__Neal W. Ackerly__ received his doctorate in anthropology from Arizona State University in 1986. In the mid-1980s, he directed a number of projects focusing on the dynamics of prehistoric irrigation systems in central Arizona. Working in New Mexico over the past ten years, he has documented historical interactions between small- and large-scale irrigators and the rivers on which they depend. His studies encompass large federal irrigation projects (EBID, MRGCD) as well as smaller community acequia systems in the Mimbres, Ruidoso, Peñasco, and Velarde areas. Among other efforts, he recently prepared an overview of the historical development of irrigation systems across New Mexico, and currently is working on a pilot project for the U.S. Army Corps of Engineers to develop a GIS of acequia systems on the Rio Chama.

PALEOHYDROLOGY OF THE RIO GRANDE: A FIRST APPROXIMATION

The issue I would like me to address today revolves around long-term discharge characteristics of the Rio Grande. Discharge fluctuations affected the people of New Mexico in the past and will certainly affect us in the future. To address this global issue, I want to focus on three interrelated subissues including:

1. What are historical trends in the flow of the Rio Grande based on gauging station data?
2. What proxy data might be used to extend our understanding of the Rio Grande's flow beyond the period for which gauging station data are available?
3. What do proxy data indicate about long-term variability in the Rio Grande's flow?

For reasons that will become clearer, I am going to touch only briefly on the issue of average long-term flow. Rather, what I want to focus more on here today is the issue of **variability** in the potential discharge of the Rio Grande.

First, then, what are the general trends in water availability during the past century? I have arbitrarily selected discharge data from the San Marcial gauging station, mostly because it is located in the center of the state. Further, San Marcial is above Elephant Butte Reservoir and is less affected by water storage than gauging stations situated further downstream. Data cover the period 1896–1964 when the station was removed. Annual discharge is aggregated into "water years" extending from October of year *n* to September of year *n+1*. Water year data for San Marcial were extracted from U.S.G.S. *Water Supply Papers* 1312 (1960), 1732 (1964), 1923 (1970), and 2123 (1974).

The general trend between 1896 and 1964 shows a downward progression over the 68 years for which gauging station data are available (Figure 1). Some might argue that this simply reflects progressively larger water diversions over the past century. However, a comparable analysis of gauging station data from Otowi station, situated between Santa Fe and Taos above any significant water diversions, shows a similar decline. Considered jointly, this trend indicates declining water availability during the past

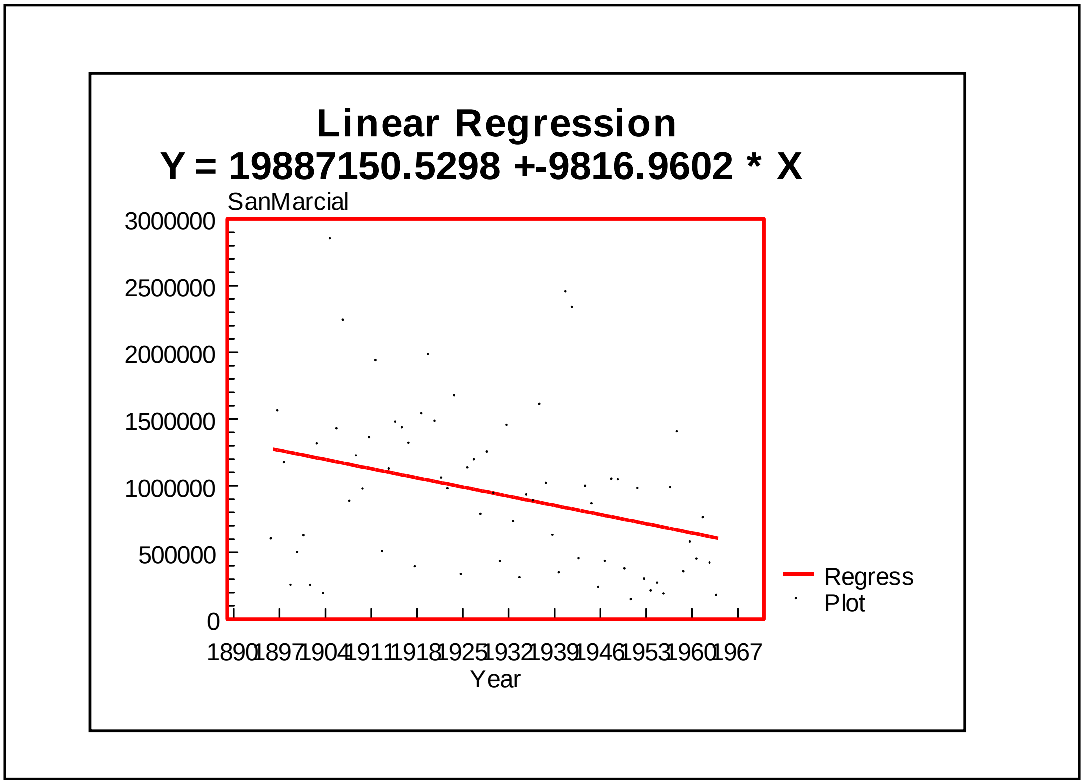


Figure 1. Simple linear regression of discharge against water year at San Marcial: 1896-1964.

century or so. At the same time, Figure 1 underscores the fact that there is a remarkable degree of variability associated with discharge during this period. Indeed the coefficient of variation is a very high 0.64 (= 940417.4, STD = 604819.5).

