Analysis of the Relation between Snow Water Equivalent in the Upper Colorado River Basin and Naturalized Flow in the Colorado River

1981 – 2016

By

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Abstract

The Colorado River is one of the most important rivers in the world, supplying water to 40 million people in seven states in the United States, and two states in Mexico. However, the river is threatened by impending climate change which may limit the availability of water resources in the basin. The purpose of this analysis was to investigate the relation between average snow water equivalent (SWE) and naturalized flow in the Colorado River. Data were analyzed from the high- resolution University of Arizona SWE product (Dawson et al., 2018) over the Upper Colorado River Basin and compared to naturalized flow in the Colorado River at Lee's Ferry. A Pearson correlation test was then performed on the five-year moving averages of each dataset to establish the statistical relation between the two continuous variables. The Pearson correlation coefficient was 0.90, which indicates a strong positive correlation between SWE and naturalized flow. Additional correlation tests were performed on the raw (unaveraged) data to further characterize this association and explore the potential for seasonal flow forecasting. SWE data were analyzed when unlagged, and then lagged one to three months. The correlation tests resulted in coefficients of 0.10 when unlagged to 0.80 at three months.

Introduction

Drought has afflicted the Colorado River Basin (CRB) and the Southwest United States, and conditions threaten to worsen because of the effects of climate change (Udall & Overpeck, 2017). Droughts lasting five or more years are projected to occur 50% of the time from now until 2060, meaning conditions are expected to be even drier and hotter (U.S. Bureau of Reclamation, 2012). Furthermore, the problems posed by drought such as water shortages will only be exacerbated by quickly growing urban centers that require an increasingly considerable amount of water. According to estimates (U.S. Census Bureau, 2018), the population of Los Angeles county has increased by more than 60% since 1960. The population of Phoenix has increased to nearly three times its population in 1960, and continues to grow as population has already increased 12.4% since 2010 (U.S. Census Bureau, 2018).

To address concerns posed by increasing demand, water managers in the CRB have had to rely on a complex flow model, which incorporates both natural and anthropogenic factors affecting the flow of the river (U.S. Bureau of Reclamation, 2012). The comprehensive model used by water stakeholders in the CRB is the Colorado River Simulation System (CRSS) (Prairie & Callejo, 2005). The CRSS is a long-term planning and policy model developed by the Bureau of Reclamation. Natural flow data for each USGS gage along the Colorado River are a key input into the CRSS system to allow for effective planning (Prairie & Callejo, 2005). Natural flow or naturalized flow refers to the flow of the Colorado River in the absence of human obstructions on the river and artificial withdraws. These natural flow estimates are made using a combination of gage data, consumptive use reports, and records of annual reservoir stores and releases. The importance of these estimates is that they allow water managers to know how much total water they are working with when distributions to stakeholders are made. The equation for naturalized flow is:

$$NaturalFlow = HistoricFlow + TotalDepletion \pm ReservoirRegulation$$

Where:

- *HistoricFlow* is measured streamflow data recorded at USGS gages along the river;
- *TotalDepletion* is consumptive uses and losses along the river as recorded in official Consumptive Uses and Losses Reports; and

- *ReservoirRegulation* is the water reservoirs' store and release each year (Prairie & Callejo, 2005). Natural flow estimates are then input into the CRSS planning model so water managers can effectively moderate risk and uncertainty.

The goal of this study was to determine if flow in the Colorado River has been affected by recent climate change by using snow-water equivalent (SWE) data as a climactic indicator and to establish if a correlation exists between the high-resolution University of Arizona SWE (UASWE) product (Dawson et al., 2018) and naturalized flow in the Colorado River. The UASWE product is a recently-developed dataset that bridges the gap between small-scale LIDAR surveys and large-scale, remotely-sensed data over a 36-year period from October 1981 to September 2016. It is a revolutionary dataset that provides the magnitude of large-scale remotely-sensed data but provides the accuracy of small-scale surveys (Dawson et al., 2018). The relation of naturalized flow with the UASWE product was then compared to SWE measurements made at the United States Department of Agriculture's (USDA) Snow Telemetry (SNOTEL) sites.

Literature Review

The Colorado River is one of the most important rivers in the world, providing water resources to 40 million people in the seven U.S. States and two states in Mexico that comprise the Colorado River Basin (CRB). The CRB recently experienced its most severe 15-year drought between 2000 and 2014, when flows averaged 19% below the 1906-1999 historical average (Udall & Overpeck, 2017). This drought highlights the uncertainty water users and managers face in the 21st century as the effects of climate change threaten to further stress the over-allocated river. Water consumption is expected to increase as the region continues to expand economically. Population in the Southwest's major metropolitan areas (Clark County, NV; Los

Angeles County, CA; Maricopa County, AZ) have ballooned since 2010 and are expected to continue following this trend (McNabb, 2017). Clark County, NV and Maricopa County, AZ have each experienced population increases of more than 10% since 2010 (U.S. Census Bureau, 2018).

Since 1988, warm years in the UCRB have been associated with corresponding decreased streamflow observations (Woodhouse et al., 2016). Projected temperature increases in the basin are expected to have a direct impact on the Colorado River's flow. One study shows a temperature increase of two degrees Celsius leads to an expected decrease of annual runoff of 4-12% (Nash & Gleick, 1991). Some earlier studies of water availability in the CRB estimate that streamflow will decrease by more than 30% (Stockton & Boggess, 1979). Even a 10% decrease in streamflow could lead to scheduled water resource deliveries to be missed nearly 60% of the time, caused by changes in streamflow seasonality (Barnett & Pierce, 2009).

A temperature increase of two degrees may result in reduced streamflow of about 10% owing to increased evapotranspiration, yet an increase or decrease of annual precipitation of 10-20% will result in a corresponding 10-20% change in streamflow (Nash & Gleick, 1991). The CRB is dominated by snowmelt-driven streamflow, making it particularly susceptible to the effects of climate change. In a similarly snowmelt-driven basin in southwestern Montana, it was found that, depending on climactic parameters, streamflow may vary anywhere from -22% to +45% (Cooley, 1990). A separate study on the mountainous Yakima River Basin in Washington found simulated streamflow measurements were particularly sensitive to climactic changes as well (Salathe, 2005). These studies illustrate how crucial SWE estimates are to understanding how the river may respond to future climactic stresses.

SWE data was previously used to examine the effect of declining trends in snowpack on streamflow in the CRB. Results from the analysis indicated a correlation between trends in snowpack and associated trends in streamflow (Miller & Piechota, 2011). Simulated SWE data in the CRB for three time periods in the 21st century show SWE between 70-76% of historical 1950-1999 climate observations (Christensen et al., 2004). More recent studies similarly project reductions in streamflow, albeit to a lesser degree. These reports suggest a decrease in mean streamflow on the order of 10-30% in the 21st century, attributable to both rising temperatures and a decrease in precipitation (Ficklin et al., 2013). Other studies reinforce these findings by predicting streamflow decreasing by as much as 35% by the mid-21st century (Udall & Overpeck, 2017).

