource managers. Reconstructions of low frequency variation can help water resource planners evaluate the potential for extended low and high-flow periods. Reconstruction of high frequency variation can
indicate that within a short amount of time conditions can change from very wet to very dry or vice versa.

The models created allow for a reconstruction of streamflow for each river. Verification statistics (Table 5-3) indicate that the American Fork streamflow has the greatest potential to accurately predict streamflow. After cutting off the chronologies based on their subsample signal strength, the reconstructions for these rivers stretch back to the year 1178 (Figures 5-4:5-6).

Figure 5-1: American Fork River Actual vs Predicted Streamflow Values
Figure 5-2: Jordan River Actual vs Predicted Streamflow Values

Figure 5-3: Spanish Fork River Actual vs Predicted Streamflow Values
Figure 5.4: American Fork (October - March) Streamflow Reconstruction
Figure 5-5: Jordan River (March - June) Streamflow Reconstruction

Jordan River (March - June) Reconstructed Streamflow
Figure 5-6: Spanish Fork (July–September) Streamflow Reconstruction
The reconstructions presented in this paper represent a long duration record of streamflow variability in the JRDB. Streamflow is reconstructed from the year 1178. The reconstruction was cut-off at the year 1178 because beyond that year the sample depth was too low to confidently reconstruct streamflow based on tree-ring width. The fact that the tree-ring chronology was used to successfully explain the variance in streamflow for several rivers in the basin suggests that the trees are responding to regional climatic variability affecting streamflow throughout the basin. Because streamflow was most accurately reconstructed for the American Fork River, and American Fork River October – March streamflow correlates well with other streams and moisture conditions in general, this analysis will focus on the reconstruction for the American Fork River.

**High Flows**

The reconstruction suggests that the high-flow years of the early 1980s were only equaled or surpassed once in the last 829 years during the 1360s and 1370s. This is perhaps a source of good news to emergency planners and residents of the Wasatch Front that hope such an extreme hazard is not likely to occur, but it also successfully places the early 1980s in context as to how often they are likely to occur. Other high-flow periods during the record occurred in the late 1700s and early 1800s, the late 1400s and early 1500s, and the 1330s.

It is especially interesting to note these high-flows because tree-ring based reconstructions generally do a better job of estimating low-flows than high-flows. This is
because there is a biological limit to how much a tree can grow when there are high amounts of moisture and low evapotranspiration (Loaiciga, 1992). This phenomenon is apparent in Figures 5-1 and 5-2. This also explains why tree-ring reconstructions generally underestimate high flows. When climate conditions limit tree growth, essentially all trees will create small growth rings due to lack of moisture. When climate conditions are favorable for tree growth trees will respond by growing larger rings, but how much growth occurs is often determined by individualistic limiting growth factors such as age, competition for light, microclimate, and a host of other variables (Fritts, 1976). Because this reconstruction adequately predicts high-flows, it further strengthens the idea that the sampled trees respond to climate conditions causing high-flow and drought conditions.

Drought

As far as drought is concerned, the reconstruction suggests that severe drought conditions experienced during the instrumental record do not accurately represent past variability in drought conditions. In other words, the region has experienced more severe and sustained droughts in the past than those experienced during the 20\textsuperscript{th} Century.

The Utah Division of Water Resources has defined the onset of a drought as two consecutive years with PDSI values averaging less than -1.0, and a drought’s end as two consecutive years of near or above normal PDSI conditions; PDSI > -0.5 (UDWR, 2007). Utah Division of Water Resources officials singled out six peak drought periods during the instrumental record: 1902, 1934, 1956, 1977, 1990, and 2002. Perhaps the most severe of these droughts in the JRDB was that which peaked in 1934. A visual analysis
of the reconstruction, however, indicates that since 1178 droughts that were more severe occurred at least six times, and several other droughts of similar intensity occurred as well (Figures 6-2, 5-4). Neighboring climate and streamflow reconstructions have revealed similar trends.

