APPENDIX 1

SELECTION OF FIVE SYNTHETIC FLOW SEQUENCES FOR DETAILED ANALYSIS WITH THE UPPER RIO GRANDE WATER OPERATIONS PLANNING MODEL,

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Selection of Five Synthetic Flow Sequences for Detailed Analysis with the Upper Rio Grande Water Operations Planning Model.

Prepared by

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Abstract:

This document describes the methods utilized to select five, ten-year climate sequences to drive the Upper Rio Grande Water Operations Model (URGWOM) Planning Model. 1000 synthetic climate sequences each 100 years in length, made up by historic years from 1950-2004 inclusive, were generated based on 604 years of tree ring data. From these sequences, 91,000 possible ten year sequences were evaluated according to the average Otowi Index Supply (OIS) for each, and the five sequences comprised of historic years from1975 forward only, closest to 10%, 30%, 50%, 70%, and 90% exceedance were selected for analysis with the daily timestep URGWOM Planning Model.

Introduction:

Managing water resources in New Mexico's Rio Grande basin as efficiently as possible requires an understanding of the uncertainties associated with water supply, as well as the operational flexibilities of storage and conveyance facilities in the basin. URGWOM has been developed to analyze the operational flexibilities of storage and conveyance facilities, however due to the computational restrictions of this daily timestep, basin scale model, it is not practical to run the model with the large numbers of long climate sequences that would be necessary to generate understanding of the range of system impacts associated with supply uncertainties. To get around this problem, the distribution of potential climate sequences based on over 600 years of tree ring data was evaluated, and five climate sequences, each ten years long were selected as representative of a wide range of hydrologic conditions in the basin. This process occurred in two steps, first synthetic sequences were generated, and second, representative, ten-year sequences were selected from within the synthetic climate sequences.

Generation of Synthetic Sequences:

The first step was generation of synthetic sequences of flow years from the observed record whose overall statistics were based on longer term climatic trends from available tree ring records. This work was done by AMEC Earth and Environmental in Boulder Colorado (AMEC) and is summarized briefly here. A 2½ degree gridded Palmer Drought Severity Index (PDSI) was reconstructed from tree ring data by Cook et al (2004). From this data set, AMEC chose a single grid cell in which the reconstructed

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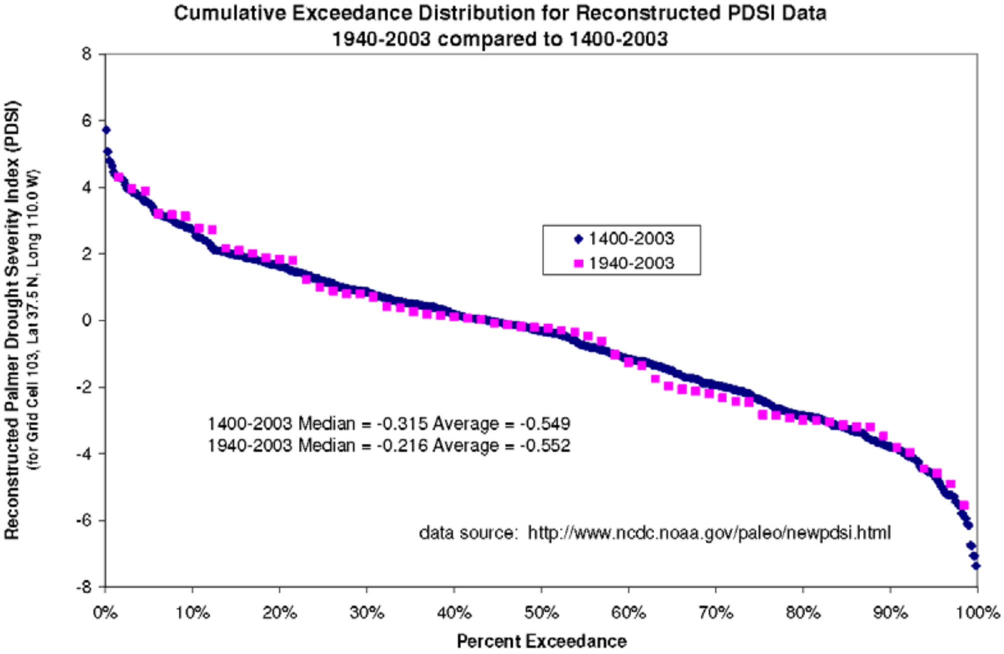
PDSI correlated most closely to the OIS for the period 1940-2003 which is the period of overlap for the two data sets. This grid cell is centered at latitude 37.5N, and longitude 110.0W, and encompasses area in Utah, Colorado, Arizona, and New Mexico. 604 years (1400-2003) of this reconstructed PDSI timeseries were then classified as either wet or dry, with the definition of wet and dry selected so that approximately half of the years fell in each class. Next, the observed state of the system (wet or dry) through time was used to generate a transient two state transition probability matrix. A two state transition probability matrix gives the likelihood of moving from a wet year to a dry year, a wet year to a wet year, a dry year to a dry year, or a dry year to a wet year from one year to the next. A transient transition probability matrix then changes through time. So, for example, a dry year was less likely to be followed by a dry year early in the 19th century than later that same century. This approach is used so that climate cycles may be captured in the synthetic sequences, rather than relying on long term averages alone. Once the transient transition probability matrix was developed, 1000, 100 year long synthetic climate sequences were generated by selecting at random an initial state (wet or dry), and moving through a randomly selected 100 year window of the transient transition probability matrix one year at a time, randomly generating either a wet or a dry climatic state based on the previous year state and the transition probability matrix that year.

The next step was to replace wet and dry climatic years with wet and dry years from the observed record, effectively going from a synthetic climatic sequence to a synthetic hydrologic sequence. This was accomplished by specifying the smallest 50% of the 1940-2007 annual Otowi Index Supply (OIS) values as occurring in "dry" years, and the rest as occurring in "wet" years, implicitly assuming that climate during the period from 1940-2007 was representative of the long term statistics derived for the 1400-2003 climate. This assumption was not listed or checked by AMEC, but was checked independently, and found to be reasonable as seen in Figure 1.

The final step was to substitute each "wet" or "dry" year in the synthetic climate sequence with a "wet" or "dry" historic year using a process called "conditional K-nearest neighbor bootstrap" selection. In transitioning from one historic year to another, transitions from similar years in the observed record were favored, thus retaining some of the year to year transition properties that have been observed historically. So if the year 1977 ("dry", 297 kAF OIS) was the last year selected, and the climate sequence called for another dry year, then "dry" years that followed a year similar to 1977 would be the most likely selections for the next year in the sequence. This selection process is referred to as a conditional K-nearest neighbor (K-nn) bootstrap selection, and is designed to maintain historically observed transition magnitudes. As a result of the K-nn bootstrap approach, in many of the sequences, historic years appear in sequential order. The combination of a transient transition probability matrix and a K-nn bootstrap approach was introduced by Prairie et al (2008) for stochastic analysis of the Colorado River at Lees Ferry, and is designed to take advantage of the strengths of both long term paleoreconstructed data, and the observed hydrologic records to generate synthetic sequences. Using this approach AMEC Earth and Environmental delivered 1000, 100 year sequences of historic years between 1950 and 2004 as synthetic sequences representative of long term climate variability in New Mexico's Rio Grande Basin. The reader is referred to the technical memo from AMEC to Dr. Nabil Shafike of the New Mexico Interstate Stream Commission dated June 24, 2008 (Gangopadhyay and Harding, 2008) for additional details on the methods used to generate the synthetic sequences.

Figure 1: Comparison of 1940-2003 Palmer Drought Severity Index (PDSI) to 1400-2003 PDSI. The close overlap of the exceedance distribution curves suggests that 1940-2003 conditions are representative of 1400-2003 conditions, and thus median Otowi Index Supply 1940-2007 can be used as the cutoff between wet and dry years.



Selection of Representative 10 Year Sequences:

Due to the computational restrictions of the daily timestep URGWOM planning model, model runs are limited to 10 year sequences and analysis of more than five potential climatic sequences is not desired. In addition, the synthetic sequences were generated with observed years from 1950-2004 so that they could be run with a monthly timestep version of the URGWOM planning model developed in the software Powersim Studio 2005 by Sandia National Laboratories (SNL), which can run any combination of historic years from 1950-2004 as input data for scenario analysis. However, the data necessary to drive the daily timestep URGWOM planning model currently extends back only to 1975. Therefore, from the 1000, 100 year synthetic sequences developed by AMEC, it was necessary to select three to five sequences of ten year duration, made up of historic years from 1975 forward only. This was accomplished as follows. There are 91 ten year sequences in each 100 year synthetic sequence (years 1..10, 2..11, …, 90-99, 91..100), thus 91,000 total sequences in the 1000, 100 year sequences. First, the average OIS for the 91,000 ten year sequences was calculated. Next, the 91,000 values for average 10 year OIS were sorted in ascending order, and ranked according to Equation 1 below.

$$\%rank = \frac{r}{n+1} \qquad (1)$$

where r is the absolute rank (1 for the smallest value, 91,000 for the largest value), and n is the number of total records (91,000). In hydrology, distributions such as this are often described with exceedance, meaning how many of the records exceed the value of the individual record in question. Percent exceedance was calculated by subtracting the percent rank from 1 as shown in Equation 2 below.

$$\%exceedance = 1 - \%rank \qquad (2)$$

Table 1 demonstrates the calculation of percent exceedance for the 12 sequences with exceedance closest to 50%. The entire table contains 91,000 data rows.