Methods

For this analysis, data were obtained from three sources: the United States Bureau of Reclamation; the USDA's SNOTEL sites; and the UASWE product. Two types of data were used in the investigation: natural flow data and SWE data.

Naturalized flow data is an estimate of unobstructed river flow derived from consumptive uses and losses (CU&L) reports, measured USGS flow gage data, and reservoir regulations. CU&L reports have been provided every five years since 1971 and provide a detailed account of use along the river (Prairie & Callejo, 2005). CU&L is divided into eight separate categories describing how water is distributed along the river. The first and most consumptive category is irrigated agriculture, which is provided by the Bureau of Reclamation. It is computed with the modified Blaney-Criddle method (Blaney & Criddle, 1962) using county agriculture statistics, census of agriculture, and GIS coverages. The next category is reservoir evaporation, which is computed from reservoir surface area and evaporation measurements. There are two categories relating to livestock agriculture: stockpond evaporation and livestock consumption. The net use of water for thermal power plants is also estimated and recorded in the CU&L reports. Another category is the water used in the production of minerals in the basin, including oil and natural gas. Estimates are mostly based on answers to phone surveys conducted by the U.S. Geological Survey (Prairie & Callejo, 2005). Municipal and industrial use values were obtained from data collected by the U.S. Geological Survey in their bi-decadal "Estimated Use of Water in the United States" reports (e.g. Hutson, et al., 2004; Maupin, et al., 2014; Dieter, et al., 2018; the complete list of 14 reports is included in the References section). The eighth and final category of water usage is Exports and Imports, which accounts for transbasin diversions both out of and into the Colorado River Basin. Reservoir regulations account for stores and releases from the various dams and reservoirs located along the Colorado River. Though these natural flow estimates are computed at gages throughout the basin, this study uses information only from USGS gage 0980000 at Lee's Ferry, Arizona, shown in Figure 1. Lee's Ferry is important to the

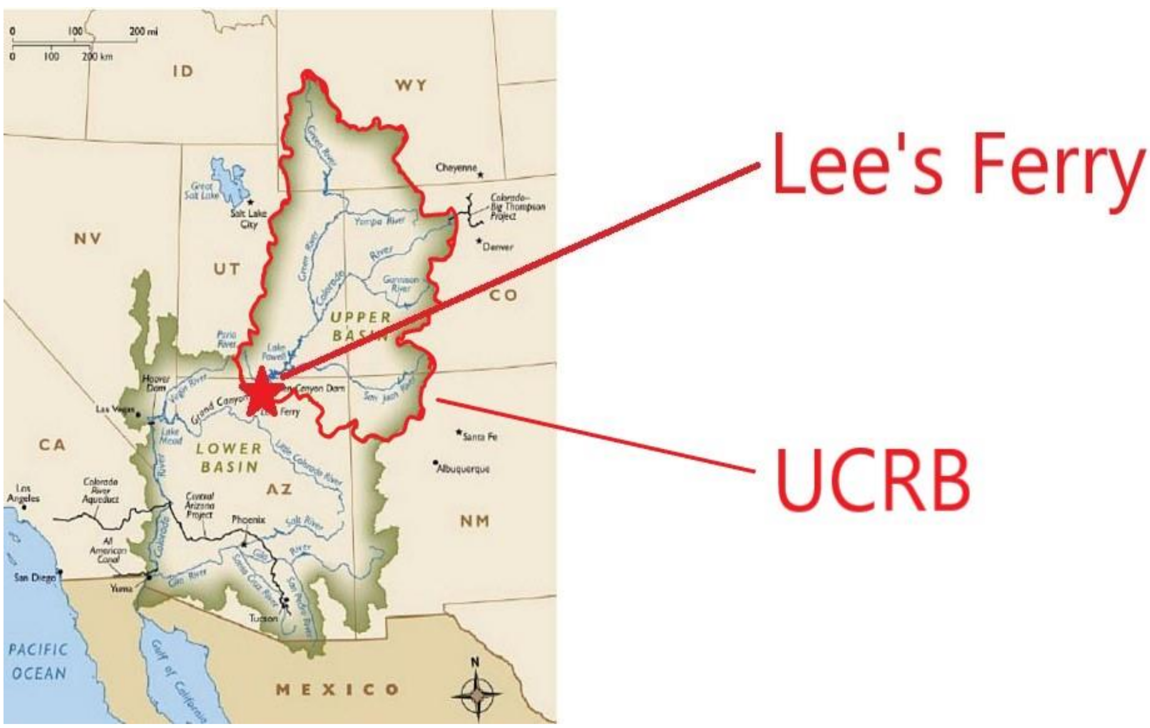

Figure 1. Map of UCRB and Lee's Ferry; SWE data were collected over the entirety of the UCRB and correlated with flow at Lee's Ferry

history of water management in the CRB as it is notably where the initial measurements for the Colorado River Compact were made. Lee’s Ferry is also the site which serves as the point of demarcation between the Upper and Lower Colorado River Basins.

Monthly naturalized flow is the smallest timescale available from the USGS gage, and was used for the purposes of this study. A time series was plotted of monthly naturalized flows for the entire record of the gage which extends from 1906-2016. The monthly naturalized flow estimates are expressed in units of acre feet per month. These values were converted to thousand cubic feet per second. Further analysis of naturalized flow was performed by creating a time series of flow anomalies. Flow anomalies were determined by computing the averaged annual cycle over the time period, then computing the difference of each month from the averaged annual cycle.

The UASWE dataset is a product created by Dawson et al. (2018). The dataset provides 4-km resolution SWE data over the entirety of the conterminous United States for every day from October 1981 to September 2016. A subset area of this dataset was used by restricting the gridded data to the extent of the UCRB as defined by the U.S. Geological Survey. The average SWE was calculated over every cell in the UCRB. The 25th percentile and 75th percentiles of SWE were also calculated to further characterize the dataset. The UASWE dataset expresses SWE as a cumulative measurement in millimeters because SWE is derived from snowpack, which is itself a cumulative measure. Therefore, only SWE measurements for the first day of each month were used to give a monthly cumulative SWE value. A time series of this data was then plotted to ascertain the temporal variability of SWE over the 36-year period.