However, gauging station data do not tell us very much about longer-term trends in the Rio Grande's flow and long-term trends that are more worrisome. Fortunately, some relatively simple statistical procedures linking gauging station data with proxy indicators of longer-term variability in discharge offer the potential to extend these analyses further back in time. I would like to suggest that long-term fluctuations in tree-rings provide a reasonable basis for modeling the flow attributes of the Rio Grande for periods with much greater time depth than gauging station records (Stockton and Boggess 1980). As most are aware, tree ring thickness varies with precipitation and, ultimately, discharge.

The first issue to be dispensed with, of course, is whether there is any correlation between discharge and tree ring widths. To begin this process, I arbitrarily selected gauging station data from San Marcial, if for no other reason that it was located (more-or-less) in the middle of the state. Annual water year discharge data from the San Marcial gauging station were then correlated with 20 corresponding annual tree-ring chronologies distributed across New Mexico (Dean and Robinson 1978, Drew 1972). A series of bivariate and multivariate analyses were employed to screen potential correlations between tree-rings and historic gauging station data.

Focusing first on a simple bivariate approach, I screened 20 ring series from around New Mexico and found a 484 year-long chronology from Ft. Wingate (Robinson 1970) to be most closely correlated with annual gauged discharge from San Marcial ($n = 69$, $r = +.75$, $r^2 = .55$). The equation of this relationship is:

(San Marcial a.f. Discharge) = 1032.658137(Ft. Wingate ring width) - 177188.102408

A scatterplot showing the interrelationship between gauging station data and Ft. Wingate tree-rings is shown in Figure 2.

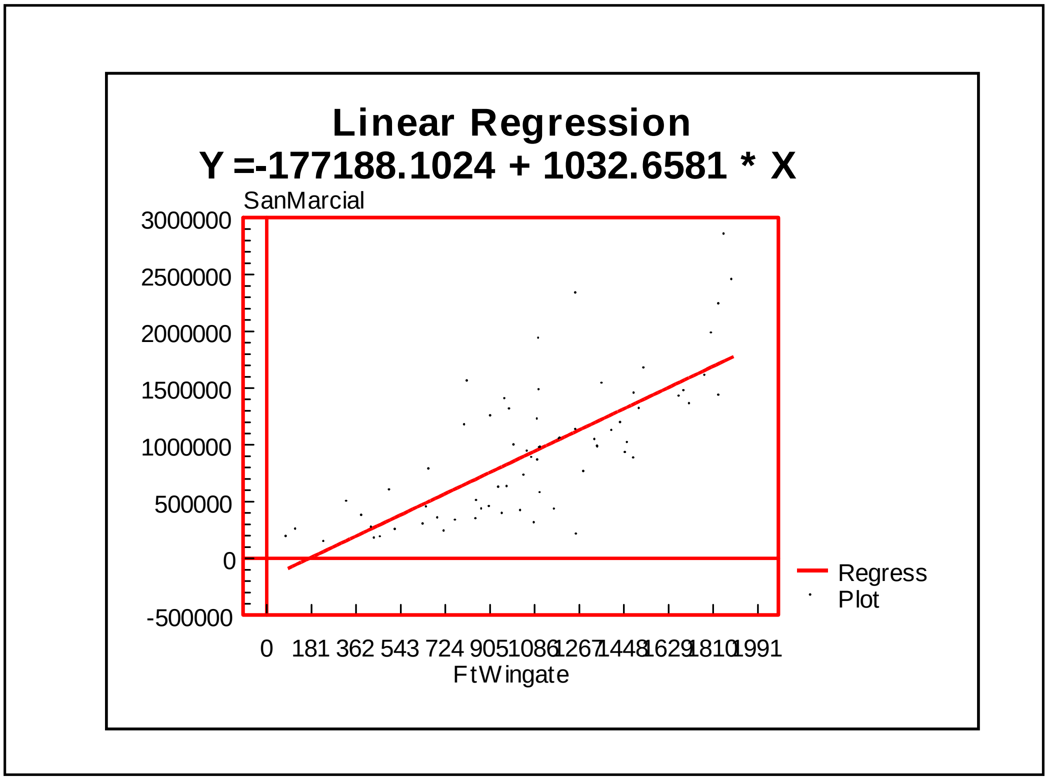


Figure 2. Linear correlation between Ft. Wingate TR and San Narcial water year discharge

Using this equation, predicted discharge values were then computed and plotted against actual discharge values at San Marcial for the period 1896-1964 when the gauge was removed. It may be seen that this equation generates a reasonably accurate correspondence between the two time series (Figure 3).