Table 1: Portion of 91,000 data row table showing ranked 10 year sequences close to 50% exceedance compared to all 91,000 sequences.

Sequence (1-1000)	10 Year Sequence Start Year (1-91)	10 yr ave Otowi Index Flow Volume [kAF/yr]	Rank r	%Rank r/(n+1)	%Exceedance 1- (r/(n+1))
532	19	883.82	45495	49.994%	50.006%
615	26	883.84	45496	49.995%	50.005%
659	53	883.84	45497	49.996%	50.004%
17	85	883.85	45498	49.997%	50.003%
380	22	883.85	45499	49.998%	50.002%
726	31	883.86	45500	49.999%	50.001%
808	37	883.86	45501	50.001%	49.999%
753	24	883.87	45502	50.002%	49.998%
800	62	883.88	45503	50.003%	49.997%
433	85	883.88	45504	50.004%	49.996%
246	27	883.89	45505	50.005%	49.995%
742	62	883.91	45506	50.006%	49.994%

Plotting the 10 year average OIS (column 3 in Table 1) against % exceedance (column 6 in Table 1) for all 91,000 ten year sequence points yields the exceedance curve shown in Figure 2. Also shown for perspective in Figure 2, are the four, ten year sequences that were used to drive the URGWOM Planning Model for the Upper Rio Grande Water Operations (URGWOPS) Environmental Impact Study (EIS).

Next, of the 91,000 10-year sequences, 1088 sequences contained years from 1975 forward only. Of these, the five sequences closest to 10%, 30%, 50%, 70%, and 90% exceedance were selected as drivers for the URGWOM Planning Model. Table A-1 in Appendix A lists alternate sequences that were the next closest sequences to the 10%, 30%, 50%, 70%, and 90% exceedance targets.

Figure 2: Exceedance distribution curve for 10-year average Otowi Index Flow for 91,000 synthetic 10-year sequences generated based on 604 years of tree ring data.

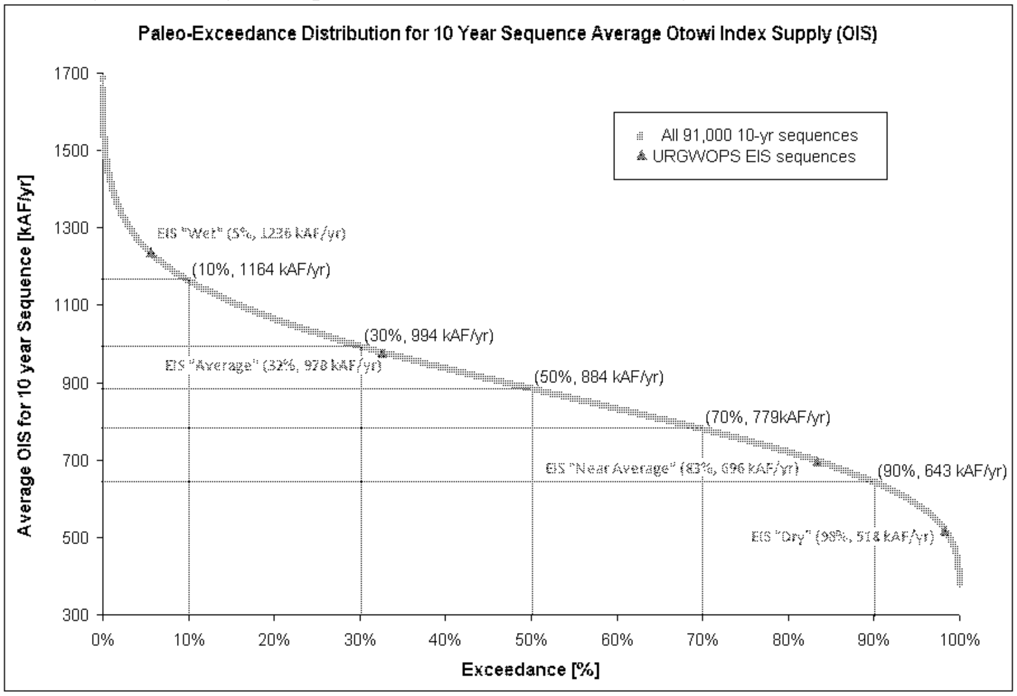


Figure 3 shows the 1088 1975 and forward sequences and the five chosen sequences in relation to the overall exceedance curve. Note that because 1975-2004 was wetter than average, sequences comprised of these years only tend to lie on the wetter (left) side of the exceedance curve distribution. Of the sequences made up only of years from 1975 forward, there were two with exactly 1164.75 kAF/yr average 10-year Otowi Index Supply. Of these, the one with the larger variation, as measured by the standard deviation of the annual Otowi Index Supply values was selected for use. This decision was based on group discussion and consensus that the high variability sequence would test the system and model more, and thus be of more use to planning efforts. Figure A-1 in Appendix A shows these two sequences in relation to one another.

The historic years making up the five selected sequences are shown in Table 2. Figures 3-7 show the individual Otowi Index Supply for the years that make up the sequences. Figure 9 compares the Otowi Index Supply for all sequence years sorted by the magnitude of annual Otowi Index Supply of each year.

Figure 3: Distribution of sequences made up of years 1975 and greater only as compared to overall exceedance curve. Note that because 1975-2004 was wetter than average, sequences comprised of these years only tend to lie on the wetter (left) side of the exceedance curve distribution. Also shown are the five sequences selected for further analysis with the daily timestep URGWOM Planning Model.

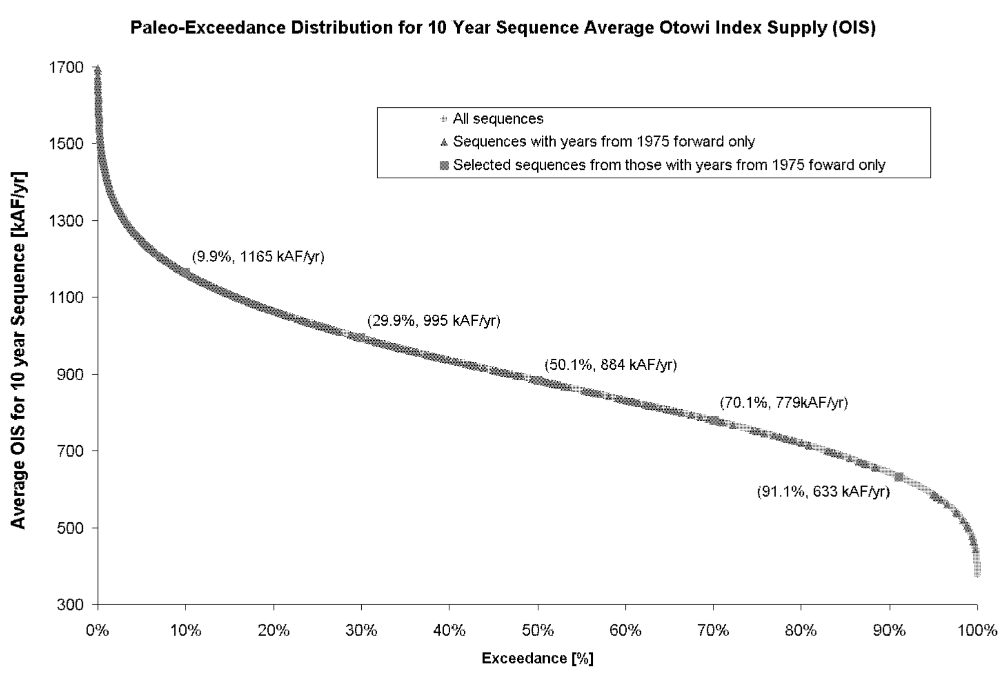


Table 2: Historic years making up each of the 5 selected sequences.

