New Mexico Climate and Hydrology:
is the Historic Record Valid for Predictive Modeling?

Karen Lewis, klewis@sspa.com and Deborah Hathaway, dhathaway@sspa.com
S.S. Papadopulos & Associates, Inc., 1877 Broadway, Suite 703, Boulder, CO 80302

ABSTRACT

In using measured stream-flow to assess water supply or to drive hydrologic models, hydrologists assume that the stream-flow record used is representative of present and future hydrologic conditions. However, in regions like the arid southwest where stream flow is highly variable from year to year and strongly affected by climate forcing like El Nino, assuming the record is representative without verifying that assumption can lead to potential errors.

This paper summarizes two studies done by S.S. Papadopulos & Associates, Inc. (SSP&A). The first study focuses on whether the 1950-1998 Otowi index flow calculated for the Rio Grande at Otowi Bridge, New Mexico is both representative of historic, and predictive of future, Middle Rio Grande flow. For this study we looked at past climate, as recorded in tree-ring and archeological records, and at local climate forcing by the Pacific Decadal Oscillation and compared these with the Otowi Index flow for the period from 1919-1998. (The index flow is calculated by the Rio Grande Compact Commission to reflect native flow under baseline development conditions.) We find that the 1950-1998 period of record is relatively representative of past conditions, but note that the period from 1978-1998 is dramatically wetter than any other period in the past 1000 years of record. Based on the response of the Otowi index flow to forcing by the Pacific Decadal Oscillation, New Mexico may be moving into a 10 to 20 year period of below-average flows.

The goal of the second study was to create a "typical" 40-year sequence, representative of a broad range of climatic conditions, to represent hydrologic inputs in the Upper Rio Grande Water Operations Model (URGWOM) "planning" model that will be used for analysis of water operations alternatives. The "pool" of available data for construction of this sequence is restricted to the period from 1975 to 1999, as this is the period for which the URGWOM team has assembled complete model input files. Tree ring climate reconstructions were used to "normalize" the recent record to the long-term record reflected in the paleo-reconstructions, to: a) determine the relative proportions of drought, average and wet conditions; and b) select representative drought and wet period events.

Keywords: Rio Grande, hydrology, paleo-climate, modeling

INTRODUCTION

Hydrologic models are commonly used in water planning to improve our understanding of the hydrologic system in a region, predict system behavior under various conditions, and forecast future supply for planning purposes. However, these models are only as good as the data that goes into them. Consequently, substantial effort is put into collecting and analyzing new data, identifying and verifying the accuracy of historical records, and identifying cyclical trends in the data and the large-scale forcing that drives these trends.

Modelers have traditionally relied on data sources, such as stream gage and meteorological data, which have been measured by hand or via installed instrumentation. There is a wealth of data to be had from these sources, and the data are generally well documented. In the Southwest, however, we are often limited to 100 or fewer years of record, and data quality becomes harder to assess as the data increase in age. Models based on these data indirectly assume that these conditions are representative of long-term behavior.

In recent years the paleo-science community has begun to provide us with excellent supplemental information. Paleo-climatologists look at natural recorders of climate variation such as sediment cores, ice cores, tree rings, and annual growth banding in corals. Of these, many tree ring records exist for the Southwestern US, some extending back more than 1000 years. These tree ring records can be accurately dated from the annual growth bands, and the variation in band width correlated with climatic factors effecting growth, such as precipitation, temperature, and drought indices, to give a record of past climate. Reconstructions of precipitation, flow, or drought indices are now available for many western drainages, including the Middle Rio Grande (Grissino-Mayer et al, 2002), the upper Colorado River (Stockton and Jacoby, 1976), the Salt and Verde Rivers (Smith and Stockton, 1981), and the Sacramento River (Meko et al., 2001). These reconstructions can be used to put measured data in perspective, to help clarify climatic cycles that affect events such as long-term droughts, and in some cases as input flows for modeling (Meko et al., 1995; Tarboton, 1995).

In addition to advances in paleo-climatology, climatology has also been making great strides forward in recent years in the area of large-scale spatial and temporal climatic variability. We see the results of this work in improved knowledge and forecasting of El Nino/Southern Oscillation (ENSO) events, and a growing recognition and understanding of decadal scale forcing such as the Pacific Decadal Oscillation (PDO) and the North Atlantic Oscillation, including their impacts on regional climatology.

In this paper, we outline how S.S. Papadopulos & Associates (SSP&A) is working to incorporate information from tree ring records and improved climate forcing information into hydrologic modeling in the Middle Rio Grande (MRG) region of New Mexico. We first present an analysis of the past 300 years of climate, as reflected in tree ring records, to look at drought and wet period events and recurrence times. Second, we analyze the impact of climate forcing by the Pacific Decadal Oscillation. Third, we assess how the measured flow record compares to the long-term record. Finally, we use the understanding we have developed to generate a synthetic 40-year sequence to drive the URGWOM planning model, to be used in analyzing water operations alternatives.

DATA

In 2000 SSP&A completed a study contracted by the U.S. Army Corps of Engineers and the New Mexico Interstate Stream Commission to develop a quantitative and probabilistic model of the conjunctive use groundwater and surface water supply available to the Middle Rio Grande from Cochiti Reservoir to Elephant Butte Reservoir (Figure 1), under the constraints of the Rio Grande Compact (S.S. Papadopulos & Associates, Inc., 2000). In 2001 we began a second phase of this study that included an analysis of past climate and climate forcing in the region. The goal of our analysis was three-fold:

- To determine if the 1950-1998 period of record used in the first phase of the Middle Rio Grande Water Supply Study was representative of the long-term hydrology of the region;
- To assess the length and recurrence period of typical drought and wet periods for use in a "failure analysis" modeling scenario;
- To evaluate regional climate forcing with an eye to what sort of near-future conditions the region should be considering.

To answer these questions, we used a tree-ring reconstruction of the Palmer Drought Severity Index (PDSI), annual flows on the main stem of the Rio Grande, annual Pacific Decadal Oscillation (PDO) index values, and a reconstruction of PDO values from 1660 to 1992.

Following this initial study, SSP&A was asked to produce a 40-year synthetic flow sequence for use with the URGWOM planning model to assess water operations alternatives under a multi-agency effort to develop an EIS for reservoir operations (Upper Rio Grande Water Operations Review, Memorandum of Agreement, December 1999, USBR, ACOE, NM Interstate Stream Commission). The "pool" of available data for construction of this sequence is restricted to the period from 1975 to 1999, the period for which the URGWOM team has assembled complete model input files. The sequence was to be representative of long-term regional climate, in particular capturing "representative" drought and wet periods but still maintaining average conditions similar to those seen historically in the basin. For this work we used data and results from our prior study in conjunction with the PDSI calculated for sub-regions in New Mexico.