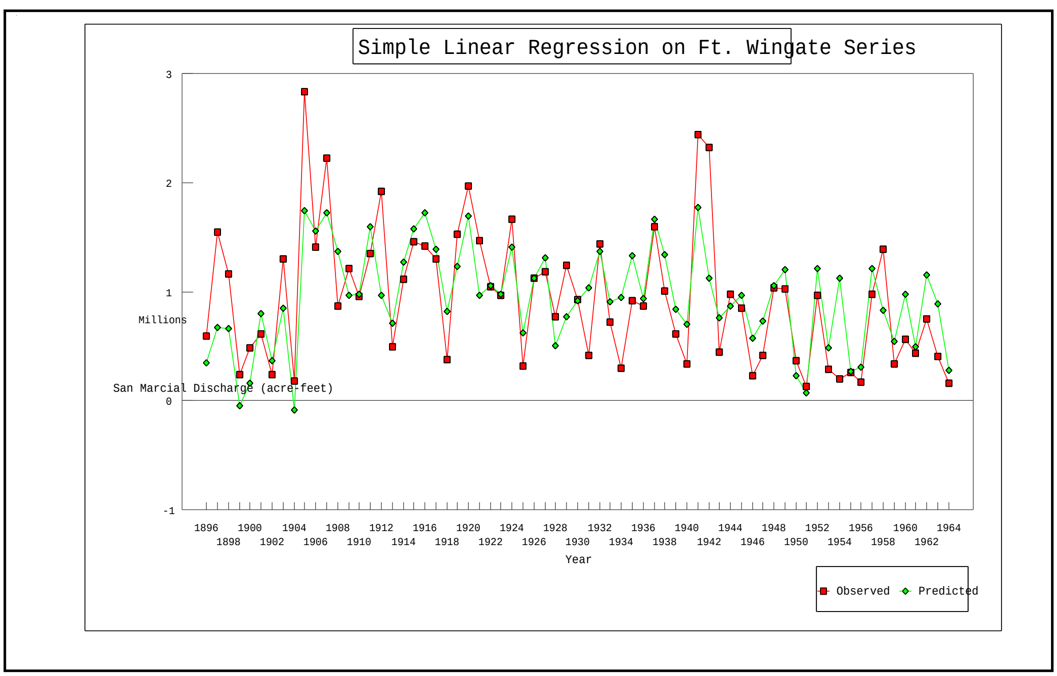


Figure 3. Correspondence between observed and predicted discharge estimates at San Marcial using Ft. Wingate Series: 1896-1964.

I should mention that relatively sophisticated analyses involving regression on principal components were performed under the assumption that perhaps principal components analyses using data from all 20 tree-ring stations across New Mexico might generate even better correlations with discharge. This more complex analysis did not, in fact, provide correlations substantially better than simple bivariate regression analyses using the Ft. Wingate sequence. This simply underscores the need to collect data from more tree-ring stations across the state to begin to adequately model paleodischarge of the Rio Grande.

For purposes of this discussion, I will simply invoke the KISS principle and focus for the remainder of my discussion on the more simple bivariate model involving regression of the Ft. Wingate ring series on San Marcial discharge. The availability of a 484-year long tree-ring sequence from Ft. Wingate allows us to begin to explore potential variability in longer-term discharge in the Rio Grande between A.D. 1480 and today. Figure 4 shows annual discharge of the Rio Grande at San Marcial estimated by rearranging the terms of the bivariate regression equation shown above. The estimated annual acre-foot discharge over this 484 year period is 847,269.88 (STD = 425430.58). A 95 percent confidence interval on the estimated mean annual discharge is 847,269.88 $\pm$ 37,669.5 acre-feet.