		Historic Year Used				
		Sequence Name				
		10% paleo-exceedance	30% paleo-exceedance	50% paleo-exceedance	70% paleo-exceedance	90% paleo-exceedance
Sequence Year	1	1985	1976	2004	1989	2000
	2	1996	1977	1991	1990	1990
	3	2004	1982	1992	1977	1977
	4	1977	1995	2000	2004	2003
	5	1978	1987	1977	1990	2004
	6	1979	1994	1978	1977	1991
	7	1980	1992	1990	1978	2002
	8	1992	1999	1991	1991	2003
	9	1986	1988	1976	1992	1982
	10	1994	1977	1979	1993	1976

Figure 4: Otowi Index Supply for individual years in 10% exceedance sequence selected for further analysis with the daily timestep URGWOM Planning Model.

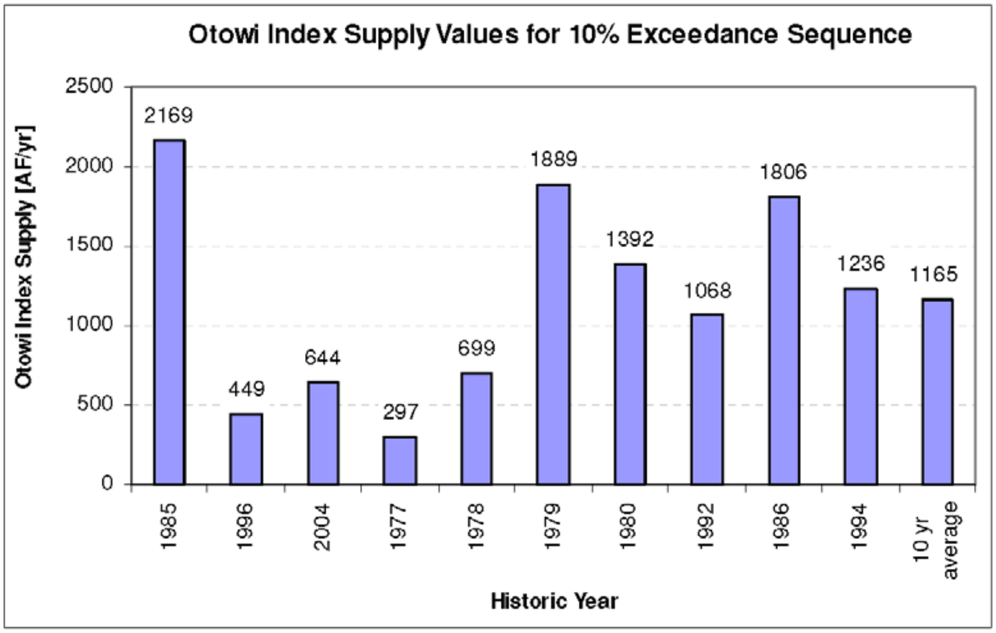


Figure 5: Otowi Index Supply for individual years in 30% exceedance sequence selected for further analysis with the daily timestep URGWOM Planning Model.

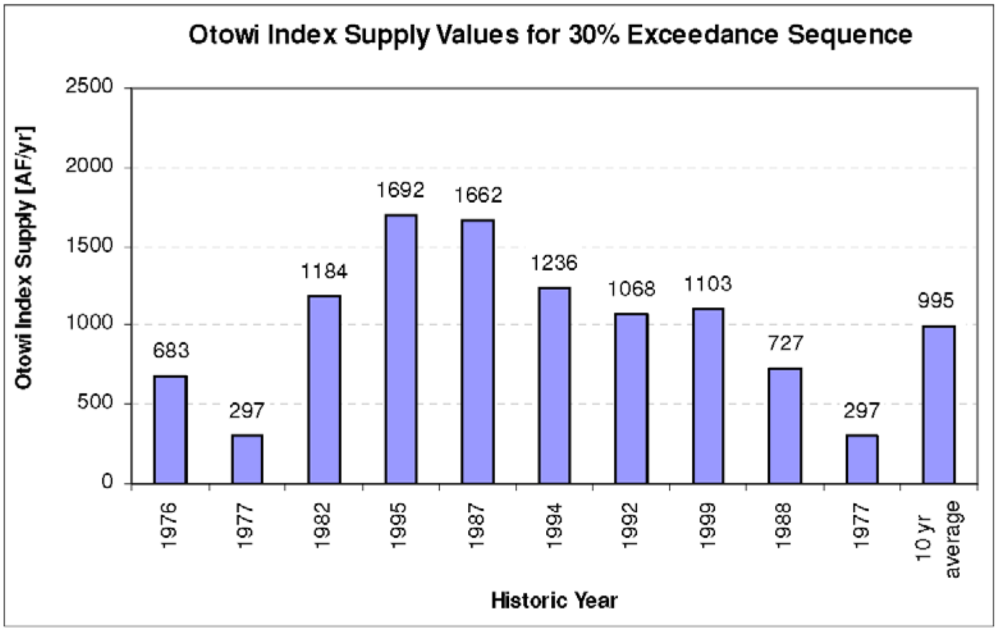


Figure 6: Otowi Index Supply for individual years in 50% exceedance sequence selected for further analysis with the daily timestep URGWOM Planning Model.

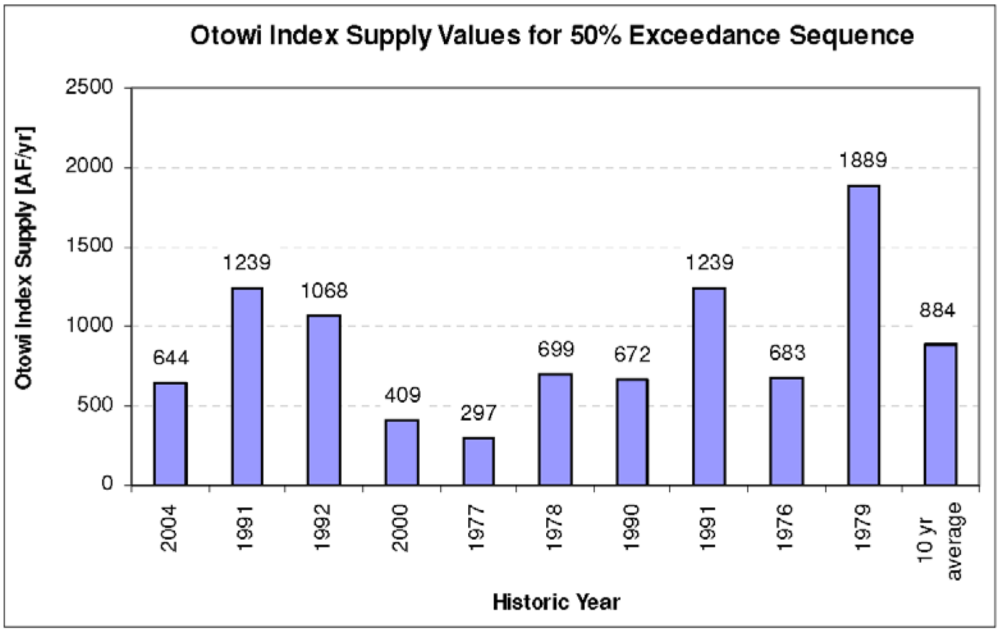


Figure 7: Otowi Index Supply for individual years in 70% exceedance sequence selected for further analysis with the daily timestep URGWOM Planning Model.

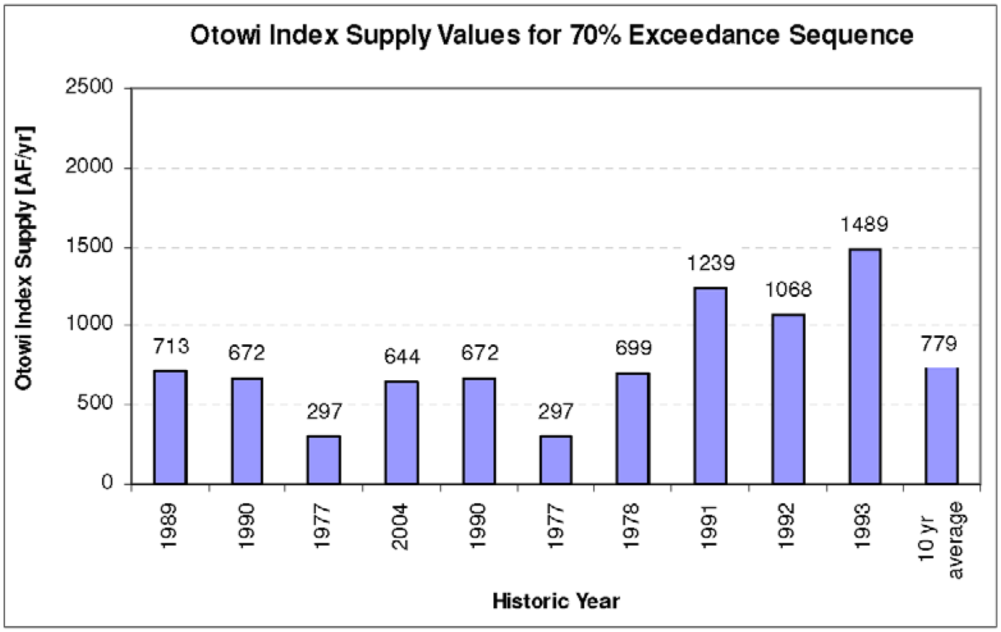


Figure 8: Otowi Index Supply for individual years in 90% exceedance sequence selected for further analysis with the daily timestep URGWOM Planning Model.

