El Niño Southern Oscillation Influences on Precipitation, Discharge, and Nutrient Concentrations in the Upper Salt River Watershed in Arizona

by

Darren Sversvold

A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science

Approved April 2012 by the
Graduate Supervisory Committee:

Susanne Neuer, Chair
James Elser
Eli Fenichel

ARIZONA STATE UNIVERSITY

August 2012

ABSTRACT

Many studies over the past two decades examined the link between climate patterns and discharge, but few have attempted to study the effects of the El Niño Southern Oscillation (ENSO) on localized and watershed specific processes such as nutrient loading in the Southwestern United States. The Multivariate ENSO Index (MEI) is used to describe the state of the ENSO, with positive (negative) values referring to an El Niño condition (La Niña condition). This study examined the connection between the MEI and precipitation, discharge, and total nitrogen (TN) and total phosphorus (TP) concentrations in the Upper Salt River Watershed in Arizona. Unrestricted regression models (UMs) and restricted regression models (RMs) were used to investigate the relationship between the discharges in Tonto Creek and the Salt River as functions of the magnitude of the MEI, precipitation, and season (winter/summer). The results suggest that in addition to precipitation, the MEI/season relationship is an important factor for predicting discharge. Additionally, high discharge events were associated with high magnitude ENSO events, both El Niño and La Niña. An UM including discharge and season, and a RM (restricting the seasonal factor to zero), were applied to TN and TP concentrations in the Salt River. Discharge and seasonality were significant factors describing the variability in TN in the Salt River while discharge alone was the significant factor describing TP. TN and TP in Roosevelt Lake were evaluated as functions of both discharge and MEI. Some significant correlations were found but internal nutrient cycling as well as seasonal stratification of the water column of the lake likely masks the true relationships. Based on these results, the MEI is a useful predictor of discharge, as well as nutrient loading in the Salt River Watershed through the Salt River and Tonto Creek. A predictive model investigating the effect of ENSO on nutrient loading through discharge can illustrate the effects of large scale climate patterns on smaller systems.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 Introduction

The El Niño Southern Oscillation (ENSO) is one of the most recognized patterns used by climatologists to make weather predictions. The terms used to describe the state of ENSO, mostly El Niño or La Niña, refer generally to whether the ocean temperature in the Eastern Tropical Pacific is above (El Niño) or below (La Niña) the average temperature. The effects of an above or below average sea surface temperature, coupled with a sea level pressure differential (measured between Tahiti and Darwin, Australia as the Southern Oscillation Index, or SOI), result in oceanic/atmospheric interactions that affect precipitation in both the eastern and western Pacific Ocean (Trenberth 1997). Variation in precipitation resulting from these ocean-born factors affect streamflow patterns observed on land (Chiew and McMahon 2002, Hamlet and Lettenmaier 1999, Kahya and Dracup 1994).

Many studies over the last two decades have examined the link between climate patterns and hydrology. Recent research has shown that the effects of a global climate pattern such as ENSO can be observed regionally on precipitation and streamflow (Araghinejad *et al.* 2006, Cayan *et al.* 1999, Chiew and McMahon 2002, Dettinger *et al.* 2003, Hamlet and Lettenmaier 1999, Kahya and Dracup 1994, Karamouz and Zahraie 2004, Pagano and Garen 2005, Piechota and Dracup 1999, Rajagopalan *et al.* 1998, Reynolds *et al.*, 2003). Studies that focus on the Western United States, including the Southwest, found that El Niño (La Niña) conditions are associated with increased (decreased) precipitation and streamflow in the Southwest (Northwest) (Cayan *et al* 1999, Dettinger *et al.* 2003, Dubrovsky *et al*. 2010, Hamlet and Lettenmaier 1999, Kahya and Dracup 1994, Karamouz and Zahraie 2004, Pagano and Garen 2005, Piechota and Dracup 1999, Rajagopalan *et al.* 1998). While the effects of the ENSO are seen for precipitation, they are magnified to an even greater degree for streamflow (Dettinger *et al.* 2003, Reynolds *et al.*, 2003).

The warm phase of ENSO (El Niño) has an effect on both duration and frequency of winter storms in the Southwest (Dettinger *et al*. 2003, Reynolds *et al.* 2003). In contrast, La Niña conditions were found to produce less intense precipitation events of shorter duration. Thus, classifying the state of the ENSO as either an El Niño or La Niña condition does not explicitly imply either a wet or dry condition, but instead indicates a relative change versus a neutral state. Reynolds *et al.* (2003) also found that ENSO has a greater effect on streamflow than precipitation; the enhanced discharge lasts longer than the winter precipitation because of the lag in snowmelt. Soil moisture buildup has a nonlinear effect on runoff, meaning that moist soil results in more discharge than dry soil, which absorbs more water (Ellis *et al.* 2008).

Cayan *et al*. (1999) found that during El Niño conditions there was a higher frequency of days with increased precipitation and streamflow in the Southwestern United States (compared to La Niña conditions). Prescott, Arizona was chosen as a representative location in the Southwestern United States to analyze the impacts of ENSO on storm events and streamflow. Although Prescott is not located in the Salt River Watershed, it is located in the Verde River Watershed, and the two discharges of both rivers were found to be highly correlated in a study forecasting discharge for both the Salt and Verde Rivers (Ellis *et al.* 2008). With the close connection between precipitation and discharge, the discharge effects due to precipitation are likely very similar between the Salt and Verde Watersheds. Karamouz and Zahraie (2004) found that the connection between ENSO and snow budget was a useful tool in forecasting streamflow on the Salt River Basin in Arizona.

ENSO indices have been used to predict discharge patterns more than a year in advance (Piechota and Dracup 1999). The magnitude and state of the ENSO can be used to make climate and discharge predictions for the purpose of managing water resources in the Southwestern United States (Cayan *et al*. 1999, Dettinger *et al*. 2003, Kahya and Dracup 1994, Karamouz and Zahraie 2004, Rajagopalan *et al.*

1998). Water resource managers such as the Salt River Project (SRP) commission require such climatic and hydrologic models to use as tools to plan for future water supply and demand (Pagano and Garen, 2005).

