Obtaining water data for oil shale research using HydroSeek

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Abstract

This paper reviews a new search engine called HydroSeek for retrieving hydrological data. The search engine enables simultaneous queries of multiple databases by overcoming structural and semantic heterogeneity issues, thereby providing the ability to discover data from diverse databases. HydroSeek locates data sources quickly and screens for data applicability prior to in-depth analysis. Representative examples of data collected with HydroSeek were used to update information on water resources in the Piceance Creek Basin of Colorado and at Lee's Ferry in Arizona. The updated information was compared with earlier oil shale documentation from the 1970s (U.S. Department of Interior, 1973). In addition, visual patterns observed in the Colorado River data were compared and correlated with the Pacific Decadal Oscillation (PDO), a North Pacific Ocean event associated with changes in North American weather patterns. The conclusions include a critique of the HydroSeek search engine and summaries of current hydrological data applicable for oil shale commercial development.

Introduction

U.S. oil shale resources may be commercially developed in the future to replace declining supplies of conventional crude oil. A potential limiting factor is the availability of reliable water supplies essential for large-scale commercialization. Although several U. S. regions have substantial oil shale deposits, this paper focuses on the Piceance Creek Basin in Colorado where most of the U. S. oil shale demonstration projects are located. Using HydroSeek, recently collected discharge and water quality data from key water resources in the Basin are presented and analyzed. The data are then summarized and compared with similar data reported in the prototype oil shale leasing program environmental statement reports of 1973.

Piceance Creek Basin Characteristics

The Piceance Creek Basin (Figure 1) is situated in Northwest Colorado between the White River to the north and the Colorado River to the south. High-grade oil shale deposits extend over an area of approximately 1,000 square miles (2,600 square kilometers). The general stream flow is to the north along the northeastern trending canyons that drain into the Piceance and Yellow Creeks, which flow into the White River. Several streams in the south of the Basin flow south into the Colorado River. The stream gauging stations, where the data were collected, are identified with triangular blue and white markers. The Colorado River and White River are major resources that could supply water for oil shale development if sufficient groundwater resources are not available. Piceance Creek, a small perennial stream, is an important resource because of its location in the center of the oil shale region. Yellow Creek is a very small intermittent stream with characteristics similar to many other streams in the area. Photographs of the area and several gauging station locations are shown in Figures 2-5.

HydroSeek

HydroSeek) is a new search engine (Beran, 2007; Beran and Piasecki, 2007) for retrieving hydrological data from multiple

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Figure 1: Map of Northwestern Colorado

databases simultaneously. It can be downloaded at http://cbe.cae.drexel.edu/search/ HydroSeek incorporates ontological aids or software, which can overcome heterogeneity issues among different databases such as structural and syntactic incompatibilities including unique data encodings and vocabularies. Data requests and outputs are standardized by the HydroSeek methodology allowing seamless searches for the same data among previously incompatible sources. This expands the available data that can be retrieved including dozens of parameters from almost two million hydrological stations maintained by several federal, state and other agencies.

The HydroSeek user interface incorporates a GIS driven location box and calendar aided time-period request. Standardized parameters are found by key word entries. The user-interface window (Microsoft Virtual Earth) is an excellent hybrid aerial and map system that visually provides the precise location and identification of the station(s) to be queried. Retrieval of standardized data is quickly obtained by an automated email system. Data delivery is received in an excel list normally within a short time dependent on the data amount. Over 50 relevant stations were found and tested for water data usefulness such as long-term continuous time-series records of stream discharge. The most appropriate

Figure 2: Piceance Creek Basin Oil Shale

Figure 3: Colorado River at Cameo, CO

Figure 4: White River near Meeker, CO

Figure 5: Piceance Creek at White River, CO

data were then further analyzed.

Data Collection and Analysis

Stream discharge data were selected and analyzed for the following stations:

- Colorado River near Cameo, CO, for 1934-2007. Station ID 09305500.
- Colorado River at Lee's Ferry, AZ, for 1922-2007. Station ID 09380000.
- White River near Meeker, CO, for 1901-2007. Station ID 09304500.
- Piceance Creek at White River, CO, for 1970-2007. Station ID 09306222.
- Yellow Creek near White River, CO, for 1972-2007. Station ID 09306255.

Using HydroSeek, most of the data records were obtained from the USGS National Water Information System (NWIS). Some NWIS stations have continuously operated for 70 to 100 years, a remarkable feat in itself. A few data records from the EPA STORET stations were also reviewed for water quality parameters when available. The following sections present the raw data and analysis for the stations listed. The water year convention is used with the water year starting on October 1 and ending on September 30 of the following year.

Colorado River near Cameo, CO

This station is located 25 miles (40 km) from the southern boundary of the oil shale region and approximately 50 miles (80 km) from its center. The station supplied 73 years of continuous time series daily discharge records for 1934-2007, the longest uninterrupted period of stream discharge on the Colorado River within reasonable distance from the oil shale. The station's average flow (3,810 cfs, 108 cms) is much lower than stations farther downstream such as Fruita (25 miles, 40 km) west (7,600 cfs, 215 cms). The water quality at Cameo is very good while it is significantly lower at Fruita. Both the flow and quality differences are due to the influx of tributaries (including the Gunnison River), which return considerable amounts of groundwater back to the river with increased dissolved minerals.

Figures 6 and 7 show Colorado River daily discharge and annual discharge in cubic feet per second (cfs). The summary statistics for the annual discharge data are shown below.