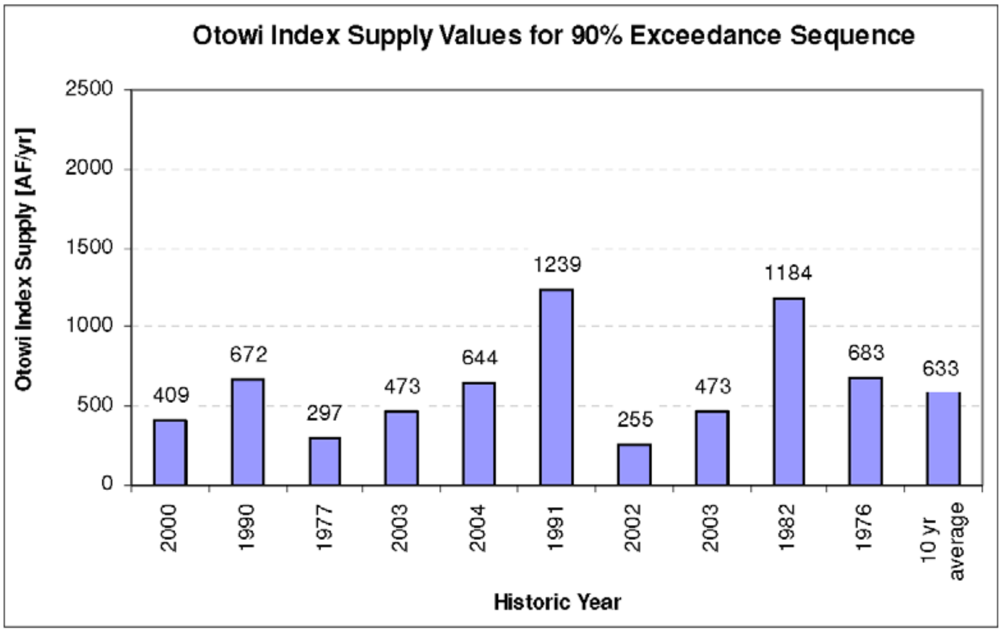
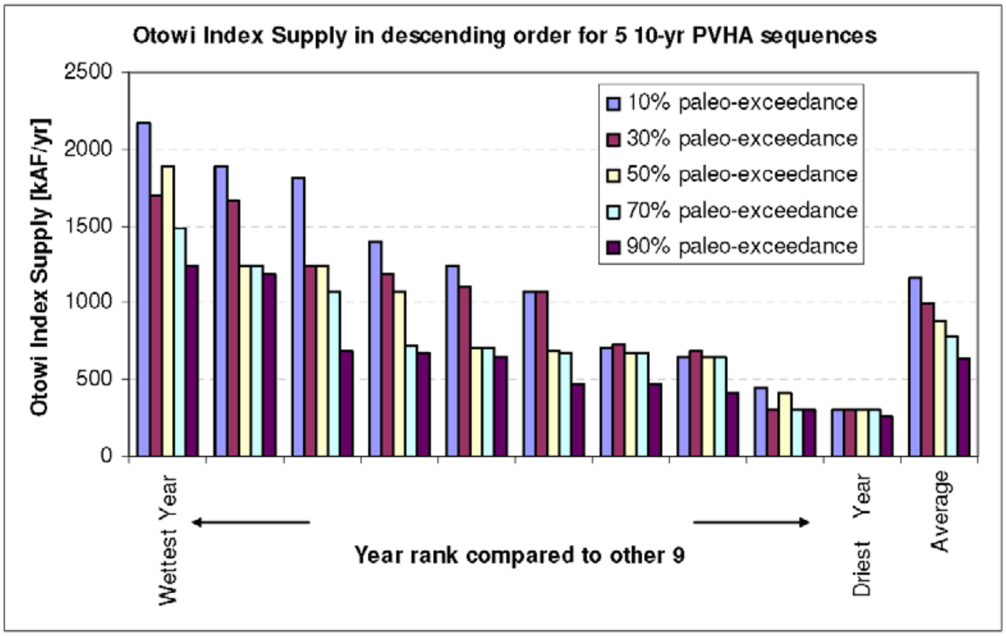


Figure 9: Otowi Index Supply for individual years in all five sequences selected for further analysis with the daily timestep URGWOM Planning Model.



Relative Monsoon Strength of Selected Sequences:

One of the most significant challenges currently facing Rio Grande water operators is in providing sufficient water to maintain established agricultural rights, growing municipal and industrial demands, and in-stream flows necessary to support endangered species habitat. Late summer can represent a bottleneck in this balance, when demands are at a peak, and supply is past the spring snowmelt generated peak. Summer monsoon based precipitation can provide an important supply during this time. Of interest to water planners is the total water that enters the surface water system below Otowi from July through September from all gaged and ungaged tributary inflows. To evaluate the relative strength of the summer monsoon, a "representative monsoon volume" was defined as the sum of gaged tributary inflows to URGWOM between Otowi and Elephant Butte Reservoirs from July through September of each year. Formally:

$$RMV^{y} = Q_{SantaFe}^{July_y - Sept_y} + Q_{Galisteo}^{July_y - Sept_y} + Q_{Jemez}^{July_y - Sept_y} + Q_{Northflood}^{July_y - Sept_y} + Q_{Southdiv}^{July_y - Sept_y} + Q_{Tijeras}^{July_y - Sept_y} + Q_{Puerco}^{July_y - Sept_y}$$

Where RMV^{y} is the annual representative monsoon volume in year y, $Q_{SantaFe}^{July_y - Sept_y}$ is the total gaged volume in the Santa Fe River above Cochiti (United States Geological Survey (USGS) gage number 8317200) for July, August, and September in year y. Similarly for Galisteo Creek below Galisteo Dam (USGS-8317950), the Jemez River near Jemez (USGS-8324000), the North Floodway Channel near Alameda (USGS-8329900), the South Diversion Channel above Tijeras Arroyo (USGS-8330775), Tijeras Arroyo near Albuquerque (USGS-8330600), and the Rio Puerco near Bernardo (USGS-8353000). The RMV was calculated for each year from 1950 through 2004. Synthetic gage data generated by the USGS was used in place of any missing data (Engdahl, et al 2008).

RMV for each year from 1950-2007 were calculated, and compared to the corresponding OIS values to get a sense of the relationship between flow at Otowi, and summer tributary inflows. Interestingly, as shown in Figure 10, with the exception of an unusual year in 1957, large summer RMV values are rarely associated with large annual OIS values, meaning that strong monsoon events almost never follow winters with heavy precipitation. The physical mechanism for this might be that monsoons are driven by land mass heating in the summer, which is reduced in summers that follow a wet winter. Average annual RMV for each ten year sequence was also calculated. Figure 11 shows RMV plotted against OIS for all 91,000 ten year sequences. The effect of the 1957outlier is lost to the 10 year average, and the pattern of no strong monsoon sequences occurring with large spring runoff sequences emerges clearly. Also plotted in Figure 11 are the five selected sequences, none of which can be classified as an outlier by visual inspection of this particular plot.

Next, RMV exceedance probabilities were calculated for all 91,000 runs according to Equations 1 and 2 above as described previously for Otowi Index Supply values. The exceedance distribution for all sequences is shown in Figure 12. Also shown in Figure 12, are the RMV values for the five selected sequences. Consistent with the preceding discussion, the 10% OIS exceedance, which is wet in terms of Otowi Volume, is dry with respect to RMV.

Figure 10: Otowi Index Supply (OIS) compared to Representative Monsoon Volume (RMV) for individual years from 1950-2007. Historic years 1950-2004 drive the 91,000 sequences considered here. Note that with the exception of 1957, strong monsoon signals as estimated by RMV almost never coincide with high annual Otowi flows.