Many tree ring records and reconstructions are available throughout New Mexico. For this work, we looked at the most recent record for the MRG region, a 1370-year reconstruction of June PDSI values for the New Mexico Middle Rio Grande basin (climate division 5) based on tree rings from El Malpais National Monument, the Magdalena Mountains, and the Sandia Mountains (Figure 1) (Grissino-Mayer et al., 2002). This reconstruction (Figure 2), since it is composed of 3 records located along the edges of the Middle Rio Grande basin (Figure 1), is the best available climate reconstruction available for the region. A paper by Scurlock and Johnson (2001), which presents a 500-year reconstruction of Rio Grande hydrologic history using pueblo and fort records, historical references, and archeology, was used to independently corroborate the tree-ring conclusions.

For the period from 1919 to 1992, the PDSI reconstruction was compared with the Otowi Index flow. The Otowi Index flow is the Rio Grande flow measured at Otowi Bridge (Figure 1) and "adjusted" to reflect pre-development conditions by correcting for upstream water storage and trans-basin water imports. The computed annual Otowi Index flow is reported in annual reports of the Rio Grande Compact Commission. This flow is the largest single source of water to the MRG and consists of flows from the Upper Rio Grande and the Rio Chama, both of which flow out of the mountains of north-central New Mexico. It is primarily a snowmelt driven river, with peak flows occurring in the spring. The MRG also obtains significant water from rivers that enter the Rio Grande below Cochiti Reservoir. However, most of these sources are primarily monsoon driven, and there appears to be little correlation between climate forcing and monsoon precipitation in New Mexico. Rivers flowing into the MRG that are not primarily monsoon driven, such as the Rio Jemez, are strongly correlated with the Otowi flow (r = 0.88). Consequently, we chose to focus solely on the Otowi inflow as a proxy for the predictable hydrologic input to the region.

Comparisons were also made between the Otowi Index flow and PDO values. The PDO is a long-lived El Niño-like pattern of Pacific climate variability. El Niño, the warm phase of the El Niño/Southern Oscillation (ENSO), occurs irregularly at intervals of 2-7 years. El Niño events typically last 12-18 months, and are accompanied by swings in the Southern Oscillation, an inter-annual seesaw in Pacific Ocean equatorial (from 4^oS to 4^oN) sea level pressure and sea surface temperature. The strongest regional ENSO signal in North America is in the southwestern U.S. and northern Mexico, where warm events (El Niño) tend to be associated with higher winter and spring precipitation. Dry springs and extensive fires are associated with cold events (La Niña) (Bradley, 1999).

The PDO is a similar climatic oscillation to ENSO, has a similar spatial climate fingerprint, but has very different behavior in time; 20th century PDO "events" persisted for 20-to-30 years. The PDO is derived from monthly sea surface temperature anomalies in the North Pacific Ocean, north of 20 degrees latitude. Just as ENSO climatic variations occur as a result of anomalously warm and cool pools of water in the equatorial Pacific Ocean, PDO climatic variations occur on a decadal time scale as a result of anomalously warm or cool sea surface temperatures in the North Pacific Ocean, north of 20 degrees latitude, and over a larger spatial scale than ENSO.

The North American climate anomalies associated with PDO are broadly similar to those connected with El Niño and La Niña, though generally not as extreme. Positive (warm, with warm water off the west coast of the Americas) phases of PDO are correlated with El Niño-like North American temperature and precipitation anomalies, while negative (cold, with cool water off the west coast of the Americas) phases of PDO are correlated with La Niña-like climate patterns (Mantua, 2000).

Monthly PDO index values from 1900 to present were downloaded from (ftp://ftp.atmos.washington.edu/mantua/pnw_impacts/INDICES/PDO.latest; Mantua, 2000). An annual PDO reconstruction of (Biondi et al., 2001a) was used to look at reconstructed PDO values prior to 1900. This reconstruction is based on tree rings from Southern and Baja California, an area where tree ring records are better correlated with PDO than with ENSO (Biondi et al., 2001b), and spans the period from 1660 to 1992.

For the 40-year synthetic sequence generation, in addition to the Grissino-Mayer PDSI reconstruction, we used measured PDSI values for New Mexico climate division 1 (northwestern New Mexico). These data were obtained from the National Climatic Data Center web site. Monthly June values, which correlate well with annual Otowi flows, were compared with the reconstructed PDSI to normalize the 1975-1999 measured Otowi flows with respect to the 1700-1992 climate.

ANALYSIS AND RESULTS

Analysis of the long-term record

We began our analysis by looking at drought and wet period occurrence in the Grissino-Mayer June PDSI reconstruction. From the PDSI reconstruction, the period from 1700 to 1992 was chosen to encompass both the current above average wet period (1801-1992) and the previous below average dry period (1714-1800) (Grissino-Mayer, et al., 2002). Additionally, 1700-1992 is fully contained within the period of western settlement in the region and therefore semi-documented. Though not done explicitly as part of this analysis, conclusions draw from analysis of the reconstructed PDSI values could be double-checked against archeological, agricultural, and fort records. The average reconstructed PDSI value for the 1700-1992 period is 0.07. An entirely unbiased period would have an average PDSI value of 0, indicating the 1700-1992 period is close to unbiased. Reconstructed PDSI values for this period, and a 5-year running average of values, are shown in Figure 3.

Since 1700, there have been 8 multi-year droughts (periods with an average PDSI < -1 over 5 or more years) encompassing 83 years in the reconstructed PDSI data. These droughts are shown in Table 1 in order of severity, where severity is based on a combination of "depth" of drought, as measured by the magnitude of the average PDSI for the period, and duration of drought. These droughts have, on average, a 40-year recurrence interval (8 droughts in a 293 year span), and an average duration of 10.4 years. Of the 83 years included in these droughts:

- 32 of the years (39%) were very dry (PDSI < -2)
- 21 (25%) were dry (-2 < PDSI < -1)
- 26 (31%) were average (-1 < PDSI < 1)
- 4 (5%) were wet (1 < PDSI < 2)
- none of the years (0%) were very wet (PDSI > 2).

Over the same timespan, there have been 7 multi-year wet-periods (average PDSI > +1 over 5 or more years) encompassing 77 years in the reconstructed PDSI data. These wet periods are shown in Table 2 in order of severity. They have, on average, a 42-year recurrence interval, and an average duration of 11-years. Of the 77 years included in these wet periods, none of the years were very dry (0%), 4 were dry (5%), 28 were average (37%), 21 were wet (27%), and 24 were very wet (31%).