Finally, after constructing time series plots of both SWE and naturalized flow, a time series of the five-year moving averages of the variables was constructed for the 36-year period. A Pearson correlation test was then performed on the five-year moving averages to assess the strength of the linear relation between the two variables. Pearson correlation coefficients can range from r = -1 to 1. An r = -1 indicates a perfect negative linear relation between variables: r = 0 indicates no linear relation between variables, and an r = 1 indicates a perfect positive linear relation between variables. The same correlation test was then performed on the unaveraged monthly datasets. Additional correlations were performed by lagging both UASWE and the naturalized flow estimates up to 12 months.

SWE data from SNOTEL sites in the UCRB were obtained and the average SWE for each month over the same time period was computed. These data were used to conduct more correlation tests to see how a raw average of UASWE over the UCRB would compare to an easily-computed average of SWE at SNOTEL sites in the UCRB. The SNOTEL sites used in this study are listed in the frequently updated SNOTEL Snow/Precipitation Update Reports (Natural Resources Conservation Service, 2019). The Colorado River Basin Forecast Center (CBRFC) relies on SNOTEL measurements as a key predictor in their flow forecasting (Werner, 2011).

Results

The time series of naturalized flow over the entirety of the flow record at Lee's Ferry (1906-2016) is shown in Figure 2. Notable features of this graph can be seen by looking at the five-year moving average. The five-year moving average is high at first because flows were higher at the beginning of the record. Then, flows decrease for an extended period of time starting in the late 1920s. Flows again increase in the early 1980s and the five-year moving average reaches a maximum. This period of flows from 1980 to present shows two minima in the five-year moving average as well: the first in 1990 and the second in 2000.

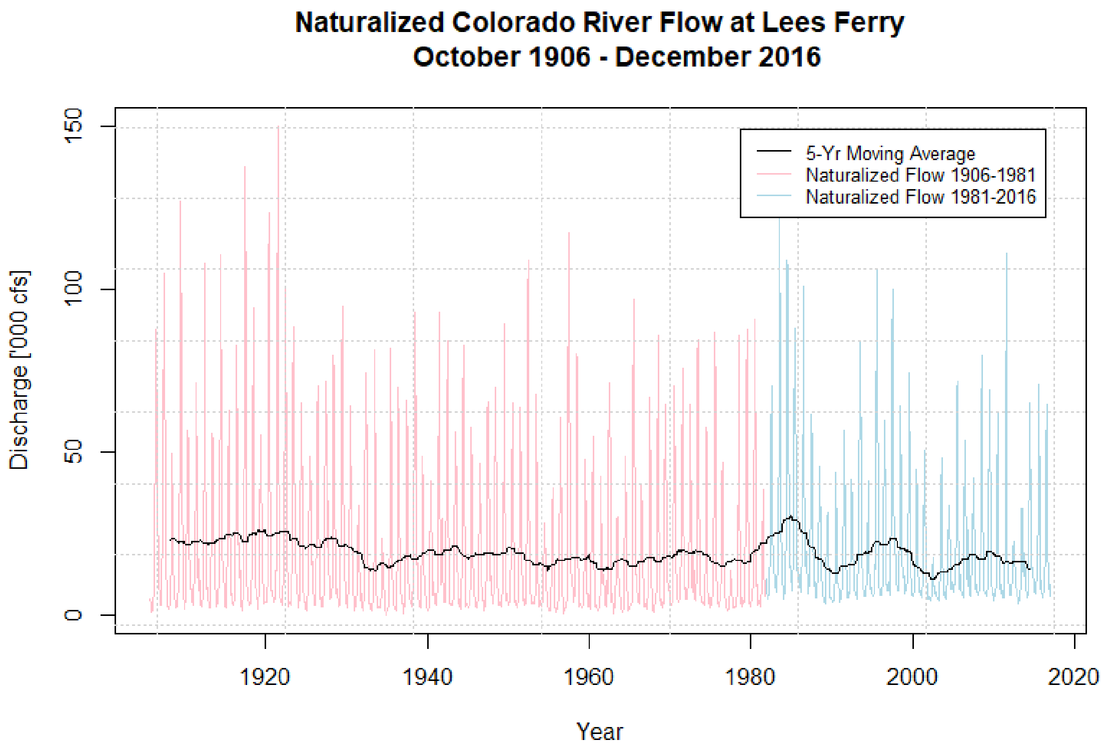

Figure 2. Naturalized flow for the entirety of the record of measurements taken at Lee's Ferry with 5-year moving average; Blue shows the time period of the UASWE dataset

A time series of flow anomalies over the record of the gage at Lee's Ferry is shown in Figure 3. The five-year moving average in Figure 3 varies identically to the five-year moving average in Figure 2. The relative high and low flow months are easier to see in Figure 3. Almost all months in the beginning have positive anomaly. The majority of months in the period of low flow from about 1930 until 1980 exhibit negative anomalies. The period after 1980 shows highly variable anomalies, marked by very high positive anomalies and very low negative anomalies.