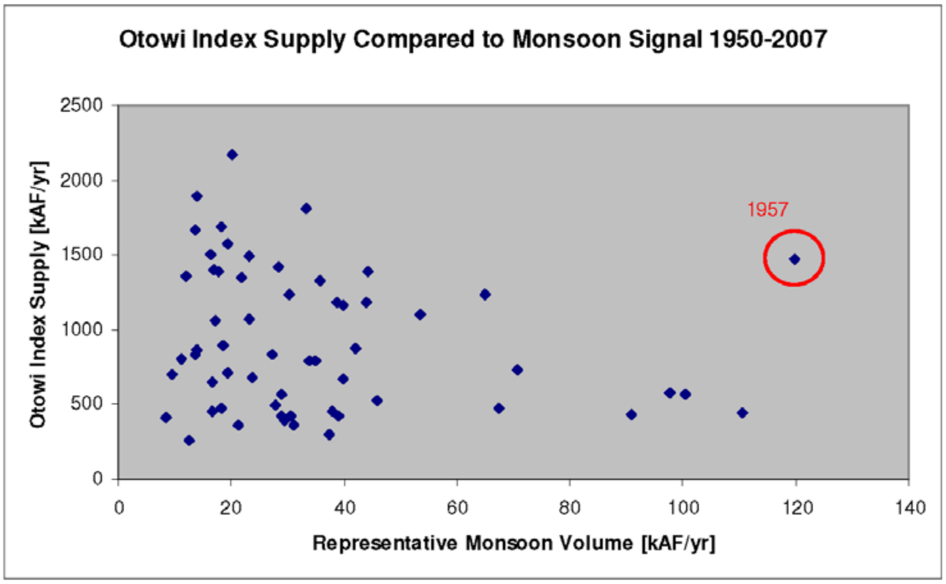


Figure 11: Ten year average Otowi Index Supply (OIS) compared to ten year average Representative Monsoon Volume (RMV) for all 91,000 ten year sequences considered here as well as the five selected sequences.

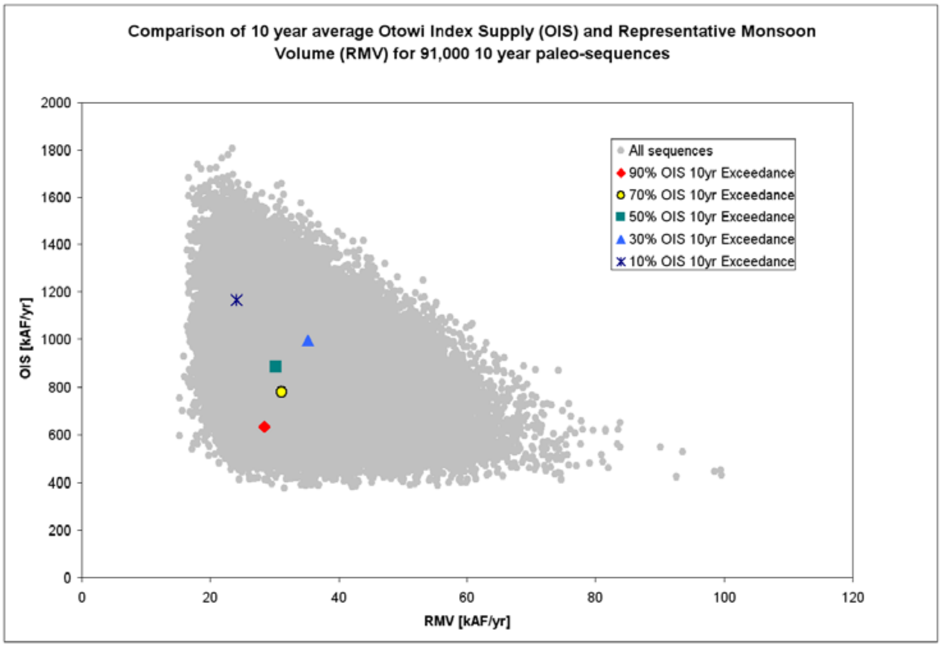
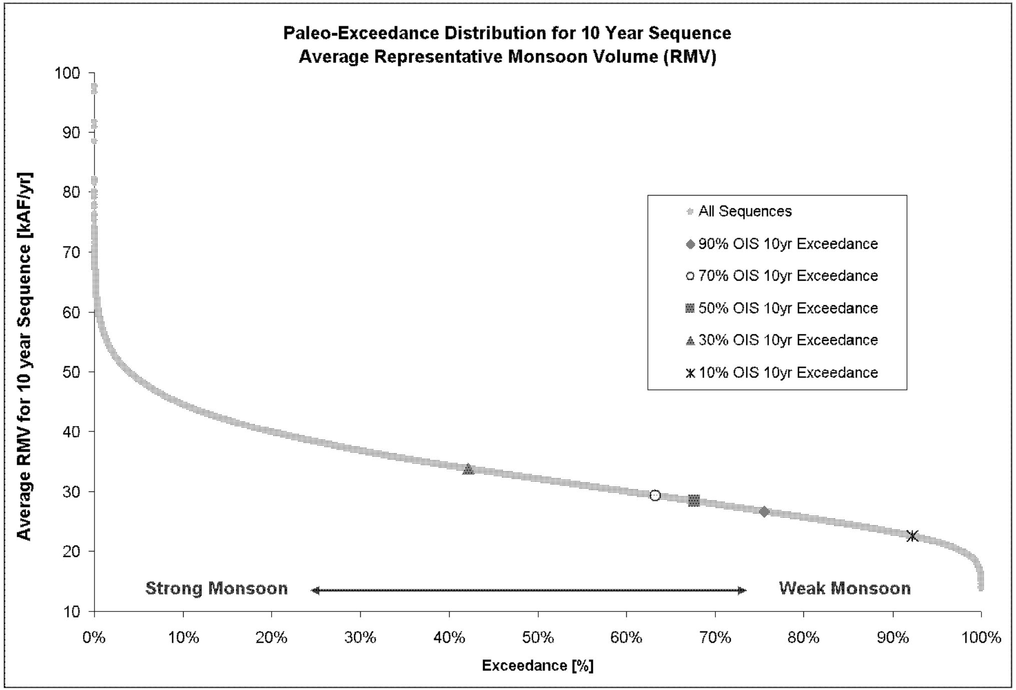


Figure 12: Exceedance distribution curve for 10-year average Representative Monsoon Volume for 91,000 synthetic 10-year sequences generated based on 604 years of tree ring data.



RMV values and their exceedance probabilities for the five selected sequences are shown in Table 3 below.

Table 3: 10 year average Representative Monsoon Volumes (RMV) and associated exceedance probabilities for the five selected sequences.

Sequence Name	10yr ave RMV [kAF/yr]	10yr RMV % Exceedence
90% OIS	26.6	76%
70% OIS	29.3	63%
50% OIS	28.3	68%
30% OIS	33.8	42%
10% OIS	22.5	92%

Figures 13-17 show the annual Representative Monsoon Volumes for all individual years in each of the five selected sequences.

Figure 13: Representative Monsoon Volume (RMV) for individual years in 10% exceedance sequence selected for further analysis with URGWOM.

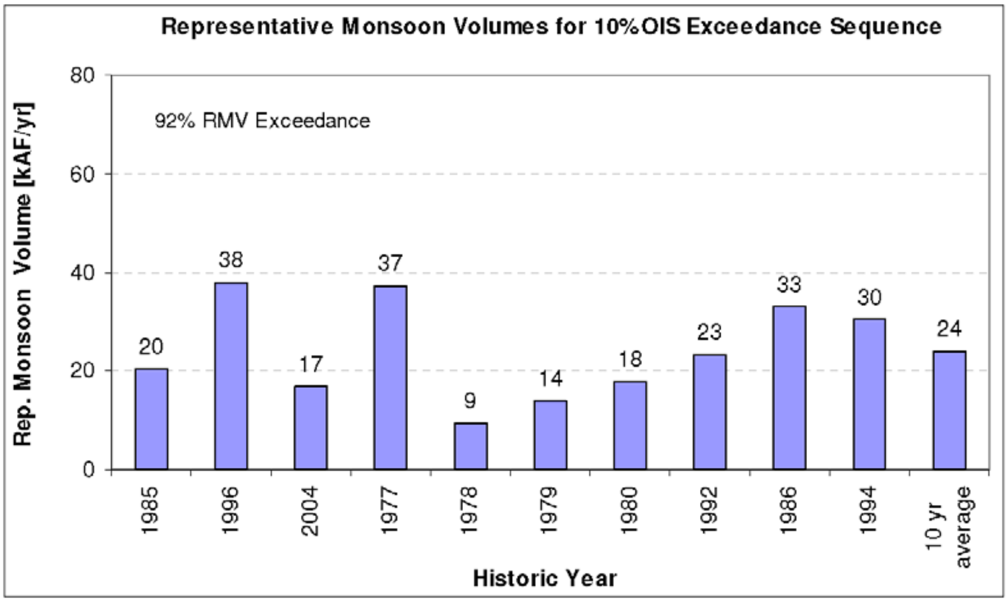


Figure 14: Representative Monsoon Volume (RMV) for individual years in 30% exceedance sequence selected for further analysis with URGWOM.