Climate patterns have also been used to forecast streamflow (Araghinejad *et al.* 2006, Cayan *et al.*1999, Kahya and Dracup 1994, Karamouz and Zahraie 2004, Piechota and Dracup 1999, Reynolds *et al.* 2003) but few studies have attempted to directly examine the effects of a global climate mode such as the El Niño Southern Oscillation (ENSO) on watershed specific nutrient loading (Dubrovsky *et al*. 2010, Keener *et al*. 2010). In one such study, Keener *et al.* (2010) examined the state and magnitude of the ENSO and its effects on precipitation, discharge, and nitrate loading in the Little River Watershed (LRW) in Georgia. Wavelet analyses were used to evaluate the teleconnections of the NINO 3.4 index (an index of sea surface temperature in the tropical Pacific) and of precipitation, stream flow, and nitrate loads. Strong correlation was observed between the ENSO and nitrate loading in the LRW. Another example is a study published by the United States Geological Survey (Dubrovsky *et al*. 2010, p.39) stating that nutrient concentrations respond to "short-term and longer-term temporal changes in streamflow".

The purpose of this investigation is to examine the associations of ENSO with hydrologic patterns, as well as the relationship between ENSO and nutrient concentrations in the Upper Salt River Watershed. If ENSO affects discharge patterns, and discharge patterns affect nutrient concentrations, then the teleconnection between climate patterns and nutrient loading in a watershed may be characterized. Finding such connections is potentially important because sampling on a frequent basis is cost and personnel intensive, (Tarrant *et al.* 2010). In this case this would mean having the ability to make a probabilistic prediction of nutrient loading into Roosevelt Lake based on ENSO.

The relationship between discharge and nutrient loading for the Upper Salt River watershed was explored in a study thirty years ago by the Arizona Department of Health Services (ADHS 1981). Nitrogen (N) and phosphorus (P) levels for the Upper Salt River Basin were examined along with discharge data. The goal was to establish water quality standards for nitrogen and phosphorus to protect Roosevelt Lake from eutrophication. The study found that N and P loads varied differently with regard to high and low flow conditions as well as by season and tributary. During high flow periods or flood events, both N and P concentrations increase over concentrations measured at base flow, with significant correlation between nutrient levels and stream flow (Fisher and Minckley 1978). It was suggested that desert washes accumulated nitrate supplied by leaching from surrounding slopes. This nitrate is then washed downstream during flood events. The combination of nitrate storage in dry river sediments washed into the watershed during flood events complicates the understanding of the nutrient regime in the Upper Salt River Watershed and a direct flow and nutrient supply relationship is not easily established. Ephemeral streams load nitrate into different parts of the watershed at different times and the flow regime is further complicated by localized thunderstorms in the summer and heavy runoff in the spring and winter. External P loading into Roosevelt Lake is mostly from land sources upstream of the lake and deposited through runoff from the tributaries, mainly the Salt River (U.S. EPA 1977).

In the Southwest, localized summer storms that do not produce large runoff events can still flush significant amounts of nutrients into the watershed (ADHS 1981). This complicates efforts to assess the correlation between discharge and nutrient dynamics. It is possible to have a low discharge associated with an increased load if the concentration of a nutrient is elevated. It was shown in the Salt River that nutrient concentrations may not only be high during flood events, but also in summer when flows are at or near base flow (ADHS 1981). Therefore, the effects of winter versus summer precipitation on stream flow, and ultimately nutrient loading, must be recognized when attempting to investigate the effects of climate variability (in the form of precipitation) on watershed nutrient loading in an arid or semi-arid environment such as the Upper Salt River Watershed.

Further, understanding how climate affects discharge, and ultimately nutrient loading, could help determine best management practices (BMPs) to help protect the lake from eutrophication. Studying both N and P is important because lake primary productivity responds to enrichment of N and P, especially in combination (Elser *et al.* 2007). With greater stress on water quantity as well as quality, the ability to forecast supply (Cayan *et al.* 1999, Pagano and Garen 2005), as well as water quality are now more important than ever (Dubrovsky *et al*. 2010, Keener *et al*. 2010). In fact, the most important factors determining the rate of removal of N from streams (denitrification) is discharge volume and rate of transformation of N from one form to another (Scott *et al* 2007). During peak runoff season in winter, discharge volume of the Salt River is determined by winter precipitation (Ellis *et al*. 2008). Large flooding events such as ones in the winter of 2005 were associated with a strong El Niño. The magnitude of this El Niño event could have been used as a predictive tool for the strong precipitation that resulted in high flood events in the Salt River and Tonto Creek.

My hypothesis is that variation in the ENSO affects precipitation, discharge, and nutrient concentrations in the Upper Salt River Watershed. Based on this hypothesis, my predictions are: (1) discharge volumes on the Salt River and Tonto Creek will show significant correlation with precipitation and the ENSO, (2) nitrogen and phosphorus concentrations measured in the Upper Salt River watershed will be significantly correlated with discharge volumes of the two tributaries, and (3) nitrogen and phosphorus concentrations measured in the Upper Salt River watershed will be significantly correlated to the ENSO.

2.0 Methods

2.1 Study Area

The Salt River in Central Arizona contains a series of dams that form reservoirs used to store water for use downstream by residential and commercial customers in metropolitan Phoenix. The first (highest) and largest lake in the system is Roosevelt Lake with a maximum storage capacity of more than 1.65 million acre feet (SRP 2012). The discharge into Roosevelt Lake is directly from precipitation and runoff and is not subject to the influence of any dams upstream. Roosevelt Lake has two major inflow tributaries: Tonto Creek from the northern end and the Salt River from the southern end (Fig. 1). The Salt River has an annual runoff of 638,800 acre feet while Tonto Creek has an annual runoff of 111,100 acre feet (USGS Water-data Reports 2010). Lake residence time is estimated at 2.2 years (1.65 million acre feet / 749,000 acre feet annual runoff). While the Salt River provides approximately to 85% of the water supply to Roosevelt Lake (based on annual runoff totals), Tonto Creek experiences flood events similar in magnitude to the high flood events on the Salt River (USGS Water-data Reports 2010). Algal blooms occur in Roosevelt Lake in both late winter and early spring, and again in summer (Tarrant and Neuer 2009).