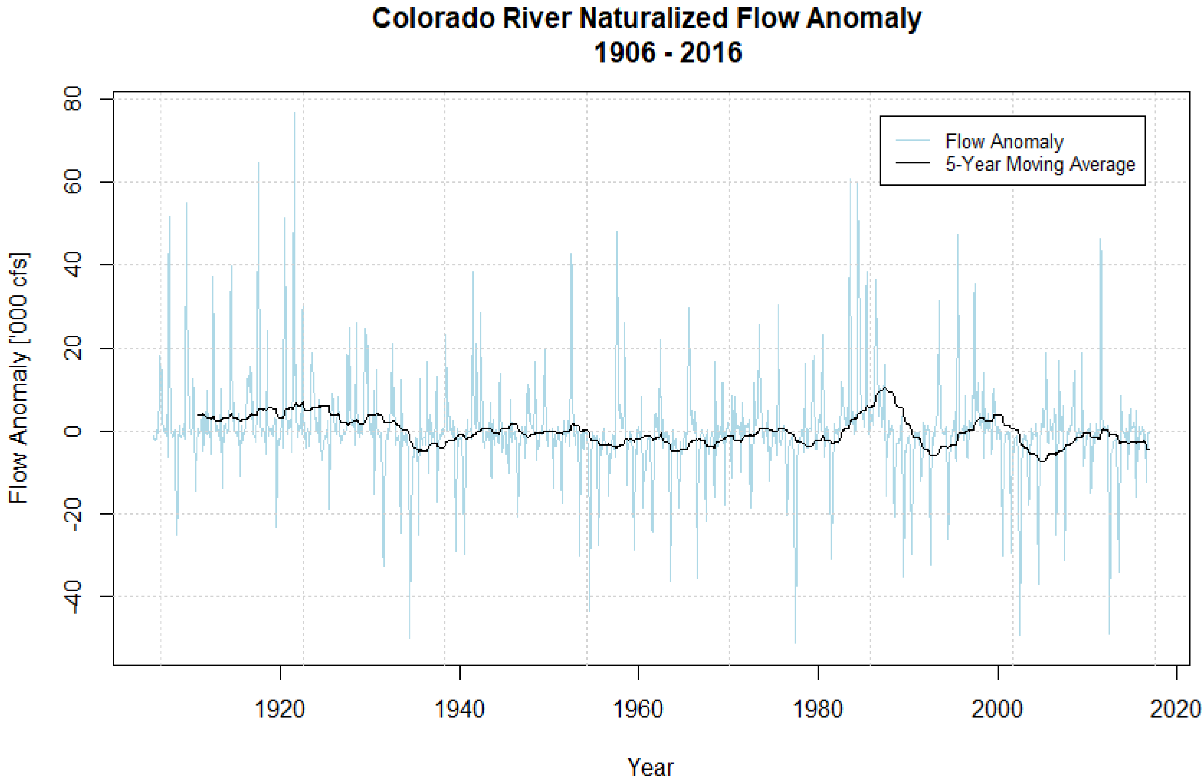

Figure 3. Plot of flow anomalies showing the deviation of flow from the average annual cycle

Five of the ten greatest months of SWE all occurred in the 1980s, and can be seen in Figure 4, which shows the average monthly cumulative SWE over the UCRB from 1981-2016. The five-year moving average stays largely steady over the 35-year period, but does have a slight variation that mirrors the five-year moving average of flow over this period.

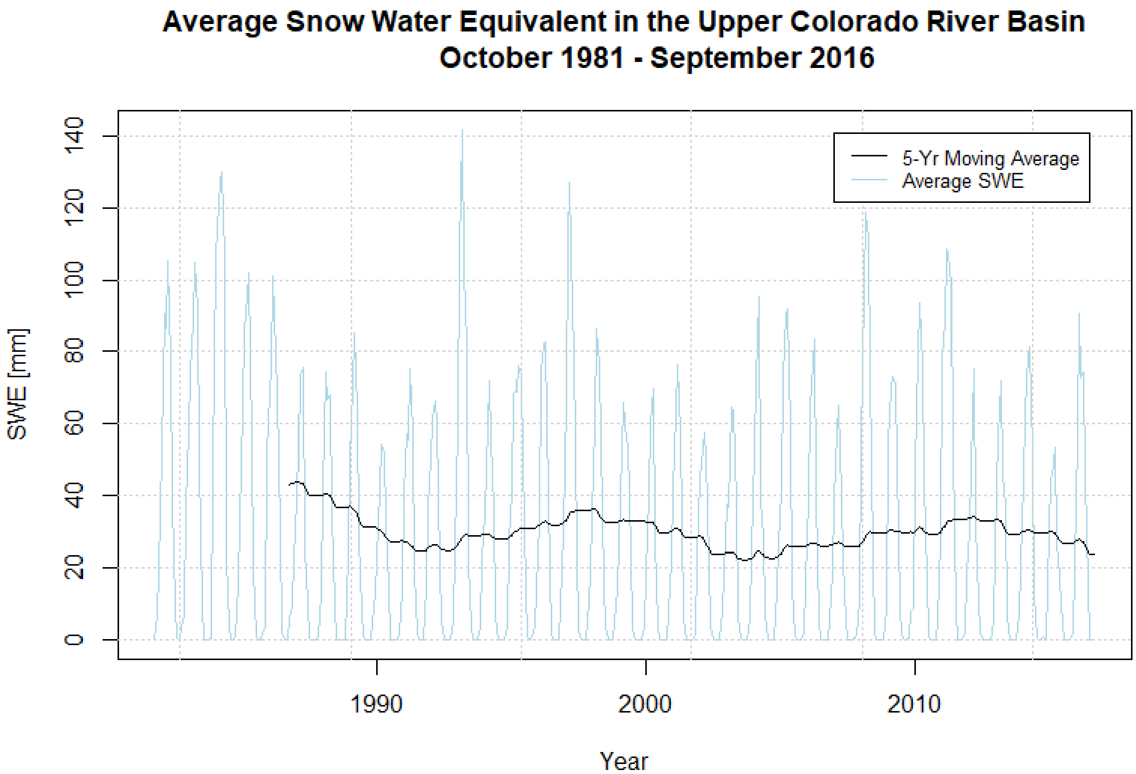

Figure 4. Average monthly cumulative SWE over the entirety of the UCRB 1981-2016

The five-year moving averages of SWE and naturalized flow are shown in Figure 5. The notable feature in this figure is that the two variables vary almost identically; they are just out of phase. The legend in Figure 5 shows the results of the correlation test. The correlation coefficient of the two variables is 0.90, indicating a strong positive relationship.

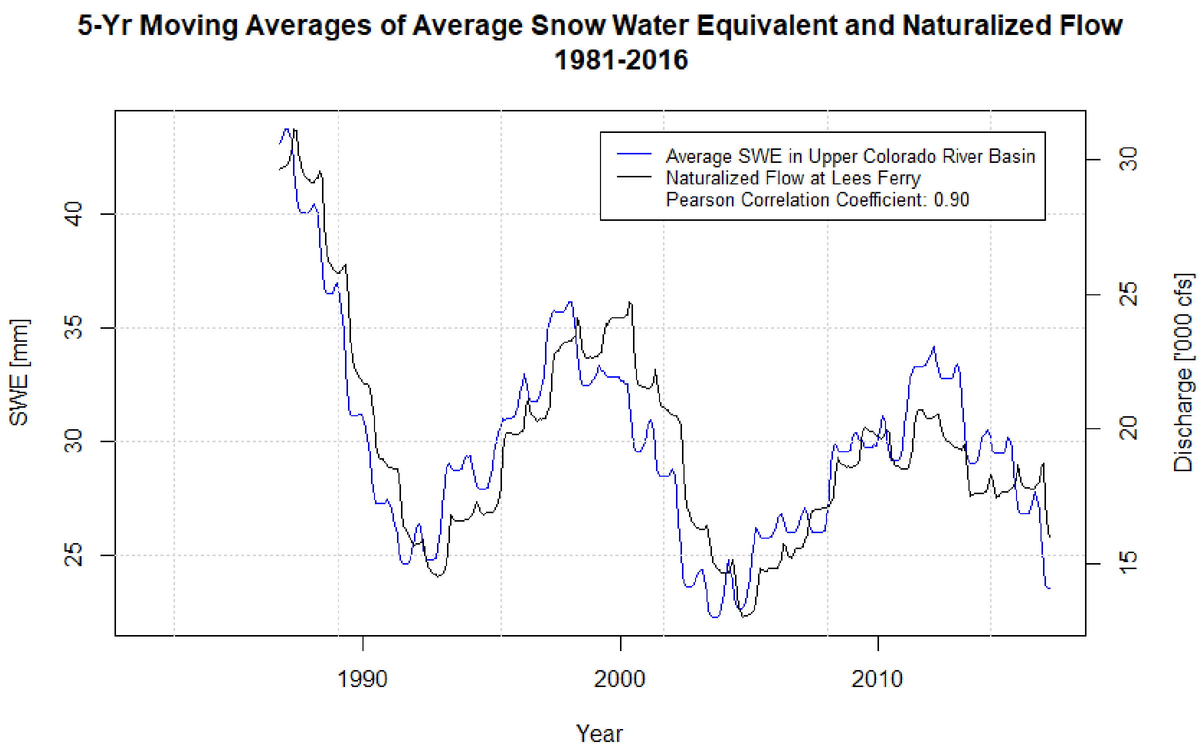

Figure 5. Five-year moving averages of SWE and naturalized flow.