Between 1700 and 1992, 83 years were drought years (Table 1) and 77 years were wet period years (Table 2). The remaining 133 years were "average" years, years that did not fall in either a multi-year drought or a multi-year wet period. Of these 133 average years, 10 were very dry (8%), 18 were dry (13%), 61 were average (46%), 26 were wet (20%), and 18 were very wet (13%). Unlike the drought and wet period distributions, which are highly skewed, this distribution of conditions is normal. The distribution of conditions for the full period is also normal, further confirming that it is representative of long-term average conditions. The percentage breakdown for the full 293 years of record is 14% very dry, 15% dry, 39% average, 18% wet, and 14% very wet.

As can be seen in Table 1, the 1945-1963 drought is ranked as the most extreme drought on record since 1700. Within the context of the entire reconstructed PDSI record, from 622-1992 (Figure 4), Grissino-Mayer ranks the 1950s drought as the third most severe drought in the record (Grissino-Mayer et al., 2002). It is exceeded by droughts occurring between 1571-1593 and 1272-1297. Both of these droughts exceeded the 1950s drought in length, by 4 and 7 years respectively. The 1571-1593 drought exceeded the 1950s drought in severity as well; the average reconstructed PDSI value during the 16th century drought was –1.99. The archeological record supports the severity of both the 13th and 16th century droughts. Both these droughts correlate with known abandonment of pueblos and cultural shifts by the Native Americans living in the region (Scurlock and Johnson, 2001).

The most extreme wet period since 1700 is 1978-1992. As with droughts, when viewed in light of the entire PDSI reconstruction, 1978-1992 drops to the third most severe wet period, behind 1553-1557 and 1627-1653 (Grissino-Mayer et al., 2002). However, the 1553-1557 period has an average PDSI of 3.6, but a duration of only 5 years (as compared to 15 years for the 1978-1992 period), and the 1627-1653 period has a duration of 27 years, but an average PDSI of 1.45 (as compared to 1.90 for 1978-1992). Additionally, unlike the 1945-1963 drought, the 1978-1992 wet period was truncated not by a return to drier conditions, but by the date of construction of the record. Measured PSDI values in New Mexico climate division 5 remained high through 1998. If this period were included in the PDSI reconstruction, it is possible that the 1978-1998 period wetness would exceed that of the two competing periods.

Climate Forcing Analysis

There is a well known correlation between ENSO and precipitation in New Mexico. Warm events (El Niño) tend to be associated with higher winter and spring precipitation, in particular in the northern portions of the state. Dry springs and extensive fires are associated with cold events (La Niña) (Bradley, 1999). Since North American climate anomalies associated with PDO are broadly similar to those connected with ENSO, we were interested in looking for similar high and low flow regimes associated with the PDO in the MRG basin.

We first compared the measured PDO index with measured Otowi index flows. Since 1919, there have been three phases of the PDO. Positive PDO phases occurred between 1925-1945 and 1977-1998; a negative phase of the PDO occurred between 1947-1976. These periods broadly coincide with the ranked drought and above average wet periods recorded in the reconstructed PDSI for the MRG basin (Tables 1 and 2). Average flows during these periods, and how these averages compare to the average 1947-1998 flow (chosen because in includes one full cycle of the PDO), are shown in Table 3. During the negative phase of the PDO, Otowi index flows were 85% of the 1947-1998 average. During the positive phases of the PDO, Otowi index flows were 118% and 121% of average. The data shown in Table 3 imply there is a strong correlation between the PDO and Rio Grande flow in New Mexico. Similar correlations can be found going back to 1660. Figure 4 shows the reconstructed PDO index (Biondi et al., 2001a) and severe droughts recorded in archeological and fort records (Scurlock and Johnson, 2001). Of the 9 severe drought recorded for New Mexico, 7 have occurred during negative phases of the PDO. Furthermore, the reconstructed PDO records 6 periods when PDO values drops below –1. Severe droughts are recorded for the MRG during 5 of these periods.

For modeling in this region, the flow-PDO correlation indicates that the period of record used to characterize regional climate should ideally be based on full cycles of the PDO, incorporating equal numbers of positive and negative phases. In terms of likely near-future conditions in the region, we need to assess upcoming PDO behavior. Climatologists believe the PDO shifted around 1998-2000 and we are now in cool phase. If true, and if past PDO behavior continues, climate in New Mexico will be dry for the next decade or two. Drawing from past observations, average Rio Grande flows at Otowi Bridge will likely be 85 or 90% of the 1950-1998 average, and around 70 to 75% of what we have seen in the past two decades.

Assessment of Otowi index flows with respect to the long-term record

Annual flows values were first measured at Otowi Bridge in 1896, and continuous annual index values are available from 1919-present. In the Grissino-Mayer PDSI reconstruction, the period since 1919 has consisted of two periods of drought (1922-1927 and 1945-1963) and three periods of above average wetness (1907-1921, 1930-1944, and 1978-1992). Only 16 years between 1919 and 1992 did not fall in either a ranked drought (Table 1) or ranked wet period (Table 2). In terms of the PDO, 1919-present is composed of two positive phases and one negative phase, suggesting the period is skewed toward wet conditions.

The correlation between Otowi index flows and the reconstructed PDSI values, from 1919 to 1992, is r = 0.56. This correlation is fairly good (for a tree-ring/climatic variable correlation) and indicates that the reconstruction can be used to explain more than half of the variability in the Otowi flows. More particularly, decadal patterns seen in the PDSI reconstruction are reproduced well in the Otowi flows. The correlation between the 10-year running average reconstructed PDSI and 10-year running average Otowi flow, from 1919 to 1992, is r = 0.72, and the broad-scale drought and wet periods are coincident (Figure 5). Consequently, we are comfortable using the reconstructed PDSI values as a proxy for flow behavior in the MRG region.

Average values of the reconstructed PDSI and Otowi index flow for 1700-1992, 1919-1992, 1950-1992 (the period of overlap between the reconstructed PDSI record and the SSP&A modeling period of record), and 1950-1998 (the SSP&A modeling period of record) are shown in Table 4. The average PDSI value for the entire 1919-1992 period, 0.27, is significantly higher than that for the 1700-1992 period, 0.07. This indicates the 1919-1992 period incorporates a higher percentage of wet conditions that the longer-term record, as expected based on both the ranked drought and wet period analysis of the reconstructed PDSI data, and the PDO analysis where the period from 1919-1992 includes a second wet phase of the PDO. The 1950-1992 period, however, has an average PDSI of 0.08, basically equal to that of the long-term record, indicating that its representation of wet and dry conditions during this period is basically balanced. This result matches our expectations based on the PDO phases – the period from 1950-1992 is roughly coincident with a full PDO cycle and should therefore be relatively balanced. Shortening the 1950-1992 period at either end omits part of all of one of the PDO phases, skewing the record in the opposite direction, as can be seen in the average PDSI values shown in Table 3.