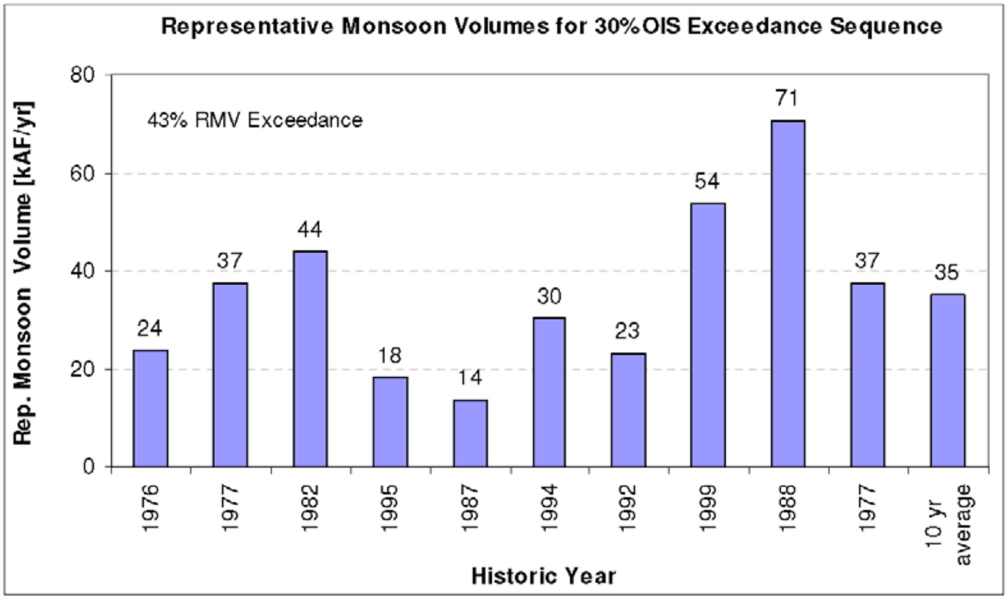


Figure 15: Representative Monsoon Volume (RMV) for individual years in 50% exceedance sequence selected for further analysis with URGWOM.

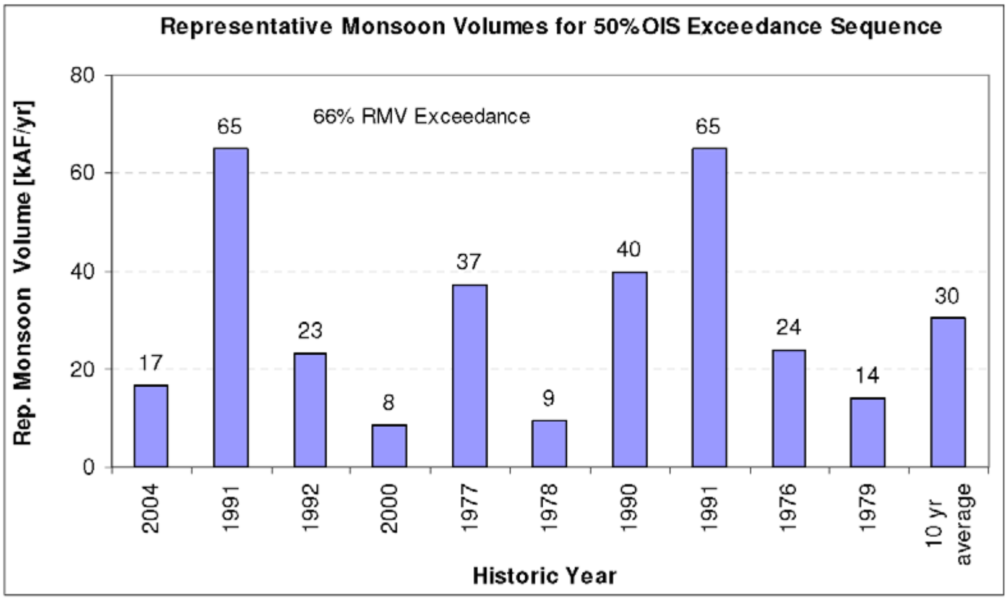


Figure 16: Representative Monsoon Volume (RMV) for individual years in 70% exceedance sequence selected for further analysis with URGWOM.

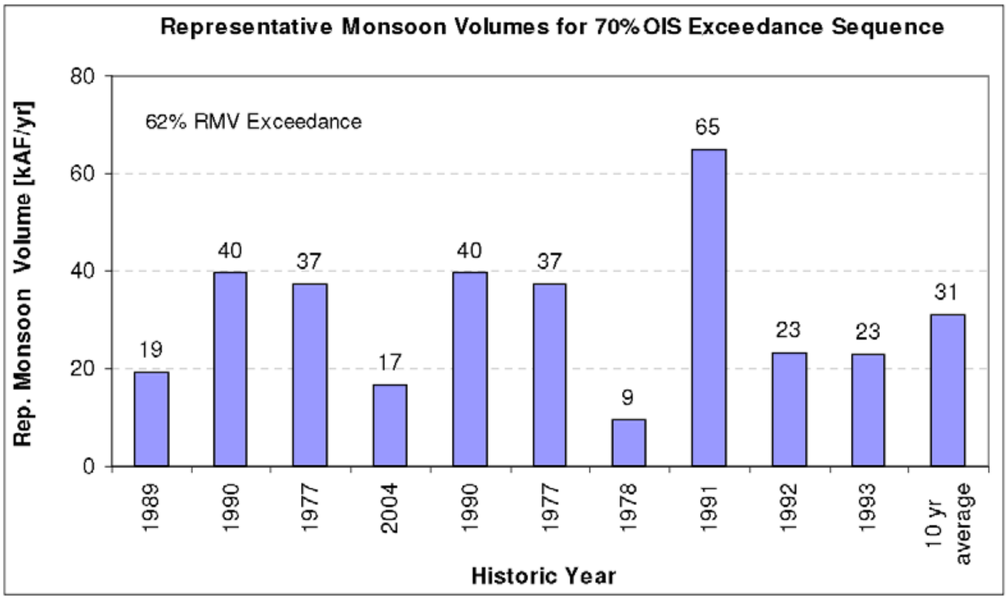
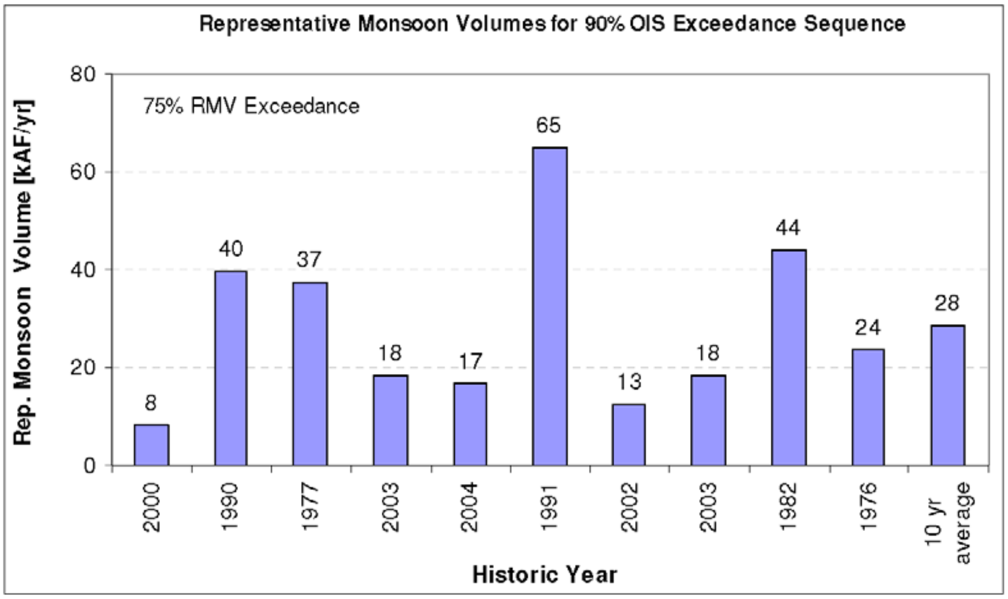


Figure 17: Representative Monsoon Volume (RMV) for individual years in 90% exceedance sequence selected for further analysis with URGWOM.



Finally, in order to compare relative Otowi flow and monsoon signal for each year of the selected sequences, OIS and RMV values were normalized by dividing by the annual average value for each from all years in the paleo based synthetic sequences. These values are 895,000 AF/year and 34,700 AF/summer for OIS and RMV respectively. The result is unitless OIS and RMV values representing a fraction of average. Figures 18-22 show year by year relative comparisons of unitless OIS and RMV values for the five selected sequences.