Mean Value	3,810 cfs	(108 cms)
Min Value	1,751 cfs	(50 cms)
Max Value	7,605 cfs	(215 cms)
Median	3,595 cfs	(102 cms)
Std Error	135 cfs	(3.8 cms)
Std Dev	1,158 cfs	(33 cms)

All of the annual discharge points are within two standard deviations (95%) of the mean except the peak value of 7,605 cfs (215 cms), which occurred in 1984. The lowest discharge year occurred in 2002, a severe drought year. Since 1980, the swings between high and low flows have

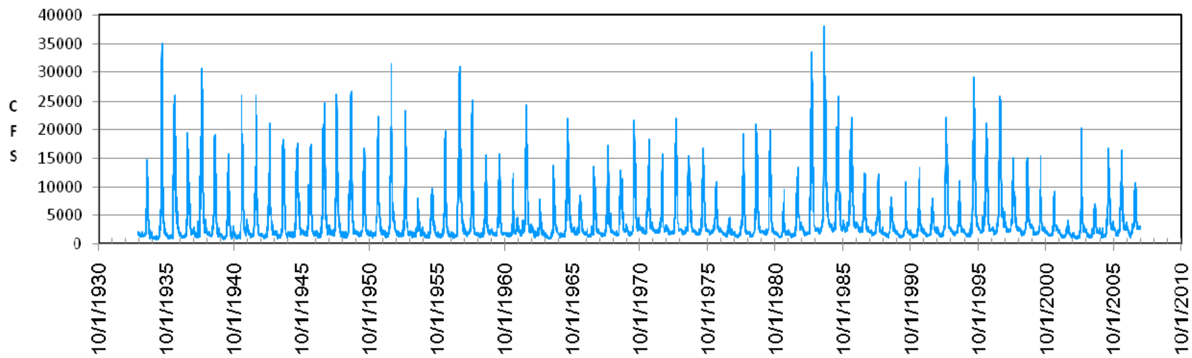


Figure 6: Colorado River Daily Discharge at Cameo, CO 1934-2007

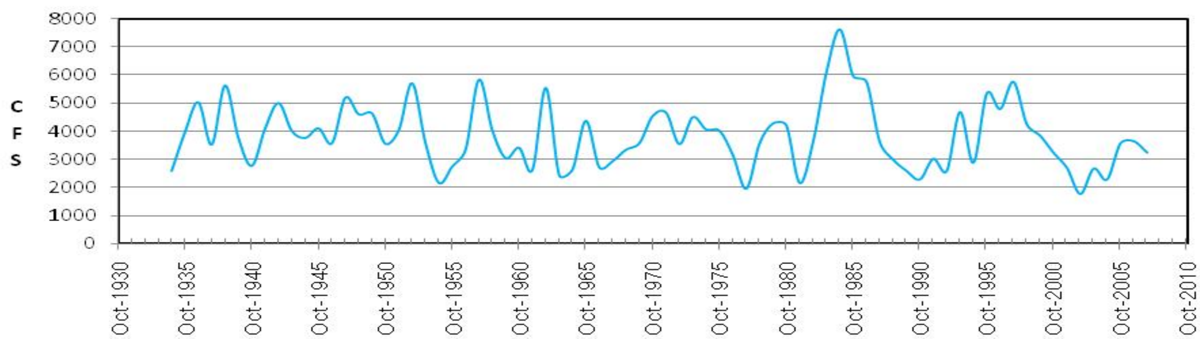


Figure 7: Colorado River Annual Discharge at Cameo, CO 1934-2007

increased in amplitude. In addition, there appears to be a low frequency modulation of the data that will be discussed in a later section.

Colorado River at Lee's Ferry, AZ

Lee's Ferry is 500 miles (800 km) southwest of the Piceance Basin. This station was selected for its historical importance as a reference point for the Colorado River Compact of 1922. Lee's Ferry is located at about the halfway point of the Colorado River's journey to the Sea of Cortes in Mexico and divides the watershed into Upper and Lower Basins. In 1922, the discharge records at this station were used as a benchmark in the Colorado River Compact, a landmark agreement among the Colorado River watershed states that compete for water rights (Gelt, 1997). The Compact established basin water allocations partially based on the Lee's Ferry discharge records, which used 16.4 million acre-ft (maf) [2.0 million hectare meters (mhm) or 22,600 cfs (640 cms)] as the base natural flow. The flow records were taken during a very wet period and resulted in higher than normal average values, which cannot be justified today.

In 1963 the Glen Canyon Dam at Page, AZ was completed and began filling up Lake Powell. This dam is located approximately 8 miles (13 km) north of Lee's Ferry and affects the discharge records by its controlled releases. To correct the low flows recorded during the dam filling period, the annual discharge data for years 1963 and 1964 were adjusted by adding back 23.5 maf (2.9 mhm), the storage capacity and present storage volume of the dam. Over the two-year filling period, this amounts to an additional 16,200 cfs (459 cms) of discharge added to water years 1963 and 1964. Figures 8 and 9 show the daily discharge and adjusted annual discharge at the Lee's Ferry station.