Since the average PDSI for the 1950-1992 period is roughly equal to that of the 1700-1992 period, and since it encompasses the bulk of the last PDO cycle, we use that as the base flow period and compare average flows for the other time intervals to average 1950-1992 flow. Table 3 shows that flow between 1950-1992 averaged 933,000 acre-ft per year. Average flow during the period SSP&A used in the Middle Rio Grande Water Supply Study, 1950-1998, is roughly equal to the 1950-1992 period (103%), which in turn, based on comparison with average PDSI values, is assumed to be representative of average conditions between 1700-1992. Thus, it appears that the 1950-1998 period used for the SSP&A water supply study is an excellent choice given the available data. Using either a shorter piece of the recent record or the entire continuous record back to 1919 would both result in an overestimate of historically available water.

Using the 1950-1998 period of record for modeling in the MRG basin also has the advantage that it captures a serious drought. Given that the 1950s drought is ranked as the third most severe since 622 A. D. (Grissino-Mayer et al., 2002), drought planning based on this period should be more than adequate. The disadvantage of the 1950-1998 period, however, is that it is composed of virtually no "average" conditions. It consists of a severe drought and perhaps the wettest period on record, and little in between. This makes it challenging to use in modeling moderate events.

CONSTRUCTING SYNTHETIC FLOW SEQUENCES

In the fall of 2002, SSP&A was tasked with producing a synthetic 40-year sequence of flows for use with the URGWOM Planning Model in the URGWOPS alternatives analysis. The model will be used to simulate river hydrographs and reservoir contents under identified operational alternatives, and model results will be used to compare the effect of alternative operations on resulting reservoir/river conditions under a range of hydrologic regimes, ranging from drought to wet periods. To support the alternatives analysis, a 40-year sequence of years is needed that represents a broad range of climatic conditions. However, the "pool" of available data for construction of this sequence is restricted to the period from 1975 to 1999, the period for which the URGWOM team has assembled complete model input files. Because the period from 1975 to 1999 is a wetter-than-average period, a simple random sampling from this period will not generate a sample representative of long-term conditions. In order to obtain a "representative" sample from this available record, the recent record must be "normalized" to the long-term record as reflected in paleo-climate data. By normalizing, the drier years within the 1975 to 1999 period will be sampled more frequently to obtain a sequence that is representative of the range of conditions reflected in the paleo-climate record of the past 300 years.

To normalize the 1975-1999 Otowi index flows, we correlated flows with the measured June PDSI for climate division 1 in New Mexico (data from the National Climatic Data Center; climate division 1 lies is northwestern New Mexico). There is a strong correlation between Otowi flow and the June division 1 PDSI (r = 0.84). We were therefore able to develop a correlation between ranked Otowi index flows and ranked PDSI values that would allow us to select flows from the 1975-1999 record for use in constructing drought sequences.

We chose to correlate the Otowi index flow values with the Division 1 PDSI, rather than the Division 5 PDSI, because, for the use of the URGWOM planning model, we are more interested in accurately capturing Otowi flows than general basin aridity, and the correlation between Otowi flows and Division 1 PDSI was better than the correlation with Division 5 PDSI (r = 0.52). However, we believe the comparison of the Division 1 1975-1999 values with the reconstructed Division 5 1700-1992 values is valid; average Division 1 PDSI for 1975-1999 was 1.39, average Division 5 PDSI for the same period was 1.35.

We chose Division 1 (Northwestern New Mexico) PDSI over Division 2 (North Central New Mexico) PDSI for several reasons. First, the correlation between Otowi flows and Division 1 PDSI (r = 0.84) was slightly higher than the correlation with Division 2 PDSI (r = 0.82). Second, we felt that Division 1 was more reflective of the type of terrain and climate that provides run-off to the Rio Grande and Rio Chama than is Division 2, since Division 2 is quite large and covers a large variety of terrain. Third, using the Division 2 PSDI, the resulting ranking and division of flows into very dry, dry, average, wet, and very wet categories resulted in values that were more normally distributed than those obtained using the Division 1 data. Since we know, from our examination of the long-term record, that the 1975-1999 period is abnormally wet, we were inclined to go with the dataset that reflected that best, which was the Division 1 data. The resulting analysis is therefore conservatively biased.

Figure 6 shows the June Division 1 PDSI, from 1975-1999, and the reconstructed PDSI from 1700-1992. This data was used to find the percentiles corresponding to very dry, dry, average, wet and very wet conditions for the 1975-1999 period. Very dry conditions correspond to PDSI < -2, dry conditions to –2< PDSI < -1, average conditions to –1 < PDSI < 1, wet conditions to 1 < PDSI < 2, and very wet to PDSI > 2. The point where the Division 1 PDSI for 1975-1999 crosses –2 on the y-axis is the very dry percentile, 19%. Values below the 19th percentile correspond to "very dry" conditions for the 1975-1999 period, relative to the long-term record. Dry conditions range from the 19th to 22nd percentile, average conditions from the 22nd to 38th percentile, wet conditions from the 38th to 53rd and very wet conditions correspond to the 53rd percentile and above. The 1700-1992 reconstructed PDSI is included in Figure 6 to show how the 1975-1999 period is skewed toward higher PDSI values. For the 1700 to 1992 period, very dry conditions are from the 14th percentile down, dry conditions from the 14th to 30th percentile, average conditions from the 30th to 66th percentile, wet conditions from the 66th to 86th percentile, and very wet conditions from the 86th percentile up.

Having obtained the percentile values for various flow categories from the ranked PSDI values, we applied those percentile values to the ranked 1975-1999 Otowi flows to find the very dry, dry, average, wet and very wet categories of flows. Figure 7 shows the cutoffs for very dry, dry, wet and very wet flows, based on the percentiles determined from Figure 6. Very dry flows were those below 703,100 acre-ft/year (values below the 19th percentile), dry flows were between 703,100 and 713,400 acre-ft/year (values between the 19th and 22nd percentile), average flows were between 713,400 and 1,089,400 acre-ft/year (22nd and 38th percentile), wet flows were between 1,089,400 and 1,236,400 acre-ft/year (38th and 53rd percentile), and very wet flows were 1,236,400 acre-ft/year and higher. Based on this initial classification, only one of the flows was classified as "dry", and five flows were "very dry". Two of the "very dry" flows were in the upper 600,000 acre-ft/year, and were very close in volume (within 32,000 acre-ft/year) to the only "dry" flow. We chose to use all three of these flows as "dry" since we believed that, given the flows we had to work with, these flows were more representative of dry flows that very dry flows. This gave us a pool of dry conditions to choose from. The result was 3 very dry flows, 3 dry flows, 4 average flows, 4 wet flows, and 11 very wet flows.