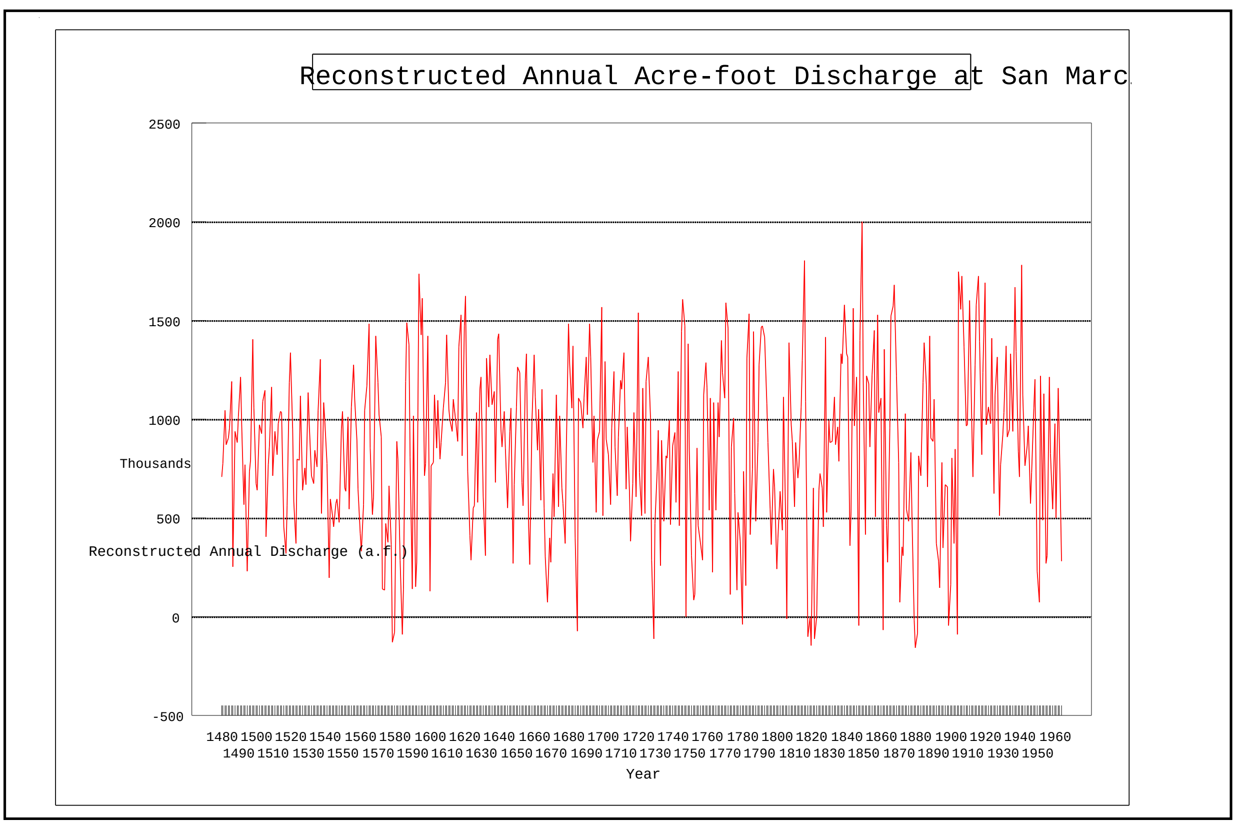


Figure 4. Reconstructed Annual A.F. Discharge at San Marcial: 1480-1964.

What is most important about this reconstruction is that it illustrates *relative* fluctuations in the Rio Grande's discharge over a long period. Whether it is absolutely correct is not crucial. Second, it demonstrates that the drought of the 1950s–a period that is perhaps our psychological touchstone for adverse drought effects–pales to insignificance compared to the number, magnitude, and periodicity of drought periods in the past.

Comparison of reconstructed annual acre-foot discharge using tree ring proxy data for the interval A.D. 1480-1895–prior to installation of a gauging station at San Marcial–with reconstructed acre-foot discharge after 1895 suggests that annual flow of the Rio Grande at San Marcial after 1895 was higher than that observed during the previous 415 years. Indeed, post–1895 discharge appears to be higher by about 13 percent than pre–1895 reconstructions (i.e., 940,417.4 acre-feet vs. 832,193 acre-feet).

Since post-1895 gauging station data are the basis for water allocations under the Rio Grande Compact, this recent period seems to reflect higher–than–average flows relative to the preceding 415 years. In short, Rio Grande water may be oversubscribed to a substantial degree relative to the long-term hydrology of the basin. Similar findings from the Colorado River lend support to the notion that water throughout the West is oversubscribed (Meko 1990:124, Stockton 1990:43). This suggests that water allocations under the Rio Grande Compact, not to mention the 1906 treaty between the United States and Mexico, may, during periods of low discharge, become highly problematic. Further, it suggests that we have not experienced the kinds of low-flow periods common in the past.