Figure 18: Normalized Otowi Index Supply and Representative Monsoon Volumes in each year of the 10% Exceedance Sequence. Values are normalized to annual average value of all years in the paleo based synthetic sequences.

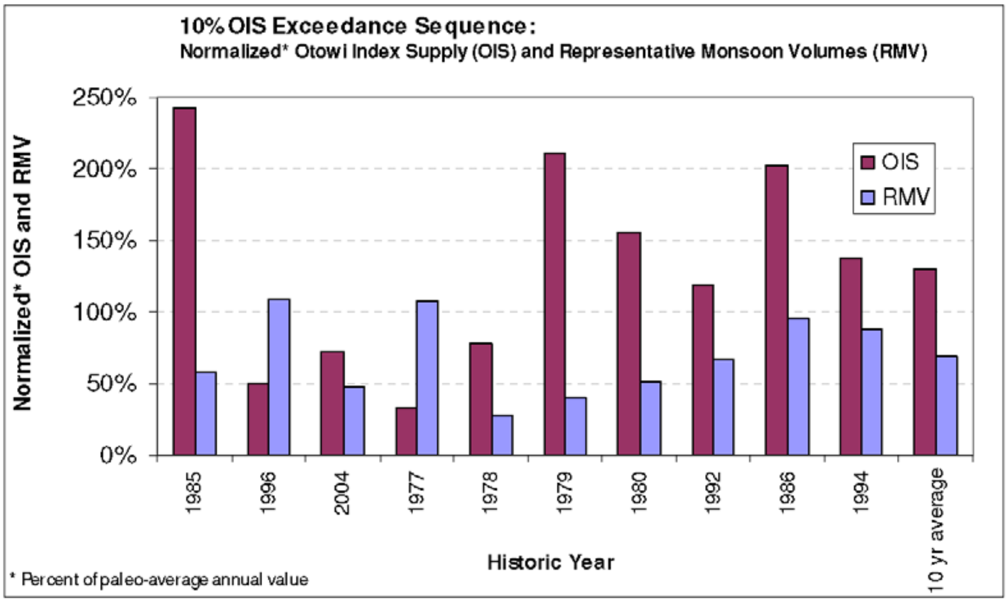


Figure 19: Normalized Otowi Index Supply and Representative Monsoon Volumes in each year of the 30% Exceedance Sequence. Values are normalized to annual average value of all years in the paleo based synthetic sequences.

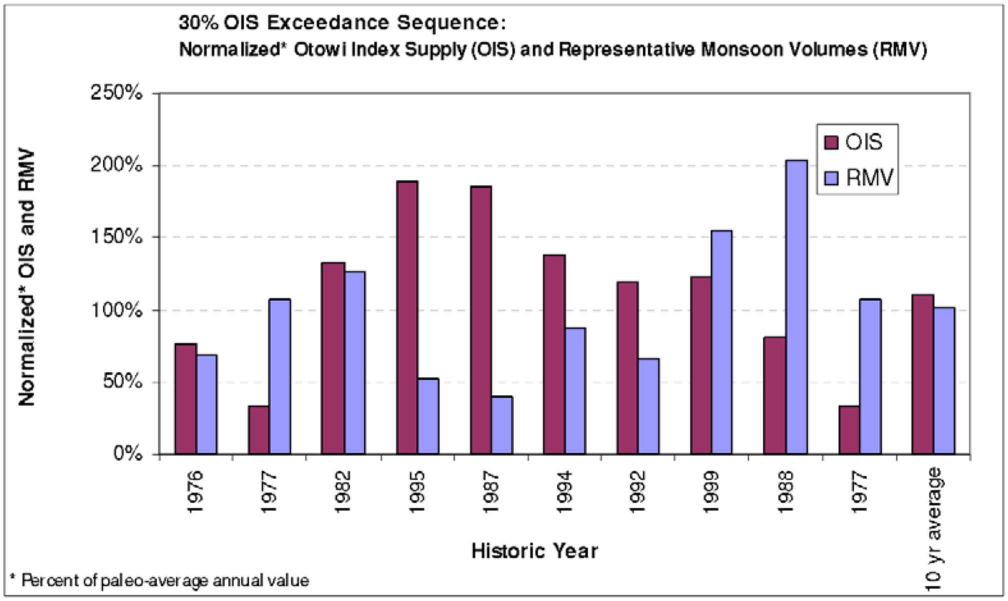


Figure 20: Normalized Otowi Index Supply and Representative Monsoon Volumes in each year of the 50% Exceedance Sequence. Values are normalized to annual average value of all years in the paleo based synthetic sequences.

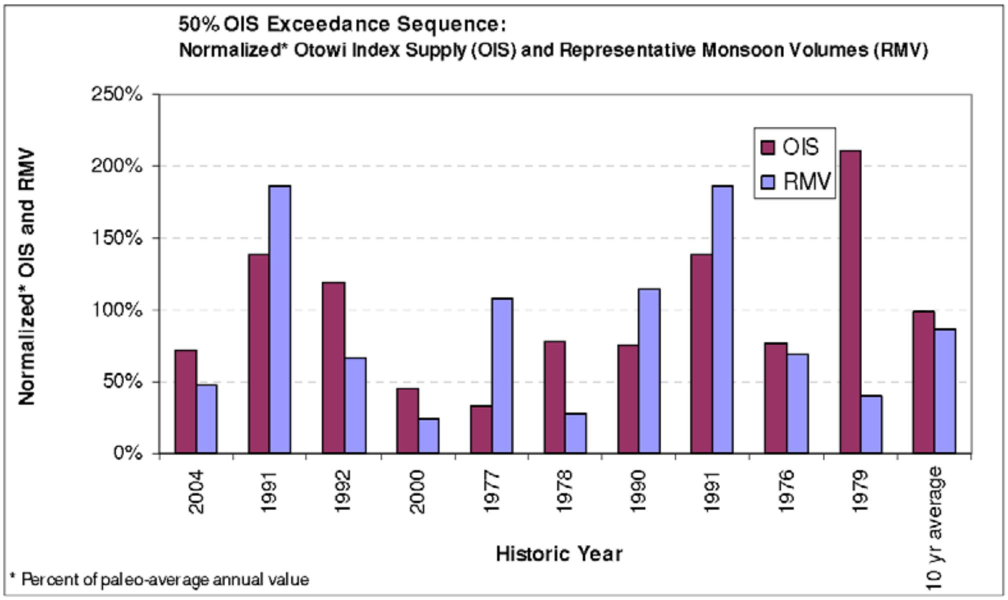


Figure 21: Normalized Otowi Index Supply and Representative Monsoon Volumes in each year of the 70% Exceedance Sequence. Values are normalized to annual average value of all years in the paleo based synthetic sequences.