Figures 6-9 show time series of unaveraged SWE and unaveraged naturalized flow plotted together. Figure 6 shows no lag, and successive figures show lags increasing up to three months. The correlation coefficients are also shown in each figure's legend. Correlation coefficients increase from 0.07 to 0.80 from no lag to three months of lag.

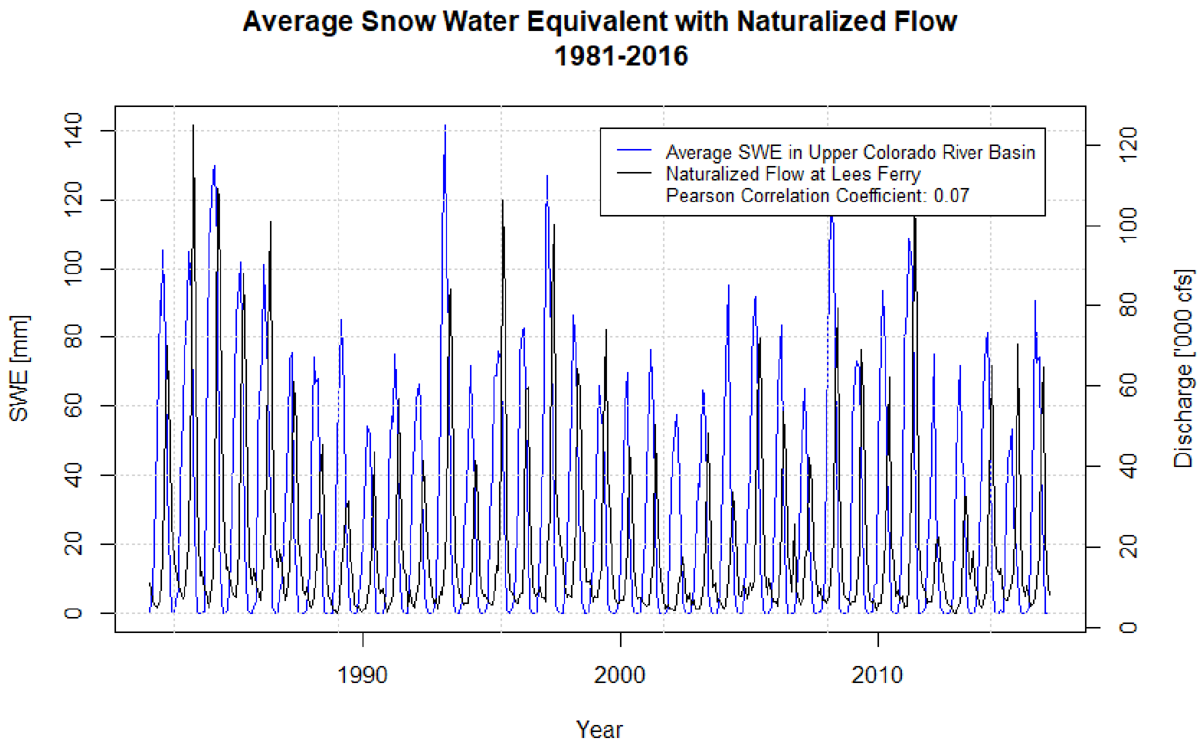

Figure 6. Unlagged SWE and naturalized flow 1981-2016

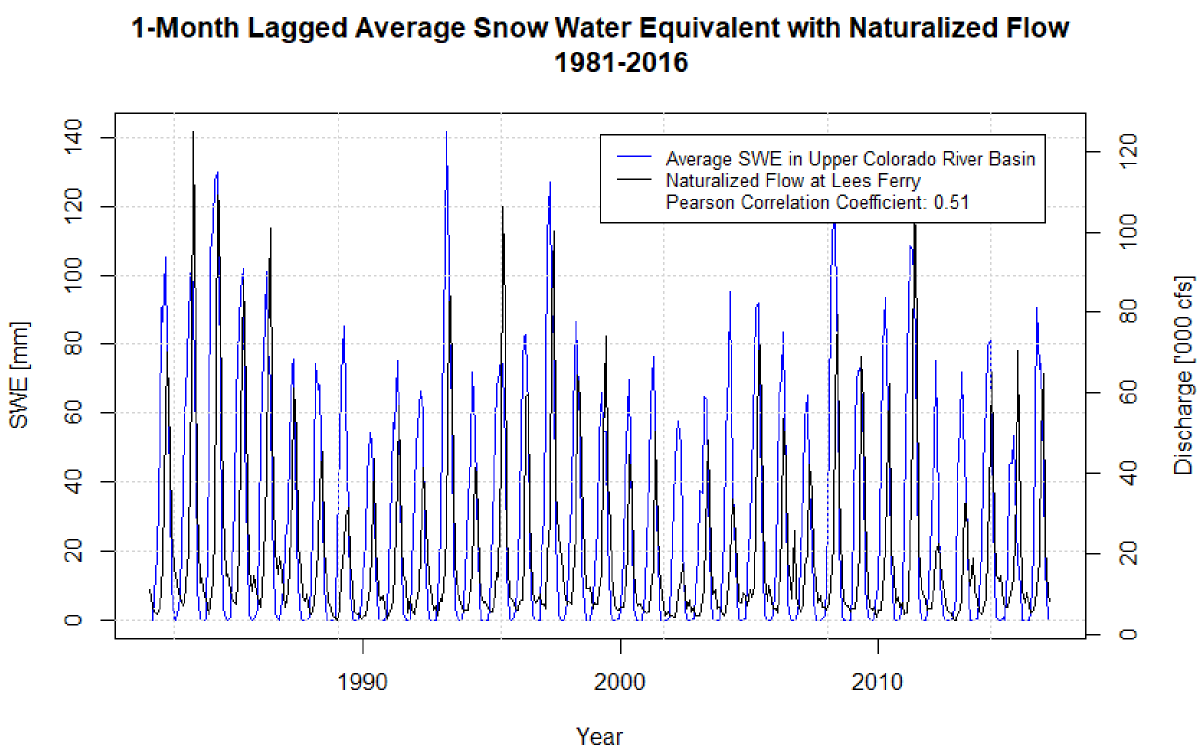

Figure 7. 1-month SWE lag and naturalized flow 1981-2016