I included three lake sample sites and one stream (river) sample site in this study (Figure 1). Water quality sample sites are located both upstream of the lake on the Salt River and on the lake itself. The United States Geological Survey (USGS 2011) has a gage station measuring discharge on each tributary (Salt River Station 09498500 and Tonto Creek Station 09499000). The Salt River gage station is also a water quality sampling site with samples collected and analyzed by the USGS.

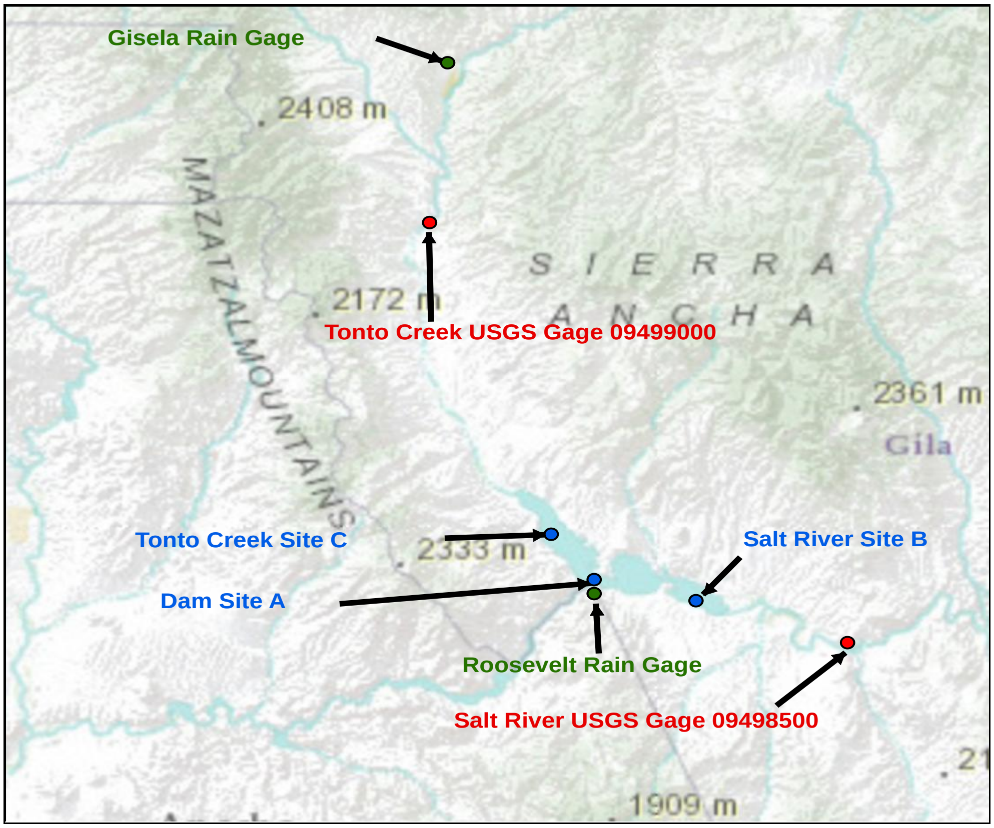

Figure 1. Map of Sample Sites, Rain Gages, and USGS Gage Stations.

2.2 ENSO Indices

ENSO conditions can be described as El Niño, La Niña, or neither (neutral). An El Niño (La Niña) condition is associated with warmer (cooler) sea surface temperature (SST) in the Eastern Tropical Pacific Ocean (NOAA 2011) vs the average monthly temperature (average SST). This increase or decrease in SST coupled with a sea surface pressure (SSP) differential between Tahiti and Darwin, Australia, results in oceanic/atmospheric circulation. The differences in SST and SSP and their effects on the atmospheric weather patterns is called the ENSO (Trenberth 1997). In brief, an El Niño condition is associated with warmer SSTs in the Eastern Tropical Pacific Ocean and a negative pressure difference between air pressure in Tahiti and Darwin, Australia quantified by the Southern Oscillation Index

(SOI). The SOI is calculated using the SSP difference between Tahiti and Darwin. El Niño (La Niña) is associated with a negative (positive) SOI, or higher pressure measured in Darwin vs. Tahiti.

The Multivariate ENSO Index (MEI) (NOAA 2011) is an index derived from observed conditions of the tropical Pacific Ocean, and is calculated based on sea-level pressure, surface wind, sea surface temperature (SST), surface air temperature, and cloudiness. The MEI is a numerical value of relative magnitude (no units) used to describe the state of the ENSO, with positive values referring to an El Niño condition (warm phase), and negative values referring to a La Niña condition (cool phase). MEI values of higher relative magnitude describe greater magnitude of the state of either an El Niño or La Niña condition and are published by NOAA on its website (NOAA 2011).

The MEI and SOI are negatively correlated with correlation coefficients for the two time series ranging from -0.7 to -0.85 (Chiew and McMahon 2002). An El Niño condition is associated with a positive MEI and a negative SOI. Both indices have been used in previous studies to assess the state of ENSO as an El Niño or La Niña condition. The MEI is used in this study because it is calculated using SST and SSP as well as other factors while the SOI is calculated based solely on SSP differential. Figure 2 shows the MEI index for the decade beginning in the year 2000.

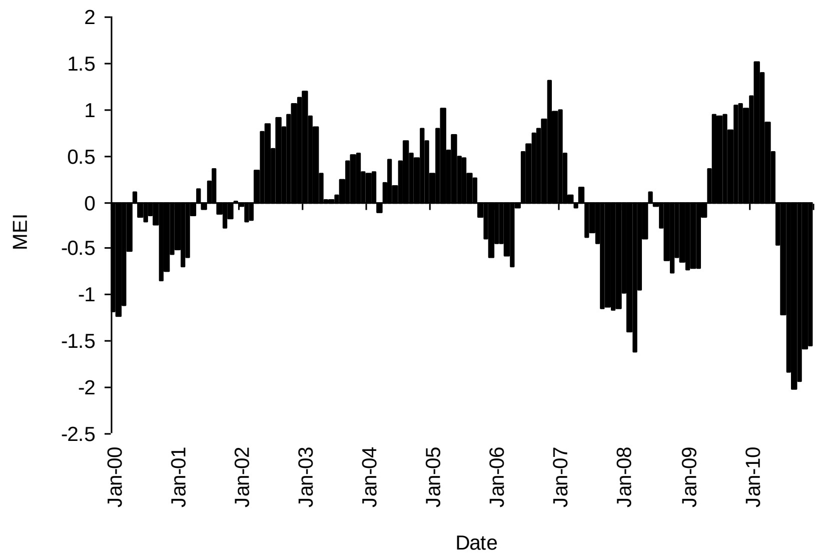

Figure 2. MEI Values for the years 2000 through 2010.