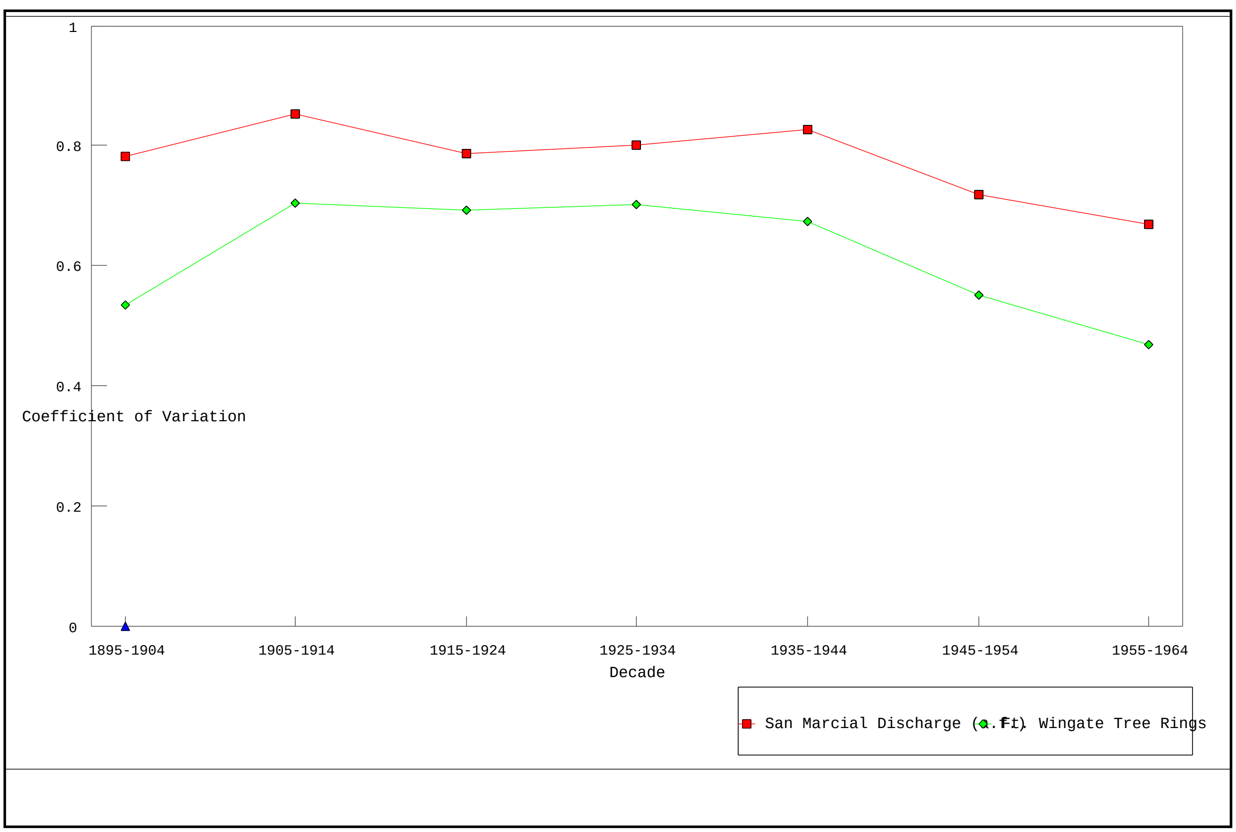
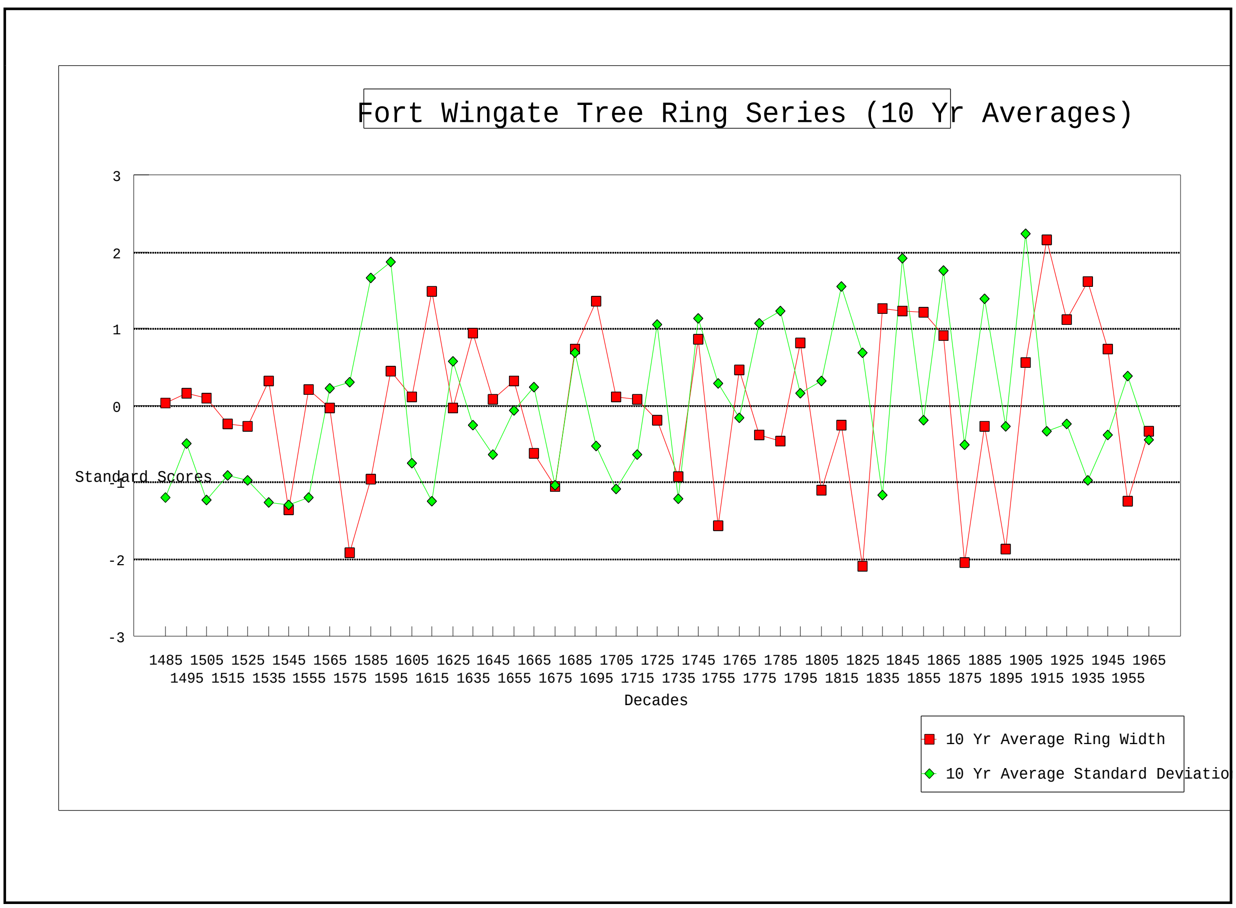


Figure 5. Comparison of Decadal coefficients of variation between San Marcial Discharge and Ft. Wingate Tree Ring Widths.

I now want to shift the focus from annual discharge reconstructions to decadal reconstructions. What is interesting about the interrelationship between the San Marcial gauging station data and the Ft. Wingate tree ring sequence is that they also exhibit a close correspondence in terms of variability estimates. As shown in Figure 5, decadal variability in gauged discharge is closely paralleled by decadal variability in the tree ring series from Ft. Wingate. This, in turn, suggests that long-term variability in the Ft. Wingate tree ring series can provide reasonable first approximations about variability in the paleo-discharge of the Rio Grande. As Figure 5 illustrates, reliance on the ring series will *underestimate* the actual magnitudes of discharge variation by an average of 25.2 percent (range=13.4–42.8 percent).