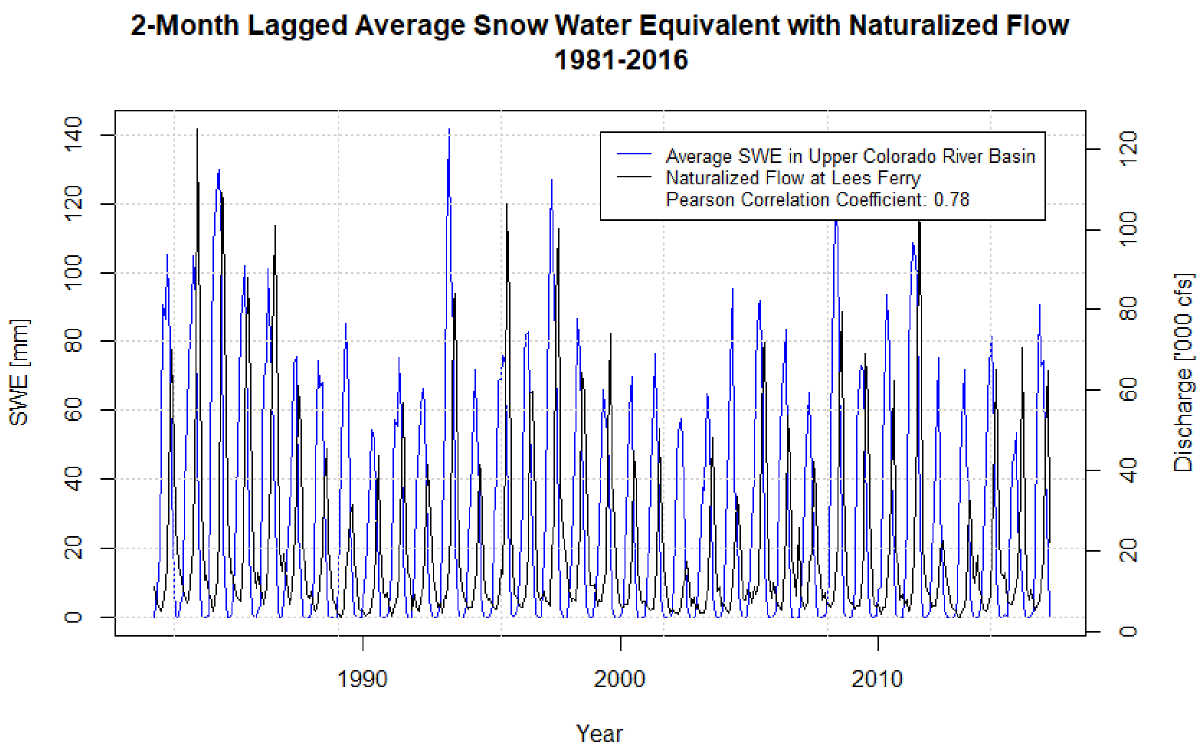

Figure 8. 2-month SWE lag and naturalized flow 1981-2016

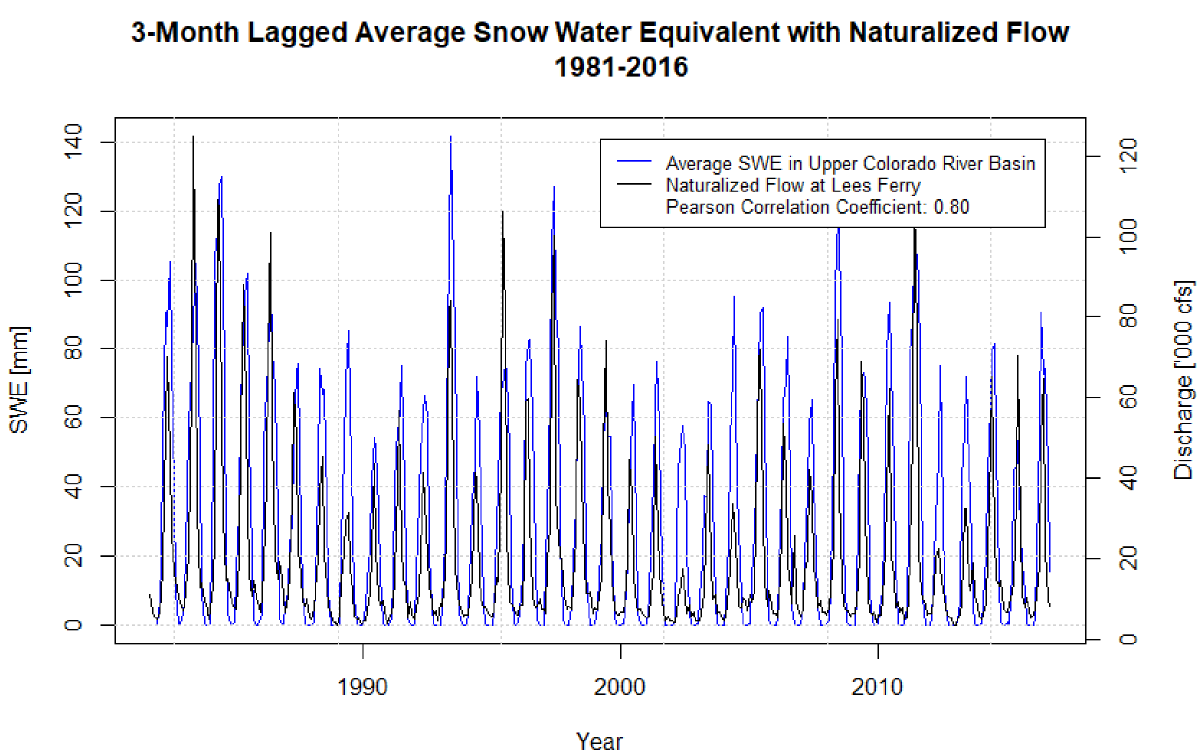

Figure 9. 3-month SWE lag and naturalized flow 1981-2016

The plot in Figure 10 shows the mean SWE, 75th percentile SWE, and 25th percentile SWE of the UASWE product for the UCRB. The 25th percentile SWE is much lower than both the mean and the 75th percentile. The difference between the 25th percentile and the mean is much larger than the difference between the mean and the 75th percentile.