2.3 Precipitation

Precipitation data were obtained from the Western Regional Climate Center website (http://www.wrcc.dri.edu/). Stations for recording precipitation were chosen based on two factors: distance to the USGS gage stations and the period of record. Precipitation amounts were obtained for climate stations Roosevelt 1 WNW, AZ (027281) and Gisela, AZ (023448) (WRCC 2010). The Gisela Rain Gage is above Roosevelt on Tonto Creek and the Roosevelt Lake Rain Gage is near the Roosevelt Lake Dam (Figure 1). Winter rain storms are generally longer in duration and greater in strength than summer storms (Ellis *et al.* 2008) while summer monsoon storms are scattered and more localized compared to winter storms (ADHS 1981). Figure 3 shows the total monthly precipitation measured at the climate stations from 2000 through 2010. Precipitation recorded at the Gisela Rain Gage regularly exceeded precipitation recorded at the Roosevelt Rain Gage.

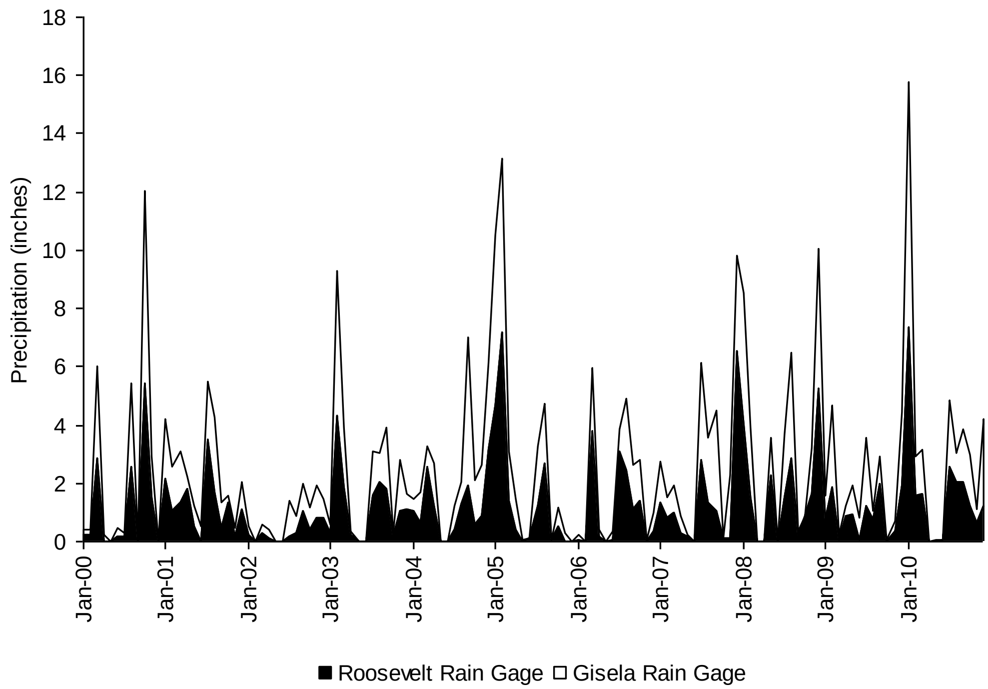

Figure 3. Total Monthly Precipitation (inches) at Roosevelt and Gisela Climate Stations. Time series of total monthly precipitation for period 2000 to 2010. Record from Western Regional Climate Center.

2.4 Discharge Measurements

Discharge data for both large tributaries, the Salt River and Tonto Creek, were analyzed in order to characterize the discharge into Roosevelt Lake. Discharge (Q) data which are expressed in cubic feet per second (cfs) were obtained from USGS (USGS Water-Data Reports 2010, and USGS Water Watch webpage, http://waterwatch.usgs.gov/new/?m=real&r=az&w=map). These records helped determine which months should be considered peak discharge months (winter) and non-peak discharge months (summer). Based on maximum daily means for any given month throughout the hydrologic record, the peak discharge months were determined to be December through May, with non-peak months June through November. There is also a summer peak discharge in August for each tributary. Peak discharge does not necessarily always correspond with peak precipitation due to the effects of temperature and soil moisture on evapotraspiration (Ellis *et al.* 2008). Therefore, some degree of signal loss is expected between precipitation and discharge. The measured discharges (maximum daily mean for each month) from 2000 to 2010 are shown in Figure 4.

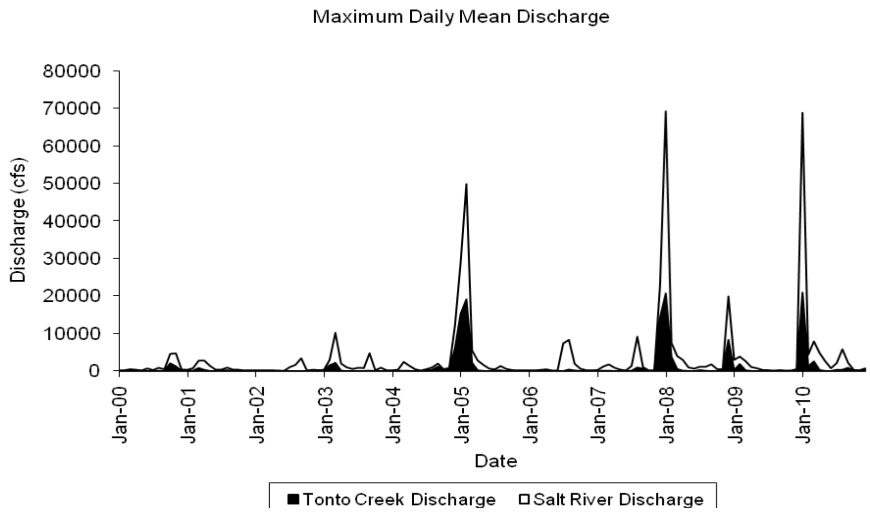

Figure 4. Maximum Daily Mean Discharge (cfs) for Salt River and Tonto Creek (cfs). Time series for Salt River and Tonto Creek discharges for period 2000-2010 taken from USGS records.