By shifting to decadal analyses, it is possible to systematically compare interactions in reconstructed decadal discharge and decadal variability. Figure 6 shows a time-sequent plot of fluctuations in decadal average ring widths, as well as decadal average standard deviations in ring widths over the period A.D. 1480-1964. Both have been standardized to facilitate presentation on a single plot.



Figures 6. Decadal variations in standardized ring widths and standardized standard deviations: Ft. Wingate.

This plot shows that there are periods of relatively low variability (e.g., A.D. 1480-1560) followed by intervals characterized by relatively high variability (e.g., A.D. 1570-1590). Even more interesting are the decades that alternate as follows:

1. High width, low standard deviations (i.e., higher discharge with less variability, e.g. A.D. 1620-1629, 1690-1699)
2. High widths, high standard deviations (i.e., higher discharge with more variability, e.g. A.D. 1740-1749, 1830-1839)
3. Low widths, low standard deviations (i.e., lower discharge with low variability, e.g. A.D. 1540-1549, 1730-1739), and
4. Low widths, high standard deviations (i.e., lower discharge with higher variability, e.g. A.D. 1580-1589, 1820-1829, 1950-1959)

Equally important, the period A.D. 1920-1964 exhibits relatively low variability relative to the entire 484 year sequence.

The issue I am concerned with revolves around the relative predictability of river discharge. Accordingly, this sequence allows us to begin to examine variability in the Rio Grande's discharge over a much longer period than what gauging station data can provide. To begin this analysis, the ring series was then divided into 50-year intervals and the occurrence of decades exhibiting standardized standard deviations greater than or equal to +1.0 and less than or equal to -1.0 were tallied (Table 1). I arbitrarily selected a cutoff of $\pm$ 1.0 simply because the evidence indicated that the bivariate regression model underestimated actual highs and lows, and underestimates actual variability.

An examination of Table 1 shows there has been a general shift from decades with low variability early in the 484-year sequence toward decades with progressively greater variability in later decades. A systematic comparison of the 249-year period prior to 1730 with the following 234-year period confirms that the variances between these two periods are significantly different ($F_{234,249} = 1.627$, $p = .0003$).

Second, our contemporary perceptions of the Rio Grande's character may be flawed as a result of our inability to remember (or even know) its history. In other words, our collective memory regarding the river's character may be erroneous since, as Table 1 shows, there have been **no** decades since the 1930s when there were large departures, either positive or negative, in decadal standard deviations so that we may think that the Rio Grande does not fluctuate wildly when, in point of fact, longer-term data suggests that this 1930-1970 period represents a short-lived anomaly.

Table 1
Frequency of Large Positive or Negative Standard Deviations by Time Period: Ft. Wingate.

Period	STD GE +1.0	STD LE -1.0	% of Decades Affected	Conclude
A.D. 1480-1520	0	2	.40	Less Variability Common
A.D. 1530-1570	0	3	.60	Less Variability Common
A.D. 1580-1620	2	1	.60	More Variability Common
A.D. 1630-1670	0	1	.20	Negligible difference
A.D. 1680-1720	1	1	.40	Equiprobable
A.D. 1730-1770	2	1	.60	More Variability Common
A.D. 1780-1820	2	0	.40	More Variability Common
A.D. 1830-1870	2	1	.60	More Variability Common
A.D. 1880-1920	2	0	.40	More Variability Common
A.D. 1930-1964	0	1	.20	Negligible Difference

To better underscore the shift that transpired over this period, the entire sequence was divided into two 250-year time periods and the occurrence of decades showing large positive or negative standard deviations were then tallied (Table 2). Table 2 shows clearly that there has been a shift since about 1729 from decades with relatively low variability to decades with much higher variability. This is what my old statistics professor, Dr. Dennis Young, used to call the inter-ocular impact finding; you don't need to run a statistic to appreciate that this is a significant difference (Fisher's Exact p = 0.02). In short, the river's discharge has been more variable over the past two centuries or so compared with the preceding two centuries.

Table 2

Period	No. of decades where STD is GE +1.0	No. of decades where STD is LE -1.0
A.D. 1480–1720	3	8
A.D. 1730-1970	8	3

On a similar note, we may not fully appreciate how different the average annual discharge of Rio Grande has been over the past few centuries. For example, based on the demonstrated correlation between ring widths and discharge presented here, fluctuations in either (a) the *relative proportions* or (b) *absolute numbers* of decades exhibiting large deviations from the long term average provides information about the river's flow.

To evaluate such fluctuations, the number of decades where the average annual ring width fluctuated above +1.0 or below -1.0 were tallied (Table 3).

Table 3

Period	No. of decades where AVG is GE +1.0	No. of decades where AVG is LE -1.0
A.D. 1480–1720	2	3
A.D. 1730-1970	6	5

Two facts emerge from this analysis. First, the **relative proportions** of decades exhibiting large positive or negative deviations in annual ring width–and, by extension, annual discharge–do not appear to have changed substantially over these two broad time periods. However, what is notable is that the **absolute number of decades** exhibiting significant deviations has increased dramatically since 1730. During the 249 years prior to 1730, there were only 5 decades where the average tree ring widths exceeded $\pm$ 1.0–only 20% of the time series. In contrast, during the 245 years *since* 1730, there have been a total of 11 decades where average tree ring widths exceeded $\pm$ 1.0; a more than doubling in the frequency to 44% of this subset of the time series. This coincides well with the rather high frequency variations indicated by analyses of coefficients of variation.