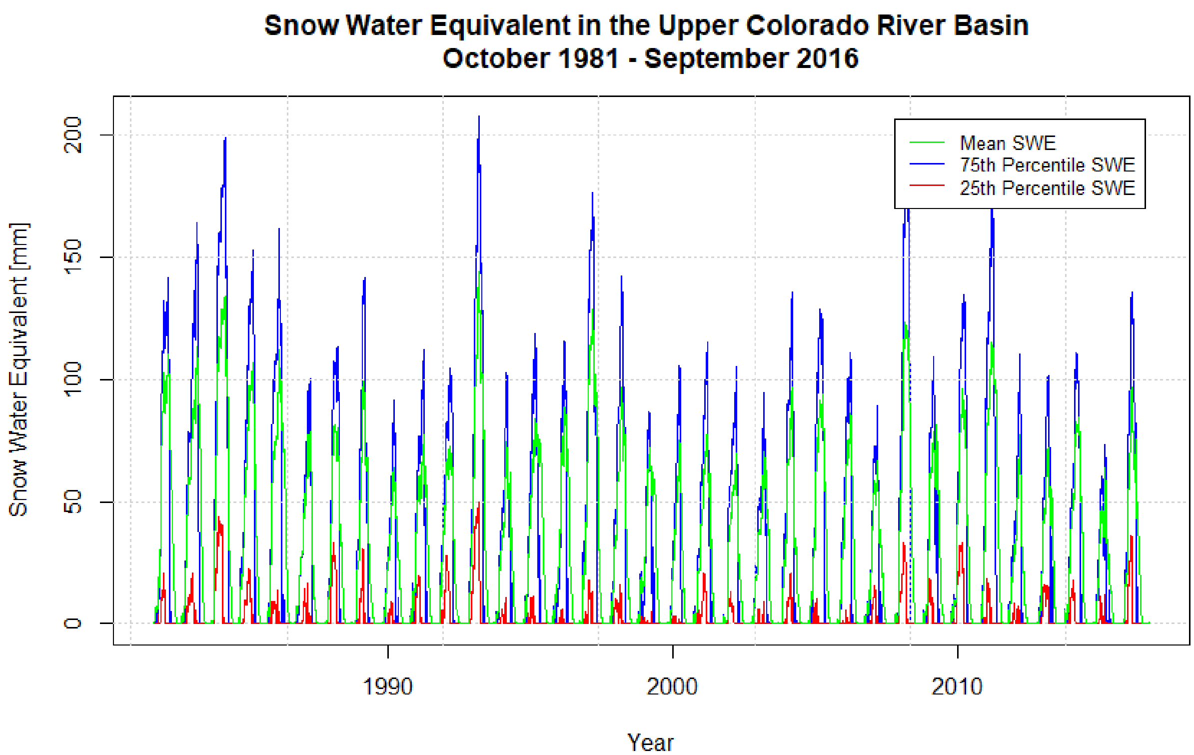

Figure 10. SWE data from 1981 2016 that shows 25th percentile SWE, mean SWE, and 75th percentile SWE

A plot of averaged SNOTEL SWE and averaged UASWE from 1981-2016 is shown in Figure 11. The UASWE product correlates with naturalized flow in the river about as strongly as averaged SNOTEL SWE, but the latter has a consistently larger SWE value than UASWE, particularly in winter months when SNOTEL SWE can reach above 500 mm. UASWE rarely has observations above 100 mm, which is consistent with the lower elevations of their locations, which would receive lower precipitation compared with the higher-elevation SNOTEL sites.

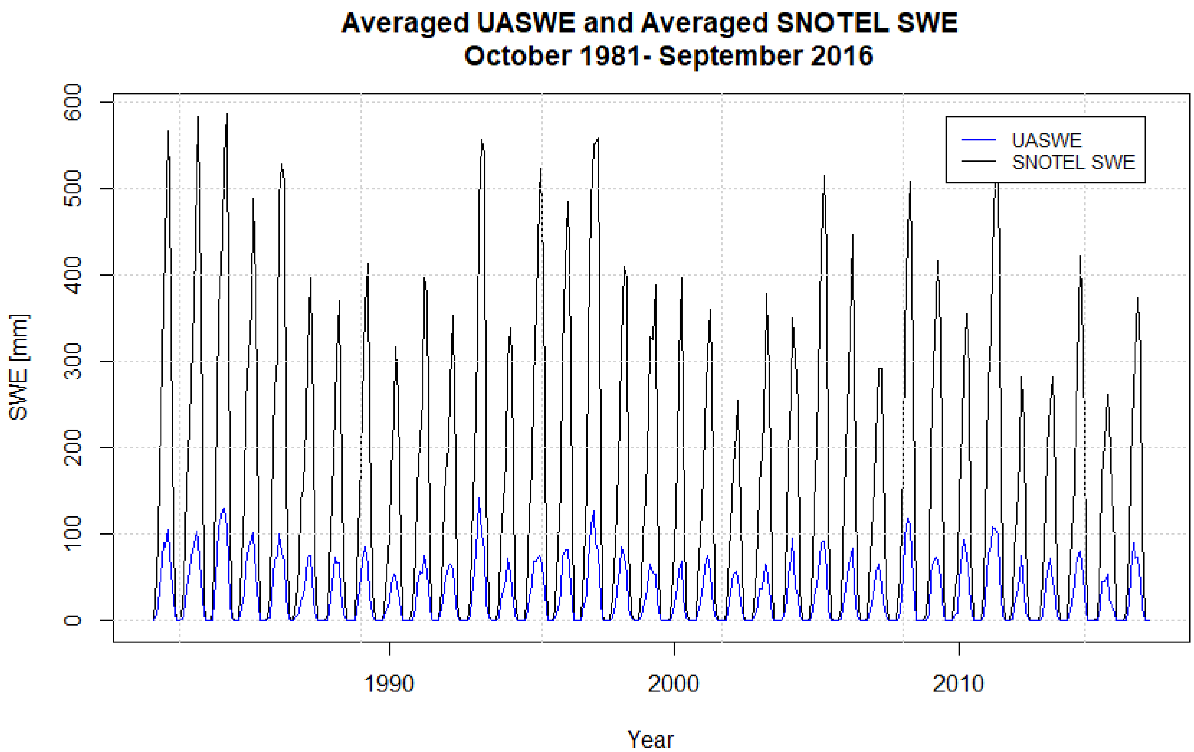

Figure 11. Difference between averaged UASWE and averaged SNOTEL SWE 1981-2016

Table 1 shows the lags of UASWE up to 12 months, and naturalized flow up to 12 months. Table 2 shows the lags of averaged SNOTEL up to 12 months and of naturalized flow up to 12 months. In both tables, a negative lag of SWE means positive lag of naturalized flow. In both tables, lags up to three months are highlighted in green to show the lags used in Figure 7, Figure 8, and Figure 9.