Based on our analysis of the 1700-1992 reconstructed PDSI data, a "typical" 40 year period consists of:

- One 10-year drought during which the distribution of conditions is roughly 39% very dry, 25% dry, 31% average, 5% wet, and 0% very wet years;
- One 11-year wet period during which the distribution of conditions is roughly 0% very dry, 5% dry, 37% average, 27% wet and 31% very wet years;
- 19 "average" years, during which the distribution of conditions is 8% very dry, 13% dry, 46% average, 20% wet and 13% very wet years.

Multiple 40-year synthetic flow sequences were constructed based the above criteria for a 40-year period. For planning model purposes, the chosen synthetic sequence needed to include both a clearly defined drought and wet period, and needed to begin with several years of non-extreme conditions to allow the model to stabilize. Consequently, we chose to construct a 40-year sequence where the first 5 years were taken from the "average" years distribution, excluding very wet and very dry years. Following the initial 5 years, we picked 10 "drought" years, 10 "average" years, 10 "wet" years, and 5 "average" years. For each year in the sequence, a flow was picked from the 1975-1999 data using the probability distributions for the three conditions ("average", "wet", "drought"). To choose a flow, a random number was generated and compared to the cumulative probability of a very dry, dry, average, wet or very wet year for the desired condition ("drought", "average", or "wet"). This provided a flow category for the flow.

A second random number was generated to pick a flow within that category. Flows were equally weighted within categories.

For each sequence, multi-year wet and dry periods were marked and compared with the desired occurrences of droughts, wet periods, and average conditions outlined above. Though "drought" or "wet" period distributions were used at particular times during the sequence to determine flows, because the flows were chosen at random, in many of the synthetic sequences drought and wet periods did not occur precisely at the specified times or for the specified number of years. Additionally, the average flow for each sequence varied significantly, from 850,000 acre-ft/year to 1,020,000 acre-ft/year. Our goal was to obtain an average flow for the 40-year sequence of near 950,000, the equivalent of the average Otowi index flow for 1950-1998. The generated synthetic sequences were visually assessed; four sequences that generally fit the desired criteria for use in the planning model were chosen and delivered to the URGWOPS Water Operations Team as candidates for use in the planning modeling. The synthetic hydrograph shown in Figure 8 was selected by the team for use in the alternatives analysis.

This process allowed us to use a highly skewed input data set to generate synthetic hydrographs which both met the planning groups needs and were representative of long-term conditions in the region.

CONCLUSIONS

Based on our analysis of past climate data available for the Middle Rio Grande region of New Mexico, as reconstructed from tree rings, the 1950-1998 period of record used in the SSP&A probabilistic water supply model is relatively representative of the long-term average climate for the area and an excellent choice as a basis for hydrologic modeling. Drawing from a more recent subset of this period, or extending the record back to the beginning of continuous measurements in 1919, would result in a record skewed toward wetter than average conditions. The 1950-1998 period includes both one of the most severe droughts on record and possibly the wettest period on record since 622 A.D. This is ideal for modeling severe droughts and wet periods for the region. However, moderate conditions may be underrepresented.

The Middle Rio Grande region is sensitive to forcing by the Pacific Decadal Oscillation. Most of the historic droughts recorded since the 1500s have coincided with negative phases of the PDO. Throughout the 1900s, Rio Grande flow measured at Otowi Bridge has correlated strongly with PDO phase. Compared to a full PDO cycle (1947-1998), flows during the positive phases (1925-45, 1977-98) are about 120% of average; flows during the negative phase (1947-1976) are 85% of average. Given that the PDO appears to have flipped into its negative phase sometime between 1998 and 2000, New Mexico may be moving into 10 to 20 years of below average Rio Grande flows.

SSP&A has found that using past climate information, as recorded in tree ring records, has been highly useful in water supply planning and for hydrologic analyses supporting EIS alternatives analyses. Incorporating past climate information has allowed us to verify that the period of record we are using in our probabilistic water budget modeling accurately reflects the historical climate in the region. Looking at how climate forcing has affected the region historically has given us a sense of what we should be planning for the near term future. Both these assessments enabled us to calibrate the measured record with past climate, so that given flows from 1975-1999, a period we know is unusually wet, we were able to construct a synthetic sequence to drive the URGWOM planning model that is both reflective of long-term average conditions and incorporates drought and wet period appropriately.

There is a wealth of paleo-climate and climate data that is only starting to be incorporated into water planning analyses. At S.S. Papadopulos & Associates, we are interested in furthering our use of paleo-climate and climate data because it enables us to better understand regional hydrology, better calibrate our models, and support more accurate hydrologic projections for regional planners.

LITERATURE CITED

Biondi, F., A. Gershunov, and D. R. Cayan, 2001a, data. Pacific Decadal Oscillation Reconstruction. *International Tree-Ring Data Bank. IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series #2001-001.* NOAA/NGDC Paleoclimatology Program, Boulder, CO, USA.

Biondi, F., A. Gershunov, D. R. Cayan, 2001b. North Pacific Decadal Climate Variability since 1661. *Journal of Climate*, 14, 5-14.

Bradley, R. S., 1999. *Paleoclimatology: Reconstructing Climates of the Quaternary*, Second Edition. Harcourt Academic Press, San Diego, CA.

Grissino-Mayer, H. D., C. H. Baisan, K. A. Morino and T. W. Swetnam, 2002. *Multi-century trends in past climate for the Middle Rio Grande Basin, AD 622-1992.* Final Report, submitted to the USDA Forest Service, Albuquerque, New Mexico.

Mantua, N., 2000. Web site. JISAO, University of Washington. http://www.atmos.washington.edu/~mantua/REPORTS/PDO/PDO_egec.htm

Meko, D., C. W. Stockton and W. R. Boggess, 1995. The Tree-Ring Record of Severe Sustained Drought. *Water Resources Bulletin*, 31(5), 789-801.

Meko, D. M., M. D. Therrell, C. H. Baisan and M. K. Hughes, 2001. Sacramento River flow reconstructed to A.D. 869 from tree rings. *Journal of the American Water Resources Association*, 37(4), 1029-1040.

Scurlock, D. and P. Johnson, 2001. Hydrologic History of the Middle Rio Grande Basin. New Mexico. *Decision-Makers Field Guide*, NMBMMR, 103-105.

Smith, L. P., and C. W. Stockton, 1981. Reconstructed streamflow for the Salt and Verde Rivers from tree-ring data. *Water Resources Bulletin*, 17(6), 939-947.

S. S. Papadopulos & Associates, Inc., 2000. Middle Rio Grande Water Supply Study. http://www.sspa.com/ashu/rio/start.htm

Stockton, C. W. and G. C. Jacoby, 1976. Long-term surface-water supply and streamflow trends in the Upper Colorado River Basin. *Lake Powell Research Project Bulletin No. 18*, National Science Foundation.

Tarboton, David G., 1995. Hydrologic Scenarios for Severe Sustained Drought in the Southwestern United States. *Water Resources Bulletin*, 31(5), 808-813.