The peak discharge months for the tributaries are shown in Tables 1 and 2. The annual means for Tonto Creek and the Salt River are 153 and 882 cfs (respectively), based on the total period of record for each USGS gage station.

Table 1. Monthly Discharge Statistics (cfs) for Salt River USGS 09498500. Monthly mean discharge statistics for the period 1913 to 2010. Water Year (WY) is the year the maximum or minimum flow was recorded for each month in the record.

STATISTICS OF MONTHLY MEAN DATA FOR WATER YEARS 1914 - 2010, BY WATER YEAR (WY)												
	Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
Mean	411	369	734	1,107	1,400	1,970	1,928	989	348	322	592	445
Max	4,832	2,150	6,327	15,990	9,072	10,390	6,281	5,933	1,365	3,276	3,607	1,852
(WY)	1984	1920	1966	1916	1980	1978	1979	1973	1941	1919	1921	1923
Min	85.5	122	127	161	161	179	164	110	74.6	78.3	119	77.9
(WY)	1957	1957	1957	1964	2006	2002	2002	2002	2002	1963	2009	1956

Source: USGS Water Data Report 09498500 Salt River near Roosevelt, AZ

Table 2. Monthly Discharge Statistics (cfs) for Tonto Creek USGS 09499000. Monthly mean discharge statistics for the period 1940 to 2010. Water Year (WY) is the year the maximum or minimum flow was recorded for each month in the record.

STATISTICS OF MONTHLY MEAN DATA FOR WATER YEARS 1941 - 2010, BY WATER YEAR (WY)												
	Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
Mean	52.7	64.2	231	359	381	451	152	43	12.8	21.4	84.4	41
Max	1,053	438	2,326	4,272	4,191	4,159	1,040	488	94.9	207	1,091	626
(WY)	1973	1973	1966	1993	1980	1978	1941	1941	1955	1955	1951	1970
Min	0	0.31	7.23	9.3	9.24	7.69	5.87	0.95	0	0	0	0.71
(WY)	2003	2003	2003	2002	2002	2002	2002	2002	1996	2000	2009	2009

Source: USGS Water Data Report 09499000 Tonto Creek above Gun Creek, Near Roosevelt, AZ

2.5 Water Quality Data

Surface water samples for Roosevelt Lake have been collected by several government agencies including (mostly) but not limited to the Arizona Department of Environmental Quality (ADEQ), the United States Geological Survey (USGS), and the Arizona Game and Fish Department (AGFD). Data from ADEQ and AGFD are stored in ADEQ's electronic water quality data base. Data are public and can be accessed by request from ADEQ's librarian. Data collected by the USGS were accessed through their website (http://waterwatch.usgs.gov/new/?m=real&r=az&w=map).

Water quality standards of 0.50 mg/L Total Nitrogen (TN) (annual mean) and 0.10 mg/L Total Phosphorus (TP) (annual mean) were established for Tonto Creek by the Arizona Department of Environmental Quality (ADEQ) (A.A.C. R18-11-109 Section F) to protect Roosevelt from excess nutrient loading and eutrophication. The corresponding standards for the Salt River are 0.60 mg/L TN and 0.12 mg/L TP. These standards were first recommended by the Arizona Department of Health Services (ADHS) in 1981. Both perennial and ephemeral tributaries upstream of Roosevelt Lake deposit N loads downstream and into the lake. External P loading into Roosevelt Lake is mostly from land sources upstream of the lake and is deposited through runoff from the tributaries, mainly the Salt River (U.S. EPA 1977).

Nutrient data from three sites in Roosevelt Lake were analyzed to determine whether there are correlations among nutrient concentrations (TN and TP), discharge and the ENSO. Sample sites were selected for their proximity to the two tributaries into Roosevelt Lake as well as one site at the dam that represents a mix of both tributaries' loads: site A (dam), site B (Salt River arm of the lake), and site C (Tonto Creek arm of the lake). Samples for sites A and B that were taken immediately following the Rodeo-Chedeski Fire were not included due to high nutrient loading resulting from runoff in burned areas. TN concentrations of >200 mg/L and TP concentrations of >100 mg/L were observed following the fire (USGS 2011).

Water quality sampling frequency varied from 1-8 times per year and sampling was spread over different seasons. Most samples were collected in winter, spring, and summer with only four sample events recorded in the fall. N and P data used in this study were taken from samples collected from the photic zone of the water column. TN and TP data for the three lake sites from 2000-2009 are shown in Figures 5 and 6 (respectively).

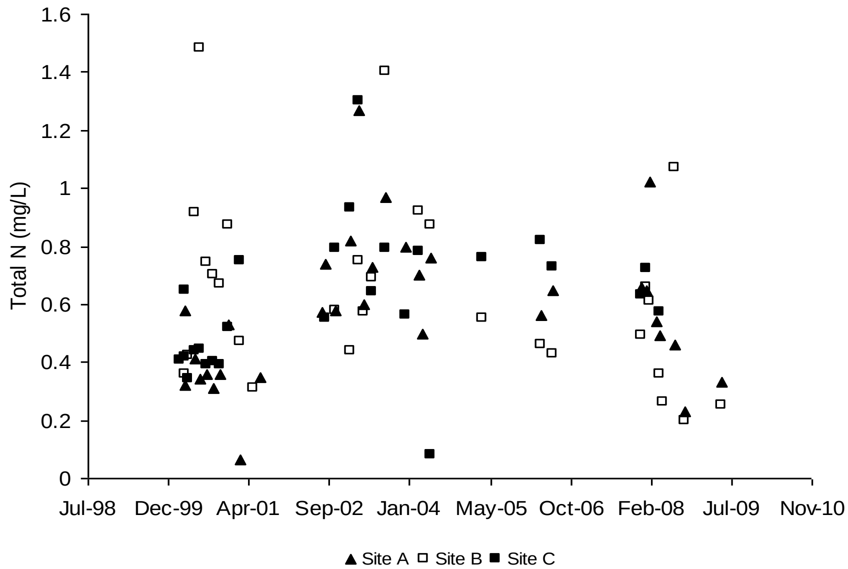

Figure 5. Total Nitrogen concentration (mg/L) for Roosevelt Lake sample sites A, B, and C in mg/L. Sample sites are site A (dam), site B (Salt River arm of the lake), and site C (Tonto Creek arm of the lake).