Perhaps of particular concern for planners are the droughts that stand out when observed by the low-frequency trends illustrated by the ten-year moving average included with the reconstruction. A drought of approximately twenty years appears to have gripped the basin from the 1750s to the 1770s. An even more severe drought, but perhaps not as lengthy, occurred during the 1630s and 1640s. Also of note are the low flow periods of the late 1500s, the 1430s, and the mid to late 1200s. It is unlikely that residents of the Wasatch Front are prepared to deal with such severe and sustained droughts.

The most notable drought period appears from approximately 1638 – 1644 where streamflow for the American Fork River was consecutively far less than any drought period of the instrumental record. Such a drought would have severe agricultural, economic, and social impacts on the JRDB and its residents. This reconstruction may help many realize that the JRDB is more vulnerable to drought than previously thought.

The average October – March streamflow for the American Fork River based on 20th Century observations was 17.9 cfs. Based on the American Fork River reconstruction, with the exception of the 1300s, this has been the century with the highest amount of streamflow compared to the previous centuries. The average reconstructed streamflow per century is listed in Table 6-1.
Average Estimated Streamflow per Century

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<tr>
<td>1900s</td>
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Table 6-1: Average American Fork River Reconstructed Streamflow per Century

Hopefully the region will not experience flows like those of the 1500s, and especially those of the 1600s. Because water policy has been based on observations from the 20th Century, lower mean flows of previous centuries could spell big problems for the Wasatch Front. However reservoir storage, educating water users, and conservation could help mitigate the effects of such a drought.

Table 6-2 ranks the wettest and driest decades of reconstructed streamflow and helps place 20th Century high and low-flows in a broader temporal context.

<table>
<thead>
<tr>
<th>Highest Decade</th>
<th>Highest Average Streamflow</th>
<th>Lowest Decade</th>
<th>Lowest Average Streamflow</th>
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Table 6-2: American Fork River Highest and Lowest Decadal Average Streamflow
Comparison with other Reconstructions

Comparing the American Fork River reconstruction with reconstructions from neighboring regions can help verify results and also indicate whether a drought had an expanded or more limited regional extent. General trends in streamflow on Ashley Creek, which drains the south slope of the Uinta Mountains and is approximately 180 km east of the JRDB (Carson & Munroe, 2005), compare favorably with those identified in the JRDB reconstruction. For example, a wet period preceding the 1800s was easily identified in both reconstructions. Though not as severe, low-flows occurred on Ashley Creek in the 1640s as they did on the American Fork River. Very low-flows in the 1770s were also identified in both reconstructions.

The other nearest streamflow reconstruction exists for the Colorado River at Lee’s Ferry which is approximately 440 km south of the JRDB (Woodhouse et al., 2006) (Figure 6-3). Because of its long distance from the JRDB relative to the proximity of the

![Figure 6-1: Streamflow Reconstruction for Ashley Creek on the South Slope of the Uinta Mountains](image)

Source: (Carson & Monroe, 2005)
Figure 6-2: American Fork (October – March) Reconstructed Streamflow

Figure 6-3: 20-year Running Averages of Colorado River at Lees Ferry, Arizona. Source: (Woodhouse et al., 2006)
south slope of the Uinta Mountains, the reconstruction of American Fork River flows are not as similar to the Colorado River as they are to the reconstruction for Ashley Creek discussed previously. However, low-flows toward the end of the 1700s were easily identified in both reconstructions and severe drought that appears to have occurred in the mid 1600s is readily evident in both reconstructions. Overall these reconstructions compare favorably.

Though the extended length of this reconstruction makes it more valuable to water resource managers and makes it unique compared to reconstructions in surrounding regions, verifying the earlier portions of the reconstruction can be more difficult because there are few proxies surrounding Utah that extend more than 800 years into the past. A comparison with Salzer and Kipfmueller’s (2005) reconstruction of temperature and precipitation in the Southern Colorado Plateau that extended more than 2,000 years into the past did however show some interesting similarities to the JRDB reconstruction. For example, the period of abnormally high streamflow in the JRDB during the 1370s is preceded by a very high spike in precipitation in the reconstruction for the Southern Colorado Plateau. Discoveries such as these can help paleoclimatologists determine if high streamflow and drought conditions migrate from north to south etc. Other periods of less than normal and greater than normal reconstructed streamflow and precipitation coincided between the two reconstructions.