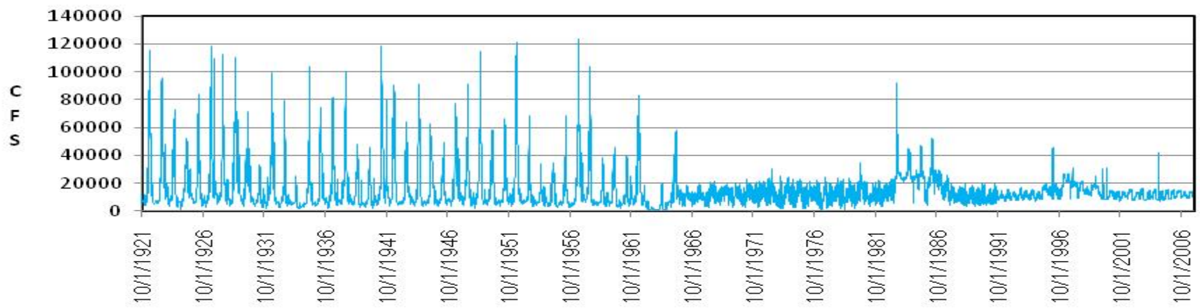


Figure 8: Colorado River Daily Discharge at Lee's Ferry, AZ 1921-2007

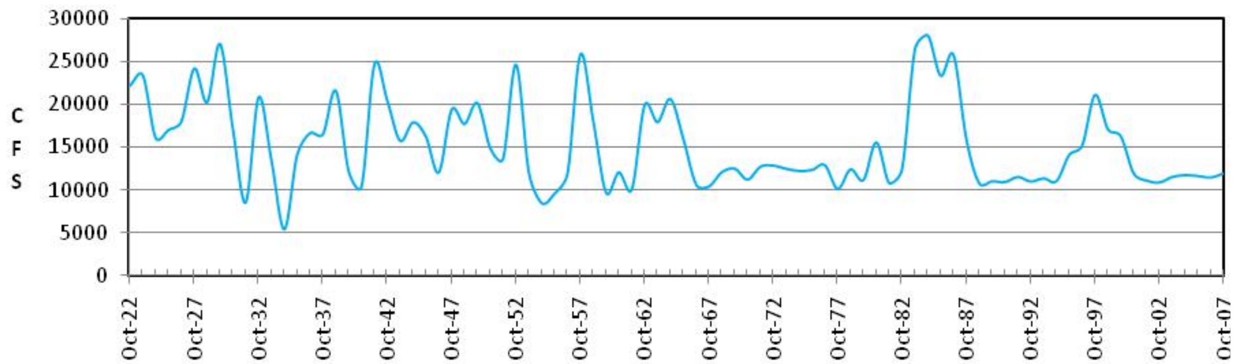


Figure 9: Colorado River Annual Discharge at Lee's Ferry, AZ 1921-2007

The Lee's Ferry graphs show a natural distribution of flow until 1965 when the dam began controlling the discharges. The descriptive statistics for these graphs are not very meaningful due to the effect of the controlled releases from the dam. The minimum flow value of 5,454 cfs (154 cms) was recorded in 1934 and the maximum value of 28,057 cfs (795 cms) in 1984. The annual mean value of flow for the entire 86-year period was 15,288 cfs (433 cms) or 11.1 maf (1.4 mhm); while the mean value for the natural flow period alone (1922-1964) was 16,614 cfs (471 cms) or 12 maf (1.5 mhm).

Both mean flow statistics are lower than the benchmark base flow of 16.4 maf (2.0 mhm) used in the Colorado River Compact agreement. However, the 16.4 maf (2.0 mhm) benchmark flow estimate was based on flow measurements made during an unusually high flow period from 1906-1921. In addition, the subsequent 1922 to 2007 period included several prolonged droughts, and this relatively short-term mean flow period would not necessarily be representative of actual long-term base flow in the river.

The Western Water Assessment has prepared an excellent review of the natural base flow of the Colorado River titled "Colorado River Streamflow: A Paleo Perspective," (Western Water Assessment, 2007). This review summarizes five proxy studies of discharge in the Colorado River using tree-ring chronologies, which estimate long-term mean flow values ranging from 13.0 to 14.7 maf (1.6 to 1.8 mhm) over the past 400 to 1,200 years (Stockton and Jacoby, 1976; Michalsen et al., 1990; Hildago et al., 2000; Woodhouse et al., 2006; and Meko et al., 2007). The average of the base flow estimates from these proxy studies is 13.9 maf (1.7 mhm).

White River near Meeker, CO

This station is located three miles (5 km) east of Meeker and approximately 25 miles

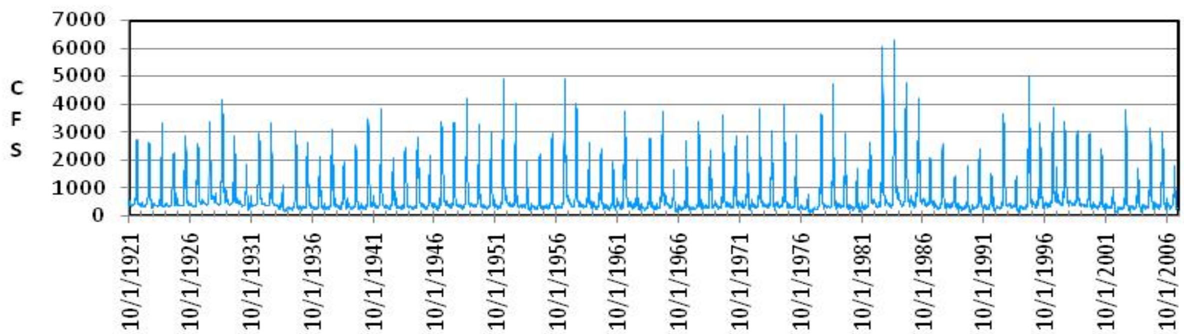
(40 km) from the center of the oil shale region (see Figure 1). The station supplied over 100 years (36,500+ data points) of almost continuous time-series daily discharge records for 1901-2007; however, three years of data are missing for years 1906-1908. Due to limitations of 32,000 data points in the excel program used to prepare the graphs, only 86 years of uninterrupted data from 1921 to 2007 are plotted although all of the data were analyzed. This station is less than 50 miles (80 km) downstream of the origin of the White River near Trapper's Lake and therefore the water quality of the White River at Meeker is very good. The mean flow over the last 106 years is 619 cfs (18 cms). Figures 10 and 11 show daily discharge and annual discharge for the White River and the summary statistics are given below.