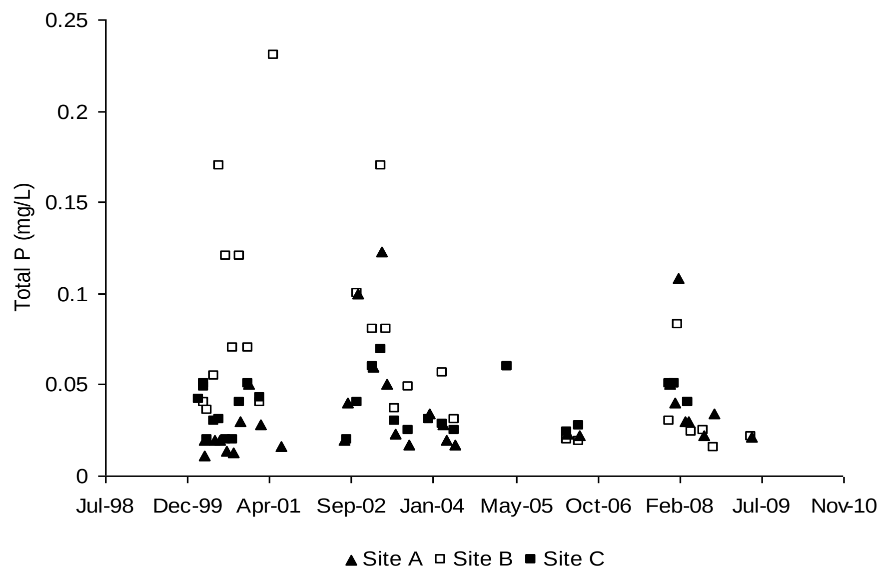

Figure 6. Total Phosphorus concentrations (mg/L) for Roosevelt Lake at sample sites A, B, and C. Sample sites are site A (dam), site B (Salt River arm of the lake), and site C (Tonto Creek arm of the lake).

Water quality data (TN and TP) from the USGS for the Salt River were also used in the analysis. This data set has been active since 1976. Although discharge measurements are still recorded at the USGS Tonto Creek gage, water quality measurements were discontinued in 1992 and not used here for comparison. The USGS site on Tonto Creek has a very small water quality data set and is no longer active.

TN and TP concentration measurements (mg/L) for the Salt River site are shown in Figure 7. Sample frequency was high from 1976 to 1981 with 8 to 13 samples per year. From 1982 through 2011 sampling frequency dropped to 0 to 4 samples per year. Years without sample data for N or P were 1983, 1991, 2000, 2002, and 2009. There were 105 samples (data points each, for N and P) for the period from 1976 through 2011.

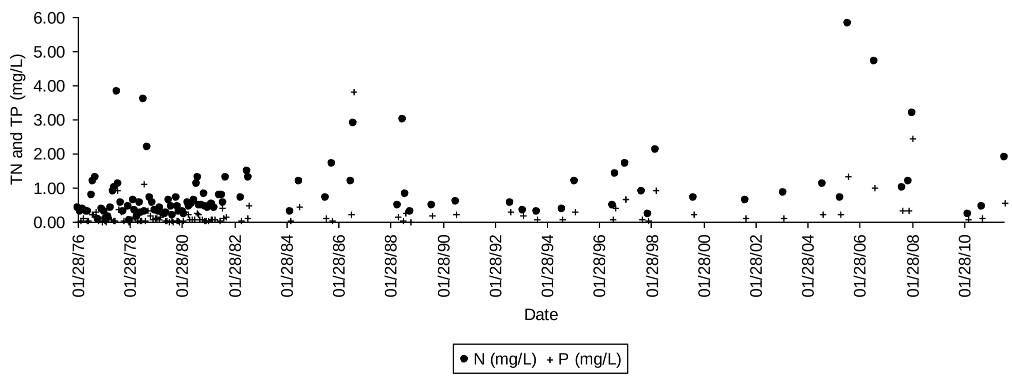

Figure 7. Total Nitrogen and Total Phosphorus at Salt River USGS Gage. Units are mg/L.

2.6 MEI, Precipitation and Discharge Data

Data were split into categorical events by season and sign of the MEI. The categories were winter El Niño, winter La Niña, summer El Niño, and summer La Niña. The winter season was considered from December through May while the summer season was considered from June through November. The seasons were chosen in this manner to capture peak discharge in the winter season from winter storms in the watershed. This assignment is based on the USGS water-data report (USGS 2010) that shows December through May as a continuous period with the highest maximum monthly mean flows. Note that a neutral condition, which has been considered in some studies to be a state where the magnitude of the MEI index was less that 0.5, was not labeled as such in this study. Some studies have classified events below a certain magnitude of the index as neither El Niño nor La Niña but as a neutral state (Dettinger *et al*, 2003). For ease of convention the state of the ENSO was assessed in this study as either El Niño (MEI>0) or La Niña (MEI<0).

To establish if weather and discharge events were correlated, I compared the following variables: MEI and monthly total precipitation, MEI and maximum daily mean discharge (in each month), and monthly total precipitation and maximum daily mean discharge (in each month). It is suggested on the National Oceanic and Atmospheric Administration (NOAA) website (http://www.esrl.noaa.gov/psd/enso/mei/) to use the previous month for the MEI value if making a prediction for precipitation, especially in the Southwestern United States (for month *i* precipitation, use MEI value for month *i-1*). Hence, the MEI values were shifted by one month to allow for this lag in all analyses.