Based on the previously discussed observations, similarities between the JRDB reconstruction and nearby streamflow reconstructions indicate that regional climatic patterns are apparent in the JRDB reconstruction. Differences between reconstructions are also apparent indicating that local climatic effects have a major effect on surface
water flows in the JRDB. One well known local factor affecting JRDB precipitation is lake-effect precipitation that falls during the late fall and winter, and it is possible that this type of precipitation could affect moisture conditions. Droughts that were extremely severe for the JRDB were not necessarily as severe for surrounding regions and vice versa.

This is perhaps best illustrated in figure 6-4 where a tree-ring based PDSI reconstruction for Eastern Utah (Gray et al., 2004b) was compared with the reconstruction for the American Fork River in the JRDB. The PDSI reconstruction was located approximately 240 km to the east of the JRDB. There are obvious similarities between the reconstructions, but there are also differences that were likely caused by local climatic effects.

In a streamflow reconstruction for the Colorado Front Range, Woodhouse (2001) suggested that local droughts could be the biggest threat to the water supply in that region. Noting the similarities and differences between streamflow reconstructions surrounding the JRDB and the JRDB reconstruction, it is quite likely that a local drought could have just as severe effect on water resource availability in the Wasatch Front as a more expansive drought. The idea that the climate of the JRDB is unique compared to surrounding regions is reinforced by noting that a dendrochronological study seeking to understand the winter air mass boundary in the western United States found that of eleven reconstructed chronologies throughout the west, the three chronologies in the Great Salt Lake Basin always grouped together (Woodhouse & Kay, 1990). In other words, the trees in the Great Salt Lake Basin responded differently compared to those in surrounding regions emphasizing that the JRDB climate is unique.
Figure 6.4: Comparison of American Fork Streamflow Reconstruction and Eastern Utah PDSI Reconstruction

Eastern Utah PDSI Reconstruction

Figure 6.4 - Comparison of American Fork Streamflow Reconstruction and Eastern Utah PDSI Reconstruction

Comparison of Standardized AF (October - March) Streamflow and Standardized Eastern PDSI

Eastern PDSI - 5 Year Moving Average

Comparison of Standardized AF (October - March) Streamflow and Standardized Eastern PDSI
The analysis of this reconstruction places 20th Century streamflow records in an expanded context that will help water resource planners better understand streamflow variability in the JRDB. Comparison with nearby streamflow records indicates that the reconstruction compares favorably with neighboring reconstructions, and further validates the success of the JRDB reconstruction.
Chapter 7 – Conclusions

The results of this study indicate that the tree-rings from high elevation sites in the Wasatch Mountains can act as an effective proxy for streamflow within the JRDB. This streamflow reconstruction extends the streamflow record back to the year 1178, almost nine times the current length of streamflow records. It provides an effective way to evaluate modern streamflow against past flows. It should, therefore, act as an effective aid to water resource managers and planners.

The findings of this research indicate that the JRDB is susceptible to droughts of greater magnitude and duration than those experienced during the instrumental period. They also indicate that the 1980s were one of the wettest decades, if not the wettest decade since 1178. Water resource managers and planners alike should be aware that extended and severe droughts have occurred in the JRDB in the past. To this end residents and policy makers can take steps to alleviate the effects of such a severe drought, if one were to occur.

Accuracy of the reconstruction could be increased by improving the spatial network of chronologies which act as predictors for the regression model. These extra chronologies would likely increase the amount of streamflow variance the multiple regression model is able to explain. Increasing the sample depth of ancient trees could make it possible to analyze streamflow variability beyond one thousand years into the past. It will, however, be challenging to find other sites that contain trees of comparable ages.
As is, this reconstruction is an extremely valuable tool to water resource planners and those interested in JRDB surface water availability. It would be wise to use this reconstruction as a springboard to obtain and improve the understanding of streamflow and water availability not only in the JRDB, but surrounding regions as well.
REFERENCES


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