Rank	Period	Ave PDSI	Duration
1	1945-1963	-1.62	19
2	1818-1826	-2.03	9
3	1772-1782	-1.83	11
4	1899-1904	-1.72	6
5	1727-1740	-1.23	14
6	1748-1757	-1.37	10
7	1889-1896	-1.12	8
8	1922-1927	-1.22	6

Table 1: Multi-year droughts in the central Rio Grande Basin, 1700-1992.

Rank	Period	Ave PDSI	Duration
1	1978-1992	1.90	15
2	1907-1921	1.65	15
3	1930-1944	1.30	15
4	1810-1817	1.60	8
5	1866-1869	1.95	4
6	1790-1797	1.53	8
7	1830-1841	1.13	12

Table 2: Multi-year wet periods in the central Rio Grande Basin, 1700-1992.

Year	Ave. Otowi flow	% of 1947-1998	PDO phase	PDSI (to 1992)
1947-1998	971,248	100		0.06
1925-1945	1,146,418	118	Positive	0.73
1947-1976	824,647	85	Negative	-0.82
1977-1998	1,171,159	121	Positive	1.70

Table 3: Phases of the PDO occurring during the 1900s, the corresponding average Otowi index flow (in acre-feet/year), how that average compares to the 1947-1998 flow, and average reconstructed PDSI (to 1992).

Year	Average PDSI	Otowi index flow	% of 1950-1992 flow
1700-1992	0.07		
1919-1992	0.27	1,048,111	112
1950-1992	0.08	933,191	100
1950-1998		963,565	103

Table 4: Comparison between average PDSI and average Otowi Index flow (in acre-feet/year) for various periods. Otowi index flow for the period is also shown as a percentage of the 1950-1992 flow.

Figure 1: New Mexico map, showing the Middle Rio Grande region, from Cochiti Dam to Elephant Butte Dam, Otowi Bridge, El Malpais National Monument, and the Sandia and Magdalena Mountains.

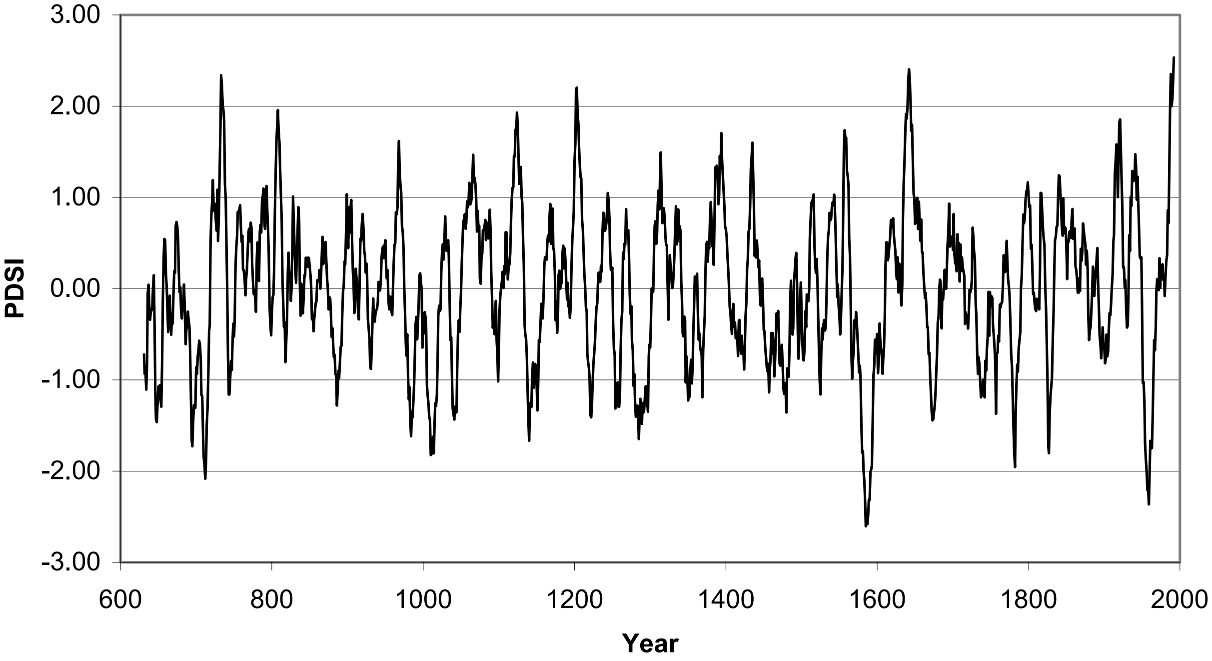

Figure 2: 10-year running average of reconstructed Palmer Drought Severity Index data for the Middle Rio Grande basin, New Mexico (Grissino-Mayer 2002 reconstruction). The droughts of the late 1500 and the 1950s can be clearly seen, as can the extremely wet period of the 1980-90s.

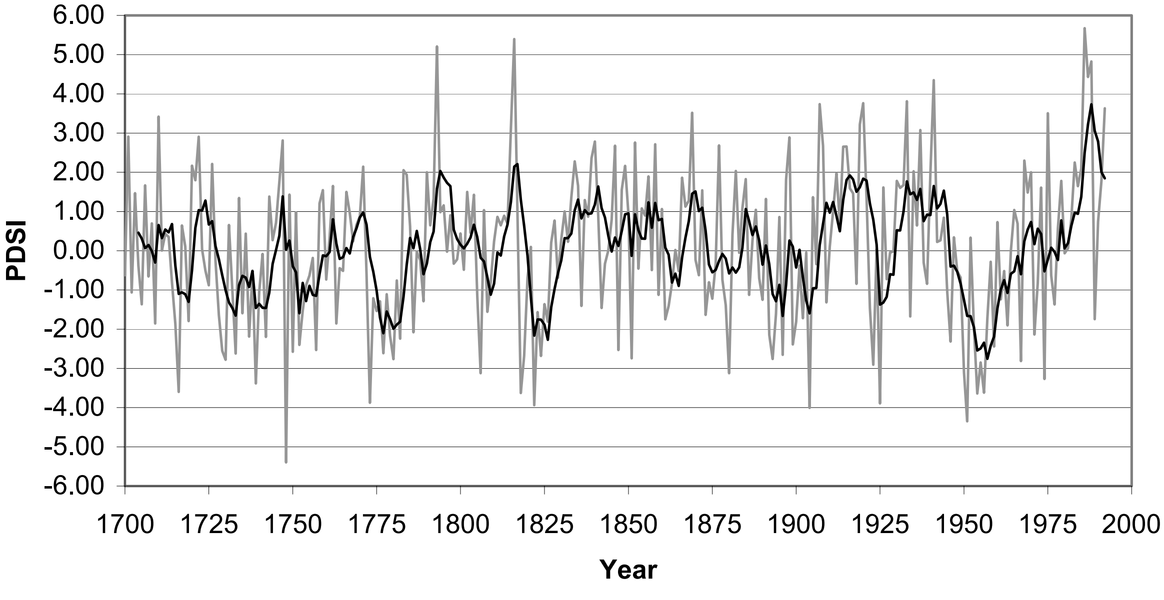

Figure 3: Reconstructed Palmer Drought Severity Index data for the Middle Rio Grande basin, New Mexico (Grissino-Mayer 2002 reconstruction), from 1700-1992 (gray), overlain with 5-year running average (black).