Mean Value	619 cfs	(18 cms)
Min Value	274 cfs	(8 cms)
Max Value	1,044 cfs	(30 cms)
Median	619 cfs	(18 cms)
Std Error	15 cfs	(0.4 cms)
Std Dev	150 cfs	(4.2 cms)

100 of the 106 annual discharge points are within two standard deviations (95%) of the mean. The lowest annual discharge (274 cfs, 8 cms) for the 106 years period was recorded in 1977, a surprisingly drought year within an otherwise series of above average flows. The second lowest flow year was 2002, which corresponds to the lowest flow year for the Colorado River at Cameo. The peak flow of 1,044 cfs (30 cms) occurred in 1984, the same as in the Colorado River.

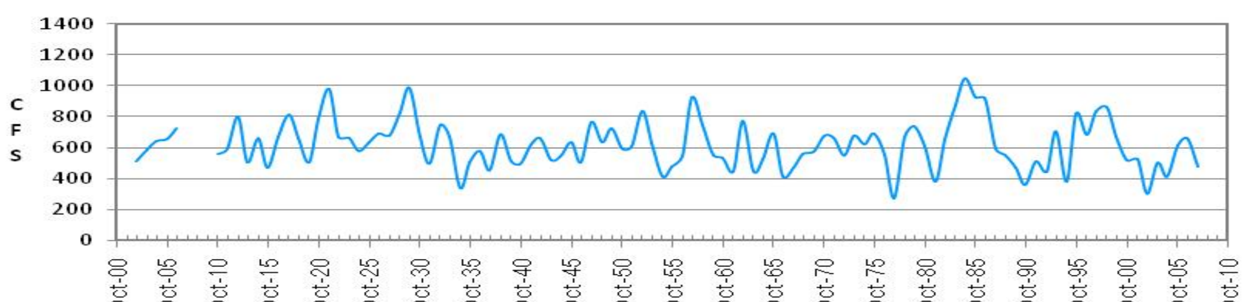
Piceance Creek at White River

Piceance Creek winds through the heart of the oil shale region for over 45 miles (72 km). The Creek starts at approximate elevation 7,600 ft (2,316 m) near Highway 13 on the east and ends at elevation 5,700 ft (1,737 m) at Highway 64 in the north where it joins the White River near Rio



Data truncated from 1901-2007 series due to graphing limitations

Figure 10: White River daily discharge near Meeker, CO 1921-2007



Data missing for 1906, 1907 and 1908

Figure 11: White River Annual Discharge near Meeker, CO 1901-2007

Blanco Lake. Discharge records for years 1964-2007 were available from the gauging station just south of this junction; however, data for years 1967-1969 were missing. Therefore, only the continuous time-series of 1970-2007 are displayed in Figures 12 and 13. The other statistics below are not very meaningful due to limited and non-normal distribution of data.

Mean Value	36.3 cfs	(1.0 cms)
Min Value	6.0 cfs	(0.2 cms)
Max Value	109.5 cfs	(3.1 cms)
Median	24.0 cfs	(0.7 cms)
Std Error	4.8 cfs	(0.1 cms)
Std Dev	29.2 cfs	(0.8 cms)

Yellow Creek near White River

Yellow Creek is a very small intermittent stream that forms at 8,400 ft (2,560 m) elevation about 6 miles (10 km) west of Piceance Creek. Yellow Creek drains several tributaries including Duck Creek, Corral Gulch and Stake Springs, and flows north parallel to Piceance Creek for about 32 miles (52 km) until it joins the White River. Discharge data for years 1972-2007 were available from the gauging station; however, data for years 1982-1987 were missing (see Figures 14 and 15). Due to intense rainfalls at the higher elevations, the daily discharge values have a range from 0 to over 500 cfs (14 cms) with a mean value of only 3.4 cfs (0.1 cms); therefore, the daily discharge values are plotted on a log scale (Figure 14). The summary statistics are as follows:

Mean Value	3.4 cfs	(0.10 cms)
Min Value	1.0 cfs	(0.03 cms)
Max Value	9.9 cfs	(0.28 cms)
Median	2.4 cfs	(0.07 cms)

Data Summary

Table 1 summarizes the water data reviewed in this study and compares them with similar data presented in the 1973 prototype oil shale leasing program (U.S. Department of Interior, 1973).