Table 1. Lags for averaged SNOTEL

Averaged SNOTEL	
SWE Lag [month]	Pearson Correlation Coefficient
-12	0.13
-11	0.55
-10	0.7
-9	0.59
-8	0.36
-7	0.1
-6	-0.15
-5	-0.36
-4	-0.48
-3	-0.51
-2	-0.46
-1	-0.24
0	0.24
1	0.7
2	0.82
3	0.67
4	0.42
5	0.14
6	-0.12
7	-0.34
8	-0.47
9	-0.5
10	-0.44
11	-0.23
12	0.18

Table 2. Lags for averaged UASWE

Averaged UA	
SWE Lag [month]	Pearson Correlation Coefficient
-12	-0.02
-11	0.37
-10	0.66
-9	0.7
-8	0.52
-7	0.21
-6	-0.1
-5	-0.33
-4	-0.46
-3	-0.51
-2	-0.47
-1	-0.3
0	0.07
1	0.5
2	0.77
3	0.79
4	0.59
5	0.26
6	-0.07
7	-0.32
8	-0.45
9	-0.5
10	-0.46
11	-0.29
12	0.03

Discussion

The significant aspect to note of the time series of flow in the Colorado River is that there are three distinct periods of flow which can be seen in both Figures 2 and 3. Figure 2 shows the naturalized flow for the entirety of the record of measurements taken at Lee's Ferry with the 5-year moving average, and Figure 3 shows the flow anomalies and the 5-year moving average over this same period. The first period is a period of relatively high flow which extends from the beginning of the record to the mid to late 1920s. The five-year moving average of flow anomaly in these years is consistently positive and only dips to negative anomaly on occasion. The second distinct period of flow starts in the late 1920s and continues through about 1980, and is a period of relatively low flow, characterized by consistently negative flow anomalies which can be seen in Figure 3. In particular, notice that in Figure 3, the 5-year moving average for flow anomalies hovers slightly below 0 starting in the late 1920s. Three of the five most negative flow anomaly records occur during this period. The third period of flow occurs from the early 1980s until the end of the study period. In this period, flow is the most sporadic. There are three months of flow where the anomalies are at their most positive since the first period of flow, yet there are also two months where flow anomalies are more representative of the second period of low flow. The five-year moving average over this time also exhibits a maximum and two local minima.

The highly variable trends discussed in the previous paragraph can be explained through analysis of the SWE. Figure 4 shows the monthly cumulative SWE from 1981-2016, and Figure 5 shows the five-year moving averages of SWE and naturalized flow. The most distinct feature which can be observed in Figure 5 is that the five-year moving averages of the two datasets vary almost identically. SWE clearly leads naturalized flow: a short time after a peak in SWE, there follows a peak in naturalized flow. However, a better view of the relation between SWE and naturalized flow can be seen in Figure 6 which shows both variables plotted over that time span. The abnormally high flow years in the 1980s which led to a peak in the five-year moving average of naturalized flow coincide nicely with very high SWE observations. Of the ten highest months for SWE, five of those years are in the 1980s. Figures 5 and 6 most clearly reflect the effect of this consistently high SWE on flow. Other variations in SWE are also reflected in the naturalized flow dataset. Figure 5 most clearly shows the how closely the two datasets vary. This relation was put into more quantifiable terms in Table 1.

Table 1 shows correlation coefficients for successive months of SWE lag. Most months of negative SWE lag show neither a positive nor a negative correlation. Because SWE leads naturalized flow, one might expect to see a negative correlation when naturalized flow is lagged. Instead, there are positive correlation coefficients for the negative SWE lags caused by the yearly cycle of high SWE in the earlier months, and low SWE in later months after the snow melts. However, it does not make physical sense to base SWE estimates on previous years' flow measurements. These correlation coefficients have thus been disregarded for this study. With no lag, there is no correlation between the two variables. A positive correlation can be surmised from the variables by applying a lag of just three months. After three months, the correlation becomes weaker. By comparing the lagged data with correlation coefficients of the averaged SNOTEL data, it can be seen that the two datasets have a similar capacity for predicting naturalized flow at Lee's Ferry. At one- and two-month lags, the SNOTEL correlation is higher. The SNOTEL correlation coefficient for a two month lag is actually the highest correlation coefficient that was found from each dataset. The three-month lag, however, is where the UASWE dataset outperforms SNOTEL and most effectively displays its potential for predictive capability.

The strongest positive correlation is associated with the averaged SNOTEL dataset because SNOTEL observations are made at elevations where snowpack may be more conducive to flow in the river. The lowest elevation of the SNOTEL sites used in this study was 7440 feet (almost 2300 meters), and the highest was 11600 feet (~3500 meters). The spatial average for the UASWE product was computed over the entirety of the UCRB where there are many more points where the elevation is lower than the lowest SNOTEL site. These lowest areas are the main contributors to the red line in Figure 10 which shows the 25th percentile of the UASWE product. Mean UASWE is lower than mean SNOTEL SWE. The peak of SNOTEL SWE is consistently more than twice the value of the peak of UASWE. Even in Figure 10, the 75th percentile of UASWE does not come close to approximating the SNOTEL SWE observations. The SNOTEL SWE average is driven by sites in the highest elevations in the UCRB.

Conclusions and Future Research

SWE leads flow in the UCRB: peaks in flow during the study period coincide with peaks in SWE which occurred up to three months before. This observation may be made over the entirety of the flow record. Yet, it would be haphazard to say there is a general trend in flow over the study period or the flow record at Lee's Ferry. Flow can be represented in three distinct, sequential periods related to the flow anomaly, but an overall trend cannot be established. At the beginning of the record, there was relatively high flow (1906 to late 1920s), low to average flow in the middle of the record (late 1920s through about 1980), then most recently (early 1980s until 2016) there was a period of flow that exhibits traits characteristic of each of the two previous periods of flow. The somewhat sporadic variation of flow in the 35-year time period is reflected strongly in the time series of SWE. Both the five-year moving average and unaveraged SWE data show this variation. Results from correlations of the two variables further supports this with strong positive correlations at seasonal time scales. The UASWE product correlates with naturalized flow in the river about as strongly as averaged SNOTEL SWE. The averaged UASWE product has a stronger correlation only at a three-month lag, but this may be improved to a stronger correlation by restricting observations to similar elevations which contribute a greater amount to flow.

Further investigation into the relation of the UASWE product with flow will be instrumental to constructing more accurate flow measurements of the Colorado River. Because the UASWE dataset is a spatially-continuous dataset, it can offer a more complete view of actual snow conditions in the UCRB. It will be necessary to analyze the strength of the lagged correlations of UASWE at different elevation bands to ascertain which areas contribute most to flow.

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