This second finding is important to us here today. The fact that a larger number of decades fluctuate well above or well below the long term average confirms that the annual discharge of the Rio Grande has been more variable, and, by extension, less predictable, since 1730. Moreover, the fact that there has been only a single large *negative* deviation (i.e., the drought of the 1950s) since 1930 may be lulling us into a false sense of security regarding the Rio Grande's predictability with respect to average annual discharge.

To briefly summarize, what I have tried to present today is a simple model of long-term variability in the flow of the Rio Grande. What I have shown that there is a significant correlation between tree-ring fluctuations and gauged river discharge during the period A.D. 1896-1964. Using a statistical model based on this correlation, I have then retrodicted variations in the Rio Grande's discharge extending back in time to A.D. 1480.

Analyses of fluctuations over this 484 year period suggest that the Rio Grande has been much more variable since A.D. 1730, both in terms of average discharge and decadal variability in average discharge. Since 1930, the Rio Grande has exhibited relatively little variability compared to the entire 484-year period for which discharge can be modeled. This suggests that our contemporary perceptions of the Rio Grande's characteristics, particularly with regard to its inherent variability in annual discharge, may be skewed. The seeming lull since 1930 may presage a return to relatively less variable conditions that, for example, typified the period between 1480-1730. If so, then it is also likely that we face the prospect of receiving average annual flows that may be as much as 10–15 percent *below* estimates based on gauging station data. On the other hand, this seemingly less variable period since 1930 may simply be a pause before the river returns to the extreme variability of the past 250 years (Stockton et al. 1983:315).

In the absence of additional information, we should plan our water use based on far more conservative estimates. Gauging station data from San Marcial between 1896-1964 indicate that "long-term" discharge averaged 940,417.4 acre-feet. In contrast, the far more long-term average estimated using proxy data from 1480-1895 indicate that the long-term average may be more on the order of 832,193 acre-feet, a difference of 13 percent *below* the nominal gauged annual flow of the Rio Grande at San Marcial. If we want to undertake planning on the basis of gauging station data that are 13 percent *above* the much longer term estimated average discharge, then, to borrow a turn of phrase from Charles Dickens' Tiny Tim, "God bless us, every one." Quite frankly, I don't think we can afford that luxury. A probability density histogram based on reconstructed annual discharge between A.D. 1480 and 1964 suggests that we should be planning our water use on higher–probability values of between 550,000 and 750,000 acre-feet (Figure 7).