The current stream discharge data mean values are less for the Colorado and White Rivers due to longer periods of measure-

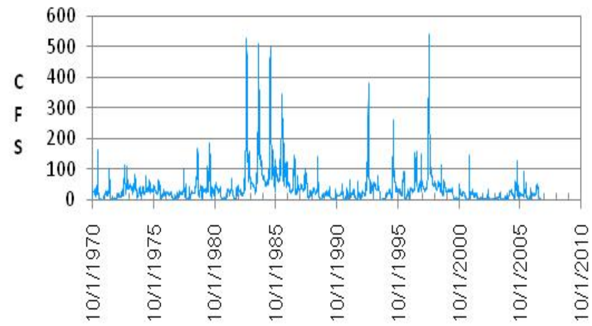


Fig 12: Piceance Creek Daily Discharge at White River, CO 1970-2007

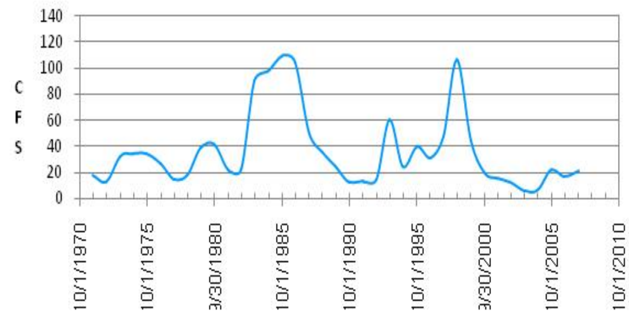


Fig. 13: Piceance Creek Annual Discharge at White River, CO 1970-2007

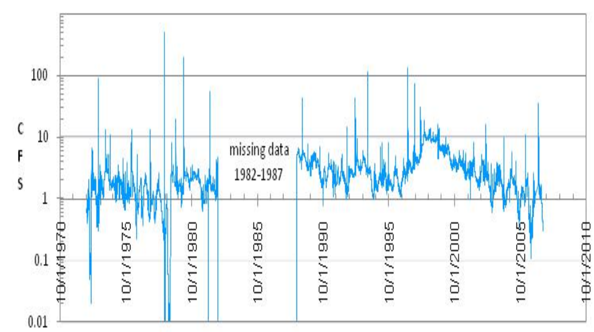


Fig 14: Yellow Creek Daily Discharge near White River, CO 1972-2007

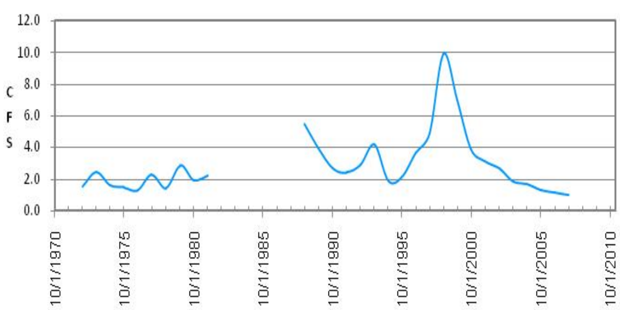


Fig 15: Yellow Creek Annual Discharge at White River, CO 1972-2007

Table 1: Summary and Comparison of Water Data

Station	Parameter	1973 Source [1]	2007 Source [2]	Comments
Colorado River Cameo, CO	Discharge Dis. Solids	4,138 cfs 387 ppm	3,810 cfs 496 ppm	>7,660 cfs @ Fruita 25 mi west >880 ppm @ Fruita 25 mi west
Colorado River Lee's Ferry, AZ	Discharge Dis. Solids	13-14 maf 609 ppm [3]	11-12 maf 502 ppm	2007 flow based on longer/dryer period. Natural base flow has been estimated at 13.9 maf [4]
White River Meeker, CO	Discharge Dis. Solids	638 cfs 344 ppm	620 cfs 370 ppm	2007 flow based on 101 years period
Piceance Creek White River, CO	Discharge Dis. Solids	17 cfs 2,500 ppm	36 cfs 1,750 ppm	2007 data based on much wetter period than 1973 data
Yellow Creek White River, CO	Discharge Dis. Solids	1.4 cfs 2,140 ppm	3.2 cfs 2,447 ppm	2007 data based on much wetter period than 1973 data

Sources

[1] 1973: *Final Environmental Statement on the Prototype Oil Shale Leasing Program,* U.S. Department of Interior, 1973. Most data were averaged over periods of 1914-1956 or 1941-1970.

[2] 2007: *Data collected in this study using Hydroseek*. Flow data are from periods of 30-100 yrs shown on graphs. Dissolved solids are based on average of last 10 years available data.

[3] *From source* [1] based on current salinity control conditions over period 1941-1970, projected to increase to 767 ppm by 2000 without additional salinity control programs.

[4] 2007: *Colorado River Streamflow: A Paleo Perspective*, Western Water Assessment, 2007. The 13.9 maf estimate is the average of five major proxy studies of Colorado River natural base flow using calibrated tree-ring chronologies.

ment (70 to 100 years) which include more dry years than the 1973 era. The Colorado River flow declined almost 8% from the prior reported values, which reflected averages over a 30 to 50 year period. This is agreement with several recently experienced drought events. The slight decrease in the White River mean discharge value is insignificant. The dissolved solids concentrations have generally increased for the Colorado and White River stations, except at Lee's Ferry in Arizona apparently due to salinity control programs. Both the Colorado River at Cameo and the White River at Meeker have low dissolved solids and reflect a high water quality of these resources at these locations. The Colorado River water quality quickly lessens farther west due to groundwater return flows and the influx of the Gunnison River. The Piceance and Yellow Creek data show a significant increase in mean discharges for these smaller streams than were reported previously. The dissolved solids concentrations are lower for Piceance Creek and higher for Yellow Creek; however, the actual dissolved solids loadings (concentration times discharge times density) have both increased for these streams.

No irrational changes in the hydrological data over the last 30 to 50 years when compared with previous reports were observed during this study.