2.7 MEI, Precipitation and Discharge Regression Models

The effects of precipitation, MEI, and season on discharge were evaluated using linear regression. The equation for the general linear regression model is given as: $y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \beta_{1:2} x_{i1} x_{i2} + \beta_3 x_{i3} + \beta_{2:3} x_{i2} x_{i3} + \beta_{1:3} x_{i1} x_{i3} + \varepsilon_i$ for $i = 1,2, \ldots n$, where y_i = natural log of maximum daily mean (for given month) discharge (cfs) , x_{i1} = precipitation, x_{i2} = absolute value of MEI for given month, $x_{i1}x_{i2}$ = interaction between absolute value of MEI and precipitation, x_{i3} = categorical seasonal factor (winter/summer), $x_{i2}x_{i3}$ = interaction between seasonal factor and absolute value of the MEI, $x_{i1}x_{i3}$ = interaction between seasonal factor and precipitation, and ε_i is model deviation (error term, mean zero). This unrestricted model (UM) was used to evaluate the effects of MEI, precipitation, and seasonality on discharges of the Salt River and Tonto Creek. Interaction factors between MEI/season, MEI/precipitation, and precipitation/season were included in the equations.

Following the general model, a restricted linear regression model (RM) was used, restricting all coefficients to zero, except the coefficient for precipitation. The equation for this RM is given as: $y_i = \beta_0 + \beta_1 x_{i1} + \varepsilon_i$ for $i = 1,2, \ldots n$, where y_i = natural log of maximum daily mean (for given month) discharge (cfs), x_{i1} = precipitation and ε_i is model deviation (error term, mean zero). The RM was used to evaluate the effects of only precipitation on discharge, excluding (restricting) MEI and seasonal variables. Both UM and RM were used to determine if the variability of discharge was better explained by a multi-parameter UM vs. a simpler RM. Likelihood ratio test (LRT) of the UM and RM was used to determine if the unrestricted model better explained the variation in discharge vs. the restricted model. The calculated chi-square (X^2) values were compared to the values in the X^2 table for k degrees of freedom (df) (where k=df/UM – df/RM) at the 0.05 significance level. The null hypothesis (H_0) is that the coefficient values in the UM (other than for precipitation) are zero. The alternative hypothesis (H_A) is that the coefficients are not zero.

2.8 Nitrogen and Phosphorus Regression Models for Salt River Site

The effects of discharge and season on TN and TP were evaluated using linear regression. The equation for the general linear regression model is given as: $y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \beta_{1:2} x_{i1} x_{i2} + \varepsilon_i$ for $i = 1,2, \ldots n$, where y_i = nutrient concentration in mg/L, x_{i1} = discharge in cfs, x_{i2} = categorical seasonal factor (winter/summer), $x_{i1}x_{i2}$ = interaction between seasonal categorical factor (winter/summer) and discharge, and ε_i is model deviation (error term, mean zero). This UM was used to evaluate the effects of discharge (Q) and season on TN and TP concentrations measured in the Salt River. For each TN and TP sample on the Salt River, there was a corresponding discharge measurement (coinciding sample time/date).

Following the general model, an RM was used, restricting all coefficients to zero, except the coefficient for discharge. The linear regression for the RM is given as: $y_i = \beta_0 + \beta_1 x_{i1} + \varepsilon_i$ for $i = 1,2, \ldots n$, where y_i = nutrient concentration in mg/L, x_{i1} = discharge in cfs, and ε_i is model deviation (error term, mean zero). The sample period for this site was 1976 to 2011. TN and TP concentrations were also evaluated as functions of the magnitude of the MEI. LRT of the UM and RM was used to determine which model better explained the variation in discharge. The calculated chi-square (X^2) values were compared to the values in the X^2 table for 2 degrees of freedom at the 0.05 significance level. The null hypothesis H_0 is that the coefficient values in the UM (other than for discharge) are zero while the alternative hypothesis- H_A is that the coefficients are not zero.

2.9 Nitrogen and Phosphorus Regression Models for Lake Sites

TN and TP concentrations measured in Roosevelt Lake were used to assess the end point effects of hydrologic external loading of nutrients into the lake using linear regression. The equation for the general linear regression model is given as:

$y_i = \beta_0 + \beta_1 x_{i1} + \varepsilon_i$ for $i = 1,2, \ldots n$, where y_i = TN or TP concentrations in mg/L, x_{i1} = discharge in cfs, and ε_i is model deviation (error term, mean zero). TN and TP concentrations were evaluated as functions of discharge for Roosevelt Lake sites A, B, and C. Total discharge (Salt River and Tonto Creek combined) was used for site A at the dam. Salt River discharge was used for site B in the Salt River arm while Tonto Creek discharge was used for site C in the Tonto Creek arm. Discharge measurements were used for the sample dates corresponding to the dates on which nutrients were collected in the lake. TN and TP concentrations were also evaluated as functions of the MEI using the same general linear regression, with the exception of x_{i1} = absolute value of the MEI instead of discharge.

3.0 Results

3.1 MEI, Precipitation and Discharge at Salt River Gage

Larger precipitation events occurred in association with higher magnitude MEI values in winter (Figure 8). The same relationship was not observed for summer. In addition, increased discharge in winter was associated with higher magnitude MEI values (Figure 9). However, the discharge/MEI relationship did not follow this pattern in summer. Finally, increased precipitation was associated with increased discharge in both seasons (Figure 10).

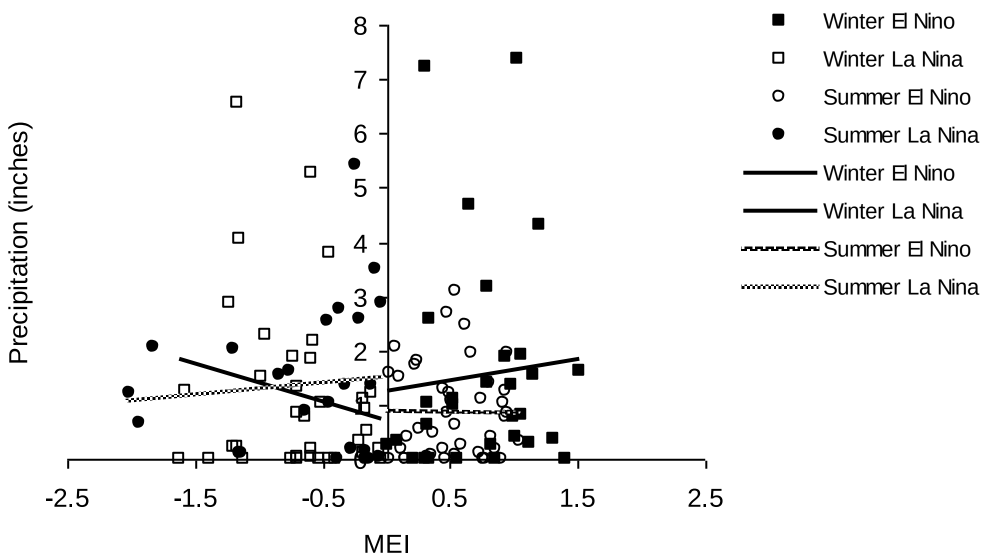

Figure 8. Total Monthly Precipitation at Roosevelt Rain Gage vs. MEI. Total monthly precipitation (inches) measured at WRCC Roosevelt Climate Station and MEI for preceding month. Time period is 2000 to 2010.