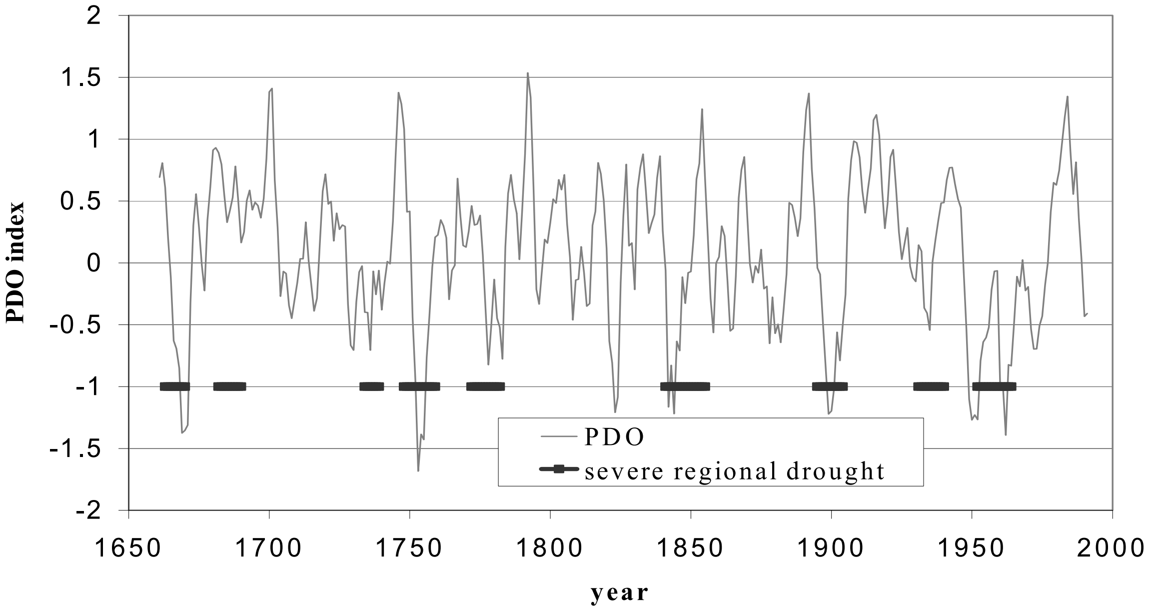

Figure 4: Reconstructed Pacific Decadal Oscillation (PDO) index values (Biondi et al. 2001 reconstruction) and severe regional droughts for the Middle Rio Grande region of New Mexico. Droughts are dimensionless and are plotted at –1 on the PDO axis for comparison.

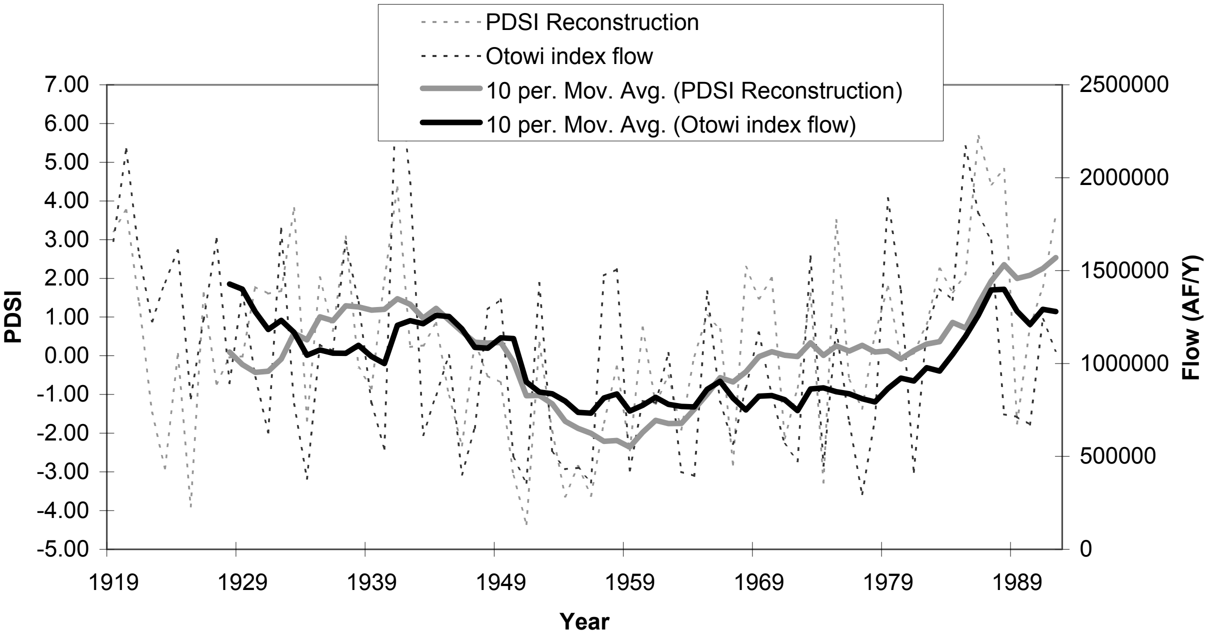

Figure 5: Reconstructed Palmer Drought Severity Index values (Grissino-Mayer 2002 reconstruction) and Otowi index flow, 1919-1992. 10-year moving averages are shown in dark, solid lines. Drought and wet periods appear in both records coincidently.