Patterns Observed in Flow Data

During this study, a low-frequency oscillation was observed in some of the stream discharge data. The Colorado River annual discharge data points near Cameo for 1934-2006 are shown in Figure 16 referenced to the median value of 3,594 cfs

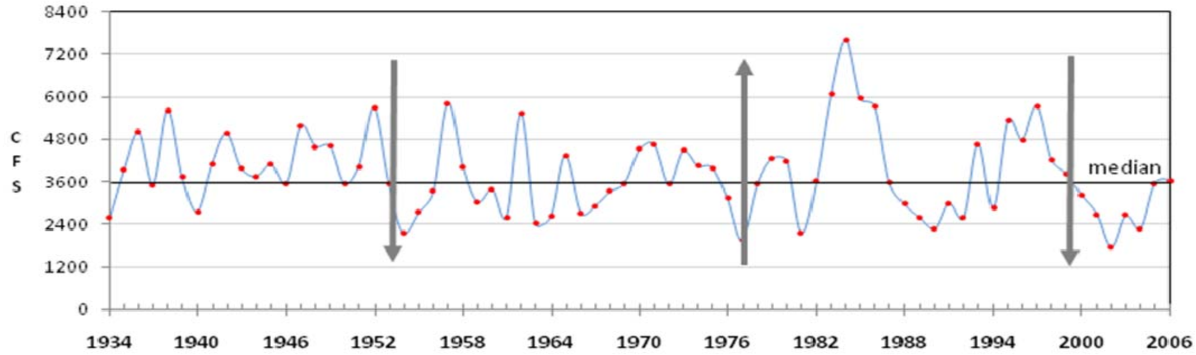


Figure 16: Colorado River Annual Discharge Data Points at Cameo, CO 1934-2006

(102 cms). Several periods of significant flow rate reversals were observed in the data as indicated by the arrows shown in the Figure.

Within the flow rate reversal boundaries, data points above and below the median were counted and their dominant ratios used to characterize the time between the reversal boundaries as either a "wet" or "dry" phase. The phase duration in years and mean flow values in cfs are shown within each flow phase in Figure 17. The first cycle is 44-years long measured from the start of the first wet phase to the end of the first dry phase. The second cycle is at least 29 years long from the start of the second wet phase to the end of the second dry phase, which is still in progress.

A polynomial trendline (Figure 18) illustrates the sinusoidal oscillation of the data. The one full-cycle peak-to-peak of the trendline shows a 44-year period and accounts for 10% of the variance. The second cycle will complete when the present dry phase reverses to a wet phase.

Global Climate Indicators

The long-term variation in flow appears to correlate with the "Pacific Decadal Oscillation" or PDO global climate indicator (GCI). The PDO is a relatively recent discovery of regular oscillations in sea surface temperatures and sea level pressures in the North Pacific Ocean above north 20^o latitude (Francis, R. C. and Hare, 1994). Climatologists have found that the PDO is associated with North and South American climate changes (Mantua et al., 1997). Calibrated proxy studies of climate-limited resources (e.g. long-lived trees) have shown evidence that the PDO has existed for hundreds of years (Shen et al, 2006).

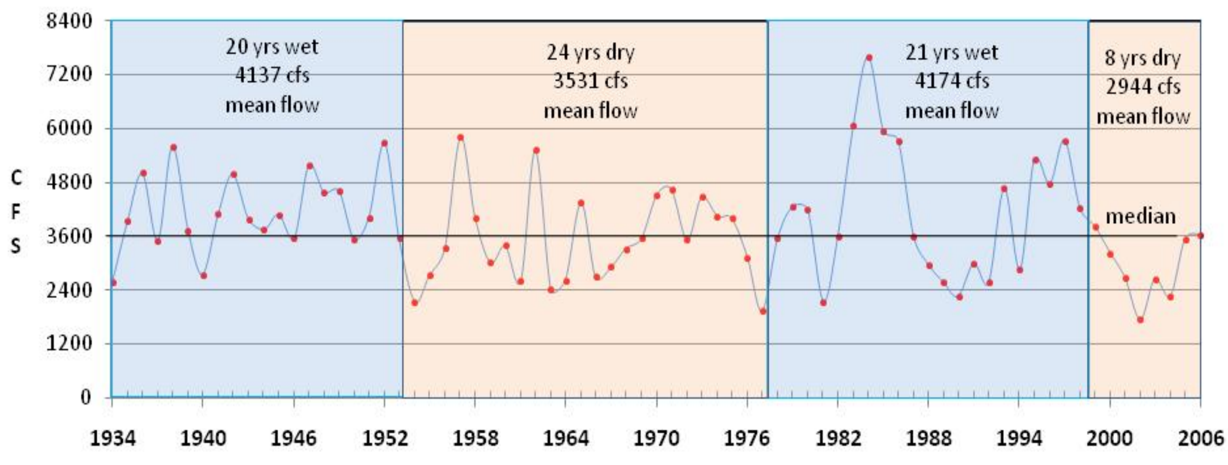


Figure 17: Major Wet and Dry Flow Phases of the Colorado River at Cameo, CO 1934-2007