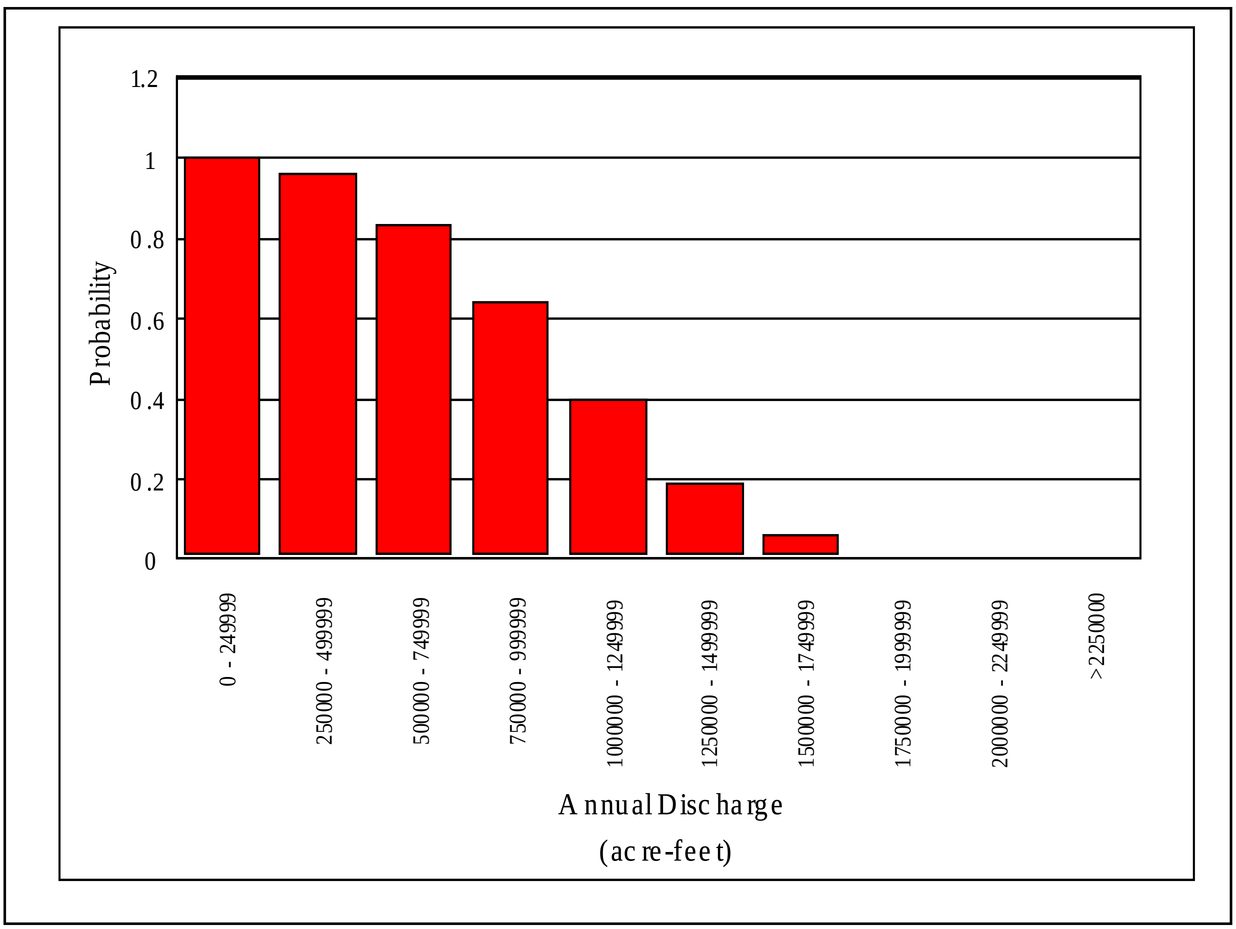


Figure 7. Probability density histogram of acre-foot discharge at San Marical based on Reconstructed discharge between A.D. 1480 and 1964.

As an anthropologist, I have spent considerable time studying past civilizations in arid lands that relied on surface water. Most of these societies failed. Analyses suggest that they failed for three reasons:

1. They overestimated the amount of water available in the rivers on which they depended;
2. They underestimated annual variability in discharge, and
3. They underestimated the frequency, persistence, and recurrence intervals of extreme low-flow events

Unlike earlier societies, we have employed two pieces of technology that buffer annual discharge fluctuations: storage dams and groundwater pumping. However, storage dams are not necessarily effective and, as the 1950s drought so amply demonstrated when Elephant Butte Reservoir was virtually dry, this technology has already failed once in our lifetime. What saved us during the 1950s drought was our ability to pump groundwater. Thanks to this technology, what should have been a wake-up call turned into a moderate inconvenience.

Today, we find ourselves not only relying on surface water to meet our water needs, but, as well, pumping groundwater to meet these needs. It is not hard to envision a scenario, perhaps unfolding sometime between A.D. 2010 or 2020, when drought once again dramatically reduces surface water supplies. Unlike the 1950s, however, our continued withdrawals during the intervening years will have significantly depleted groundwater reserves and we will then find out, in spades, whether we should have used water in the fashion to which we are now accustomed. When–not if–this does happen, it may come as a shock to find that we, too, have repeated the mistakes of past civilizations and, like them, are faced with a water crisis..

References Cited

Dean, Jeffrey S., 1996. Demography, Environment, and Subsistence Stress. In Joseph A. Tainter and Bonnie Bagley Tainter (eds.) *Evolving Complexity and Environmental Risk in the Prehistoric Southwest.* Santa Fe Institute, Studies in the Sciences of Complexity, Proceedings Volume 24, Santa Fe.

Dean, Jeffrey S. and William J. Robinson, 1978. Expanded Tree-Ring Chronologies for the Southwestern United States. University of Arizona, Laboratory of Tree-Ring Research, *Chronology Series III*, Tucson.

Drew, Linda G (ed.), 1972. Tree-Ring Chronologies of Western North American, II. Arizona, New Mexico, Texas. University of Arizona, Laboratory of Tree-Ring Research, *Chronology Series I*, Tucson.

Meko, David M., 1990. Inferences from Tree Rings on Low Frequency Variations in Runoff in the Interior Western United States. Proceedings of the Sixth Annual Pacific Climate Workshop, California Department of Water Resources, Interagency Ecological Studies Program, Technical Report 23, Sacramento, pp. 123-127.

Robinson, William, 1970. Ft. Wingate Tree-ring Sequence (NM031). http://www.ngdc.noaa.gov/cgi-bin/paleo.

Stockton, Charles W., 1990. Climatic, Hydrologic, and Water Supply Inferences from Tree Rings. *Civil Engineering Practice* 37-52.

Stockton, Charles W. and William R. Boggess, 1980. Tree Rings: A Proxy Data Source for Hydrologic Forecasting. Symposium Proceedings, Unified River Basin Management, Gatlinburg, TN 4-7 May 1980, American Water Resources Association, Minneapolis, MN, pp. 609-624.

Stockton, Charles W., Peter T. Quinlan, and W. R. Boggess, 1983. Climatic Change and Surface Water Availability in the Upper Rio Grande Basin. Regional and State Water Resources Planning and Management, American Water Resources Association, pp. 311-321.

U.S. Geological Survey (U.S.G.S.), 1974. Surface Water Supply of the United States, 1966-70, Part 8. Western Gulf of Mexico Basins. *Geological Survey Water Supply Paper* 2123, U.S. Government Printing Office, Washington, D.C.

1970. Surface Water Supply of the United States, 1961-65, Part 8. Western Gulf of Mexico Basins. *Geological Survey Water Supply Paper* 1923, U.S. Government Printing Office, Washington, D.C.

1964. Compilation of Records of Surface Waters of the United States, October 1950–September 1960, Part 8. Western Gulf of Mexico Basins. *Geological Survey Water Supply Paper* 1732, U.S. Government Printing Office, Washington, D.C.

1960. Compilation of Records of Surface Waters of the United States Through September 1950, Part 8. Western Gulf of Mexico Basins. *Geological Survey Water Supply Paper* 1312, U.S. Government Printing Office, Washington, D.C.