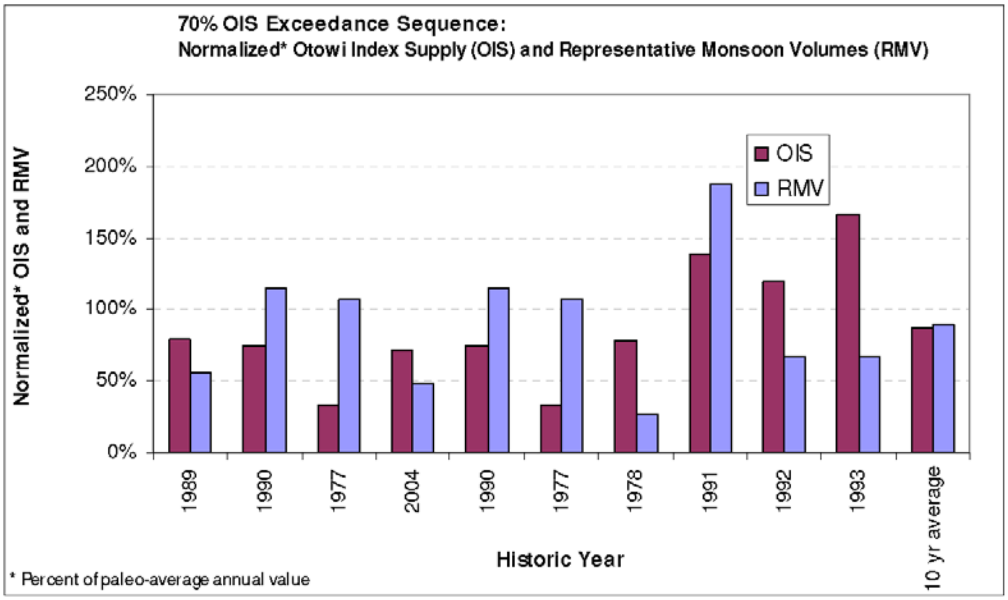
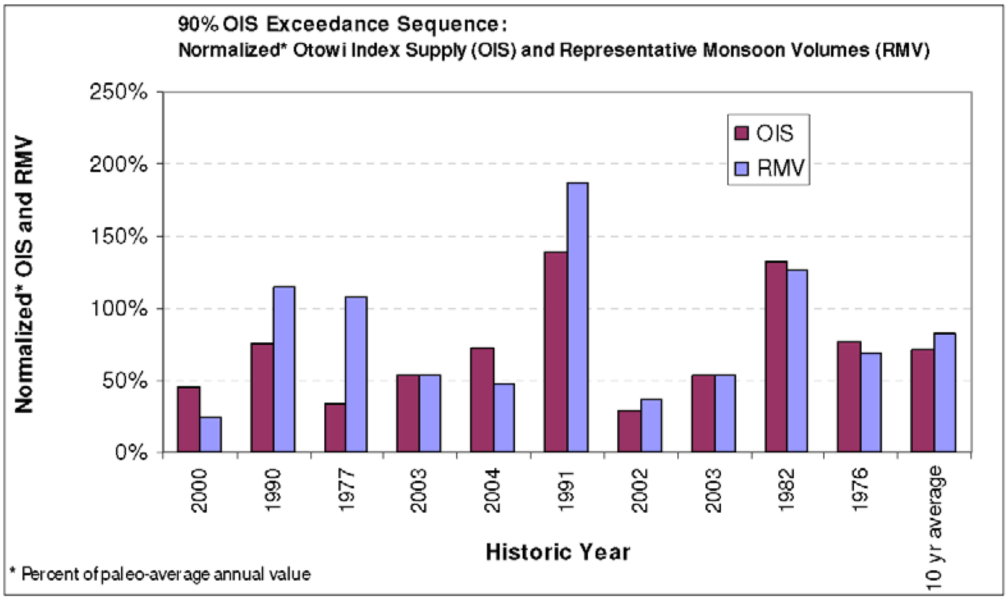


Figure 22: Normalized Otowi Index Supply and Representative Monsoon Volumes in each year of the 90% Exceedance Sequence. Values are normalized to annual average value of all years in the paleo based synthetic sequences.



Reference:

Cook, E.R., C.A. Woodhouse, C.M. Eakin, D.M. Meko, and D.W. Stahle, 2004. Long-Term Aridity Changes in the Western United States. *Science*, Vol. 306, No. 5698, pp. 1015-1018, November 5, 2004.

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Gangopadhyay, S. and B. Harding, 2008. *Stochastic Streamflow Simulations for the Otowi gage.* Memo to Dr. Nabil Shafike, P.E., New Mexico Instream Commission. June 24, 2008.

Prairie, J, K. Novak, B. Rajagopalan, U Lall, and T. Fulp, 2008. A Stochastic Nonparametric Approach for Streamflow Generation Combining Observational and Paleo Reconstructed Data. *Water Resources Research*, Vol.44, W06423, doi:10.1029/2007WR006684, 2008 http://www.agu.org/pubs/crossref/2008/2007WR006684.shtml

Acknowledgment:

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Appendix A:

Figure A-1: Otowi Index Supply for individual years in two sequences with identical 10-year average Otowi Index Supply. The sequence (in blue) beginning with 1985 was chosen for further analysis with the daily timestep URGWOM Planning Model because of a larger OIS standard deviation (647 kAF/yr) than that of the sequence (in red) beginning with historic year 1994 (385 kAF/yr).

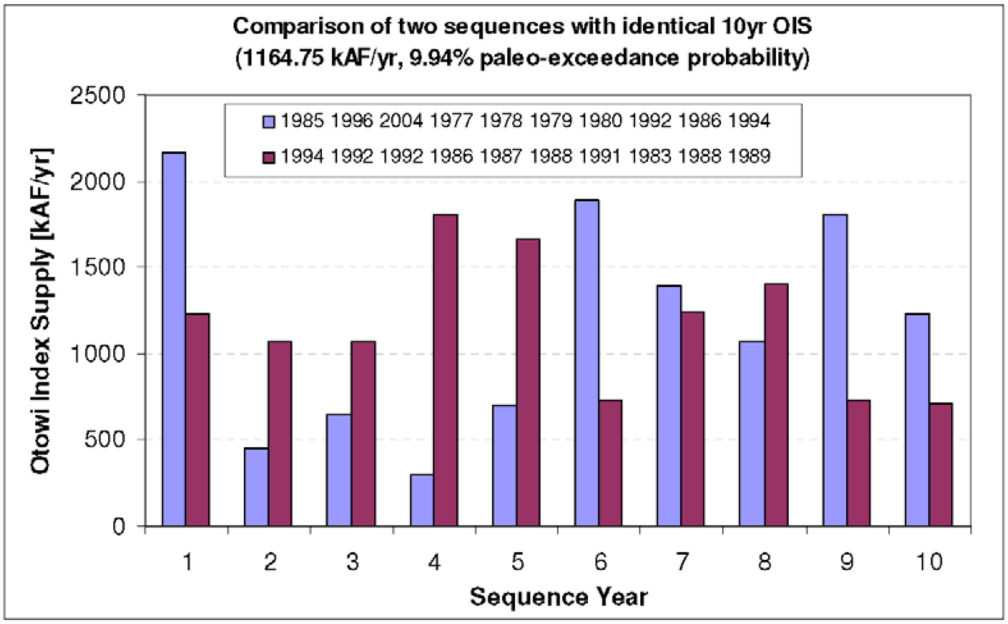

Table A-1: This table shows the sequences chosen for further analysis (named 10%, 30%, 50%, 70%, and 90%), along with two alternate sequences for each. This table is included in case additional analysis on a similar sequence is desired, or in case one of the selected sequences is discarded after additional analysis.

Sequence Name	10 yr ave OIS [kAF/yr]	% Exceed	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
10%	633	91.1%	2000	1990	1977	2003	2004	1991	2002	2003	1982	1976
10% alt1	632	91.2%	2004	1978	1989	1977	1978	1990	1977	2004	1991	1981
10% alt2	655	88.6%	2002	1989	1990	1977	2004	1990	1977	1978	1991	1992
30%	778.81	70.09%	1989	1990	1977	2004	1990	1977	1978	1991	1992	1993
30% alt1	778.76	70.10%	1981	1982	2000	2003	1997	1992	1983	1981	2001	2002
30% alt2	778.65	70.11%	1982	2000	1977	2001	1981	1997	1976	1989	1991	1976
50%	884	50.05%	2004	1991	1992	2000	1977	1978	1990	1991	1976	1979
50% alt1	886	49.64%	1998	1992	1983	1984	1984	1976	1989	1977	2003	2004
50% alt2	882	50.42%	1982	2002	2001	1993	1994	1983	2002	1982	1976	1977
70%	995	29.93%	1976	1977	1982	1995	1987	1994	1992	1999	1988	1977
70% alt1	993	30.23%	1982	1976	1991	1992	1983	1994	1998	1992	1976	2003
70% alt2	997	29.60%	1980	1981	2001	2002	1978	1979	1980	1981	1982	1993
90%	1164.75	9.938%	1985	1996	2004	1977	1978	1979	1980	1992	1986	1994
90% alt1	1164.75	9.939%	1994	1992	1992	1986	1987	1988	1991	1983	1988	1989
90% alt2	1165.2	9.90%	1980	2000	1982	1994	1993	1994	1995	1994	1996	1997

Table A-2: Historic Annual Otowi Index Supply Values. Values provided by Dr. Nabil Shafike, New Mexico Interstate Stream Commission, personal communication August 2008. To read table, add year number to decade. For example, the Annual Otowi Index Supply Value for 1944 was 1363.2 kAF/yr.

Annual Otowi Index Supply [kAF/yr]											
		Year									
		0	1	2	3	4	5	6	7	8	9
Decade	1940	590	2686.8	2079.9	693.6	1363.2	1137.9	474.2	754.4	1370.9	1344.7
	1950	492.2	358.3	1423.2	522.3	431.3	438.7	359.8	1473.2	1507.1	424.8
	1960	798.8	788.6	1056.2	416.7	394.7	1387.5	793.8	567.6	870.6	1167.2
	1970	832.2	566.1	474.3	1576.3	450.4	1185.8	682.5	296.5	699	1888.7
	1980	1392.2	416.9	1183.5	1402.5	1343.1	2169.1	1805.9	1662.4	726.5	713.4
	1990	671.5	1239	1067.8	1489.4	1235.7	1692	449.1	1329.3	892.5	1103.2
	2000	409.2	833.7	254.8	473	643.5	1353	574.3	859.9	-	-