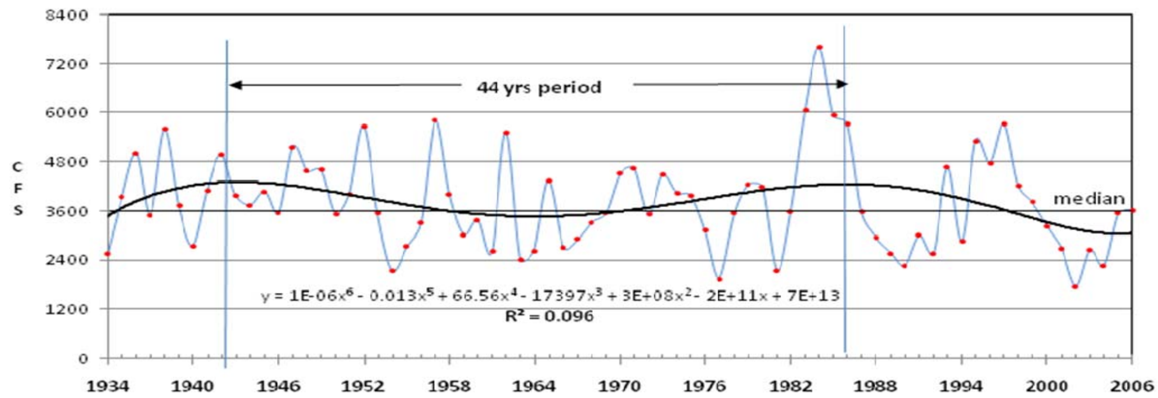


Figure 18: Polynomial Trendline Showing a 44-yr Period of Oscillation

The PDO was discovered by fishery scientists and ecologists who found profound changes in marine ecosystems that correlated with the PDO measurements. The causes of the PDO and other GCI phenomena are not known.

The PDO is similar to, but much more persistent than, the "El Nino and La Nina" warm and cool South Pacific Ocean oscillation events whose affect on climate have been known for over 100 years. El Nino and La Nina typically have short-term phases of six to 24 months with combined periods of two to seven years. Although they occur in the South Pacific Ocean, they have secondary effects on North American climate. The El Nino and La Nina indices have been combined into a single index called ENSO for "El Nino Southern Oscillation." The interactions between PDO and ENSO are complex and when further understood could lead to improved long-range climate forecasts.

The PDO individual phases are associated with precipitation and temperature changes in Mexico and the southwestern United States including Colorado (Hereford et al, 2002; Pavia et al, 2006). The PDO positive anomalies indicate warm ocean temperatures and higher pressures, which correlate with increased precipitation in the Colorado region. The changes are proportional to the strength and consistency of the PDO reversals and are caused by a shift in the Jet Stream and changes in weather patterns from the Gulf of Mexico and Gulf of California, which bring more or less moisture into the region. The individual phases are not necessarily symmetrical and usually last from 20 to 30 years with an average period of about 50 years.

Figure 19 shows a modified water-year index reconstructed from data available on the internet (Mantua, 2007). The PDO is reported in units of standard deviations and has been modified by the author to coincide with the water-year convention of October through September. Figure 20 shows the modified water-year PDO index superimposed on the Colorado River flow data for a visual comparison. The raw data show a weak correlation coefficient of 0.14 ($P > .05$). The Colorado River flow data were then converted to standard deviations from their mean (3,810 cfs, 108 cms). Both the PDO and stream discharge data were then smoothed with a 5-year moving average, which yielded an improved correlation of 0.30 ($P < .05$). It is assumed that a Colorado stream flow effect, if it exists, will lag a global climate index of ocean parameter oscillations occurring thousands of miles distant, since stream flow is a more complicated and delayed function than precipitation alone. Therefore, by trial and error, a one-year phase lag added to the stream data provided a maximum correlation coefficient of 0.34 ($P < .01$). These moving averages and correlations are shown in Figure 21. In this manner, the PDO for water year 1934 was corre-

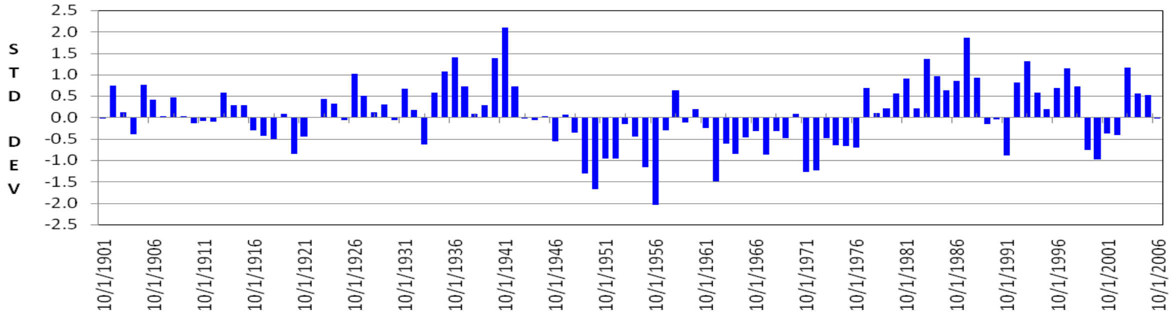


Figure 19: Reconstructed Water Year PDO Index for 1901-2006

lated with the flow data for water year 1935, etc. Although only a moderate correlation, the probability of the two data sets being independent is less than 1% (P value =.004).

The PDO is not independent of the ENSO events, which some climatologists believe actually trigger the PDO (Newman et al, 2003). It has also been speculated that the two events might work together to either reinforce or suppress the combined climatological effects dependent on their respective phases, strengths and timing. This area is still not well understood and is the cause for considerable debate. Climatologists are refining these global climate indices and are researching their cause and effects vigorously. Furthermore, hydrologists are now investigating correlations of various GCIs on specific watersheds. An example is the USGS paper (Hereford et al, 2002) on the PDO and its association with precipitation patterns in the Colorado Plateau Region over the last 100 years. In this study, a moderate correlation was established between the PDO and averaged precipitation in the Colorado Plateau.