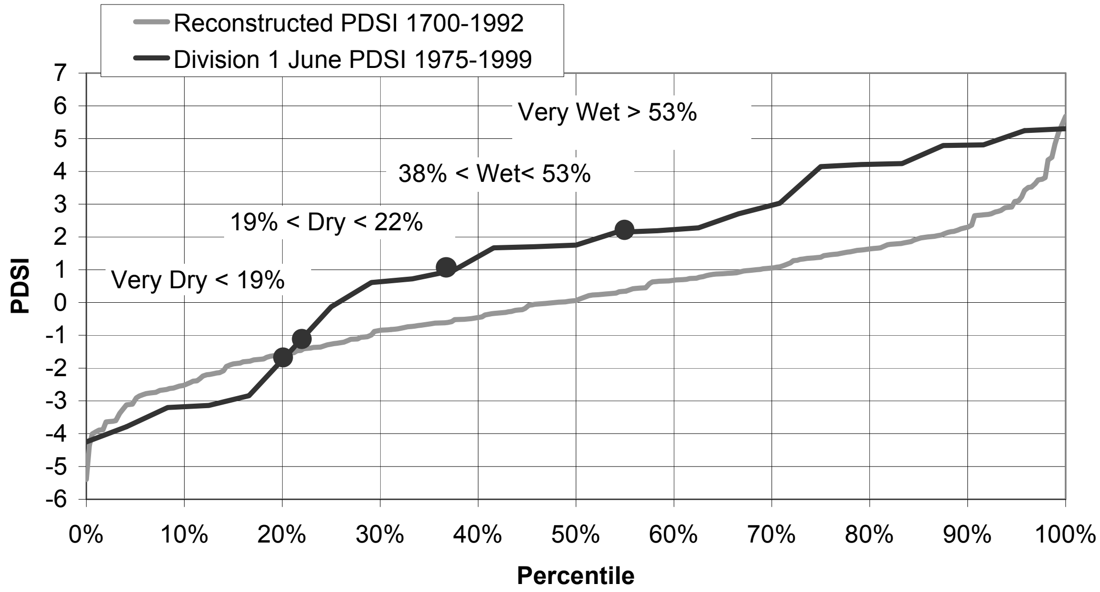

Figure 6: June Division 1 Palmer Drought Severity Index (PDSI), from 1975-1999 and reconstructed PDSI from 1700-1992. Very dry conditions correspond to PDSI < -2, dry conditions to –2 < PDSI < -1, average conditions to –1 < PDSI < 1, wet conditions to 1< PDSI <2, and very wet to PDSI > 2. This graph is used to find the percentiles corresponding to very dry (<19%), dry (19 to 22%), average (22 to 38%), wet (38 to 53%) and very wet (>53%) conditions for the 1975-1999 period. The 1700-1992 period is included to show how the 1975-1999 period is skewed toward higher PDSI values.

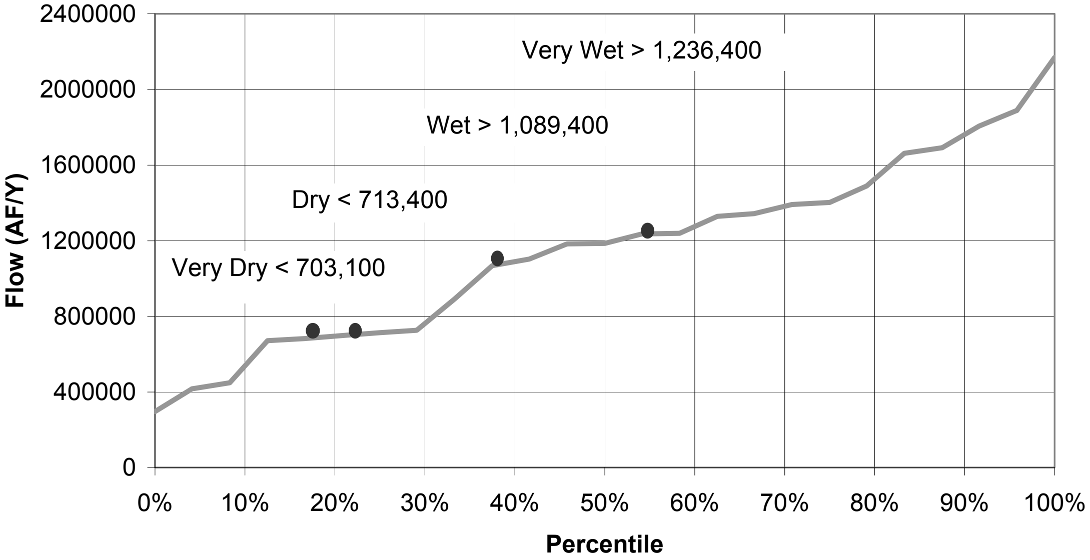

Figure 7: Ranked Otowi index flows from 1975-1999, with very dry, dry, wet and very wet cutoff points (in acre-ft/year) based on the percentiles determined in Figure 6.

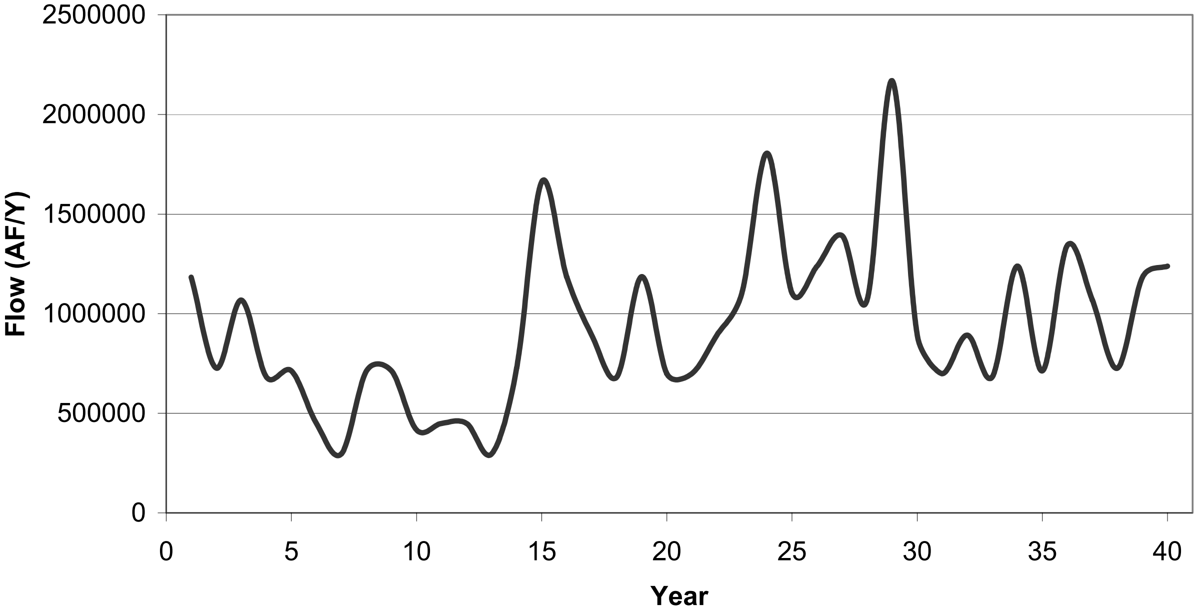

Figure 8: Hydrograph of the chosen 40-year synthetic sequence for use in Upper Rio Grande Water Operations Planning Model alternatives modeling.