The correlated data shown herein are not spatially averaged over a large area and the time frames are relatively short, which together challenge vigorous correlations. But the PDO appears to be a potential indicator for Colorado River long-term climate related effects such as the probability of a reversal from a wet to dry phase, or vice versa. Decadal climate predictions may become possible once the ocean set-up conditions that lead to climate change events become clear. If the PDO remains in a negative state and its influence on the Colorado River flow is confirmed, the dry phase begun in 1999 is likely to last another 10-15 years with consequent effects

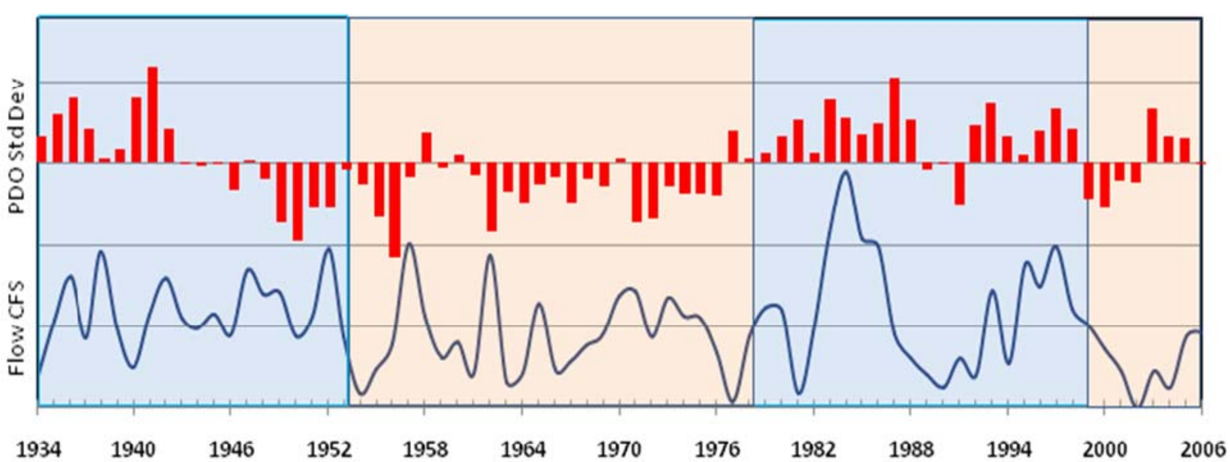
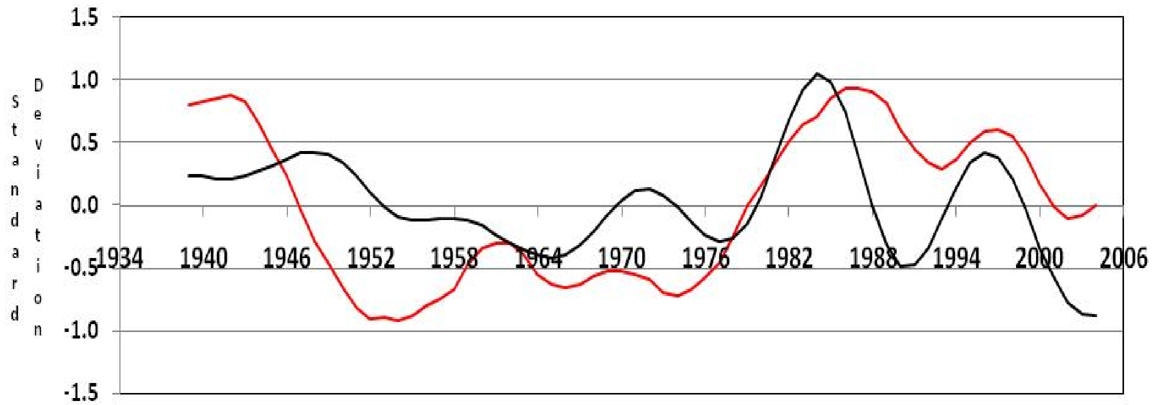


Figure 20: Water-Year PDO Index (top) and Colorado River Annual Discharge at Cameo, CO (bottom) for the Period 1934-2006



R = 0.34 (P = .004)

Figure 21: Correlation of 5-yr Moving Averages of Water Year PDO (Red) and Colorado River Streamflow (Black) with 1-yr Phase Lag in Flow for 1934-2006

on the availability of already strained water resources.

Results and Conclusions

- The HydroSeek search engine proved to be very effective in locating and retrieving large sets of hydrological data from the Piceance Creek Basin and Colorado River Watershed.
- Stream discharge data of 35 to 100 years periods from key water resources at five different locations were analyzed for general characteristics and compared with similar data documented in the 1973 Prototype Oil Shale Leasing Program Environmental Statement (U.S. Department of Interior, 1973).
- In general, the long-term mean discharge of the larger streams declined over the last 30 to 50 years as might be expected, while the smaller stream discharges increased significantly over the last 35 years. The dissolved solids concentrations and/or mass loadings generally increased for the streams studied with the exception of Lee's Ferry station in Arizona.
- No irrational changes in the Piceance Creek Basin water data over the last 30 to 50 years (compared with previous reports) were observed during this study.
- A low-frequency modulation of 44-years period was observed in the Colorado River stream-flow data and found to moderately correlate (R = 0.34, P = .004) with the Pacific Decadal Oscillation (PDO) measured in the North Pacific Ocean.
- Due to progress in identifying global climate indicators such as the PDO, it may be possible in the future to predict long-term changes in available oil-shale water supplies, such as impending droughts.

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Maps

Figure 1. Map of Northwestern Colorado. Copyrighted and published by www.Colorado-Directory.com. Modified and reprinted with permission of the publisher