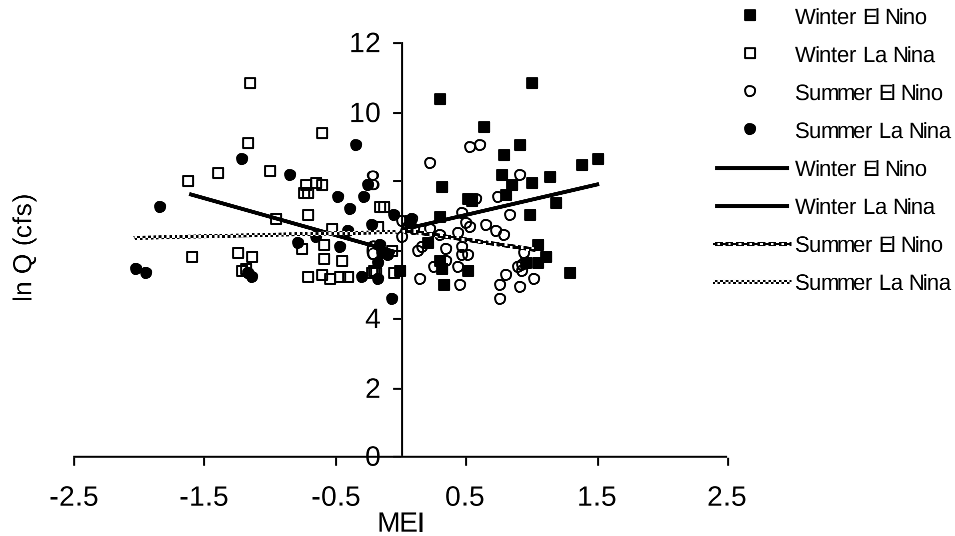

Figure 9. Natural Log of Maximum Daily Mean Discharge of Salt River vs MEI. Maximum daily mean discharge (cfs) (each month) measured at USGS 09498500. Time period is 2000 to 2010.

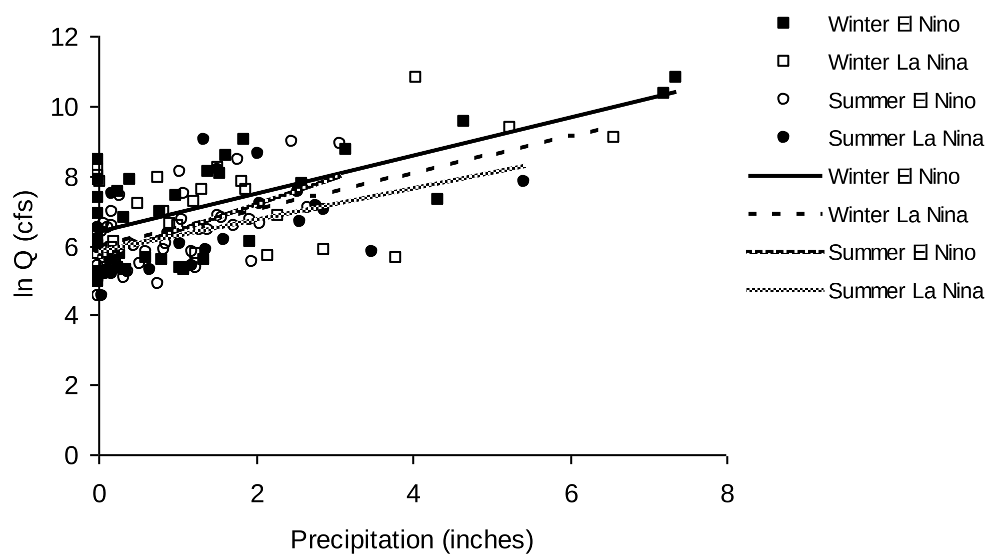

Figure 10. Natural Log of Maximum Daily Mean Discharge of Salt River vs Total Monthly Precipitation for Roosevelt Rain Gage. Discharge measured at USGS 09498500. Precipitation from WRCC Roosevelt Climate Station. Time period is 2000 to 2010.

Both the UM and the RM for the Salt River were statistically significant (Table 3). The results of the LRT comparing the UM and the RM support not rejecting H_0 that the coefficients other than the precipitation coefficient are zero. Therefore, H_0 was not rejected and H_A was rejected.

Table 3. Regression Model Results for Salt River. Dependent variable is natural log of discharge (cfs) for both models. Independent variables are PRECIP (precipitation in inches), MEI (absolute value of MEI) season (winter/summer), MEI/PRECIP (interaction between MEI and precipitation), MEI/season (interaction between magnitude of MEI and season), and PRECIP/season (interaction between precipitation and season).The two regression models are UM including all variables and RM with all coefficients other than discharge held at zero. Adjusted R^2 values were 0.40 (UM) and 0.38 (RM). The LRT of the UM/RM X^2 value was 10.24 compared to the X^2 value 11.07 at 0.05 significance level for 5 degrees of freedom (see hypothesis test section 2.7).

Model	Coefficients:	Estimate(SE)	p-value	R^2
UM	(Intercept)	5.85(0.26)	0.00	0.40
	MEI	-0.18(0.36)	0.61	
	PRECIP	0.55(0.14)	0.00	
	season	-0.18(0.37)	0.63	
	MEI/PRECIP	0.03(0.18)	0.87	
	MEI/season	0.88(0.43)	0.04	
	PRECIP/season	-0.04(0.16)	0.79	
RM	(Intercept)	5.93(0.12)	0.00	0.38
	PRECIP	0.56(0.06)	0.00	

3.2 MEI, Precipitation and Discharge at Tonto Gage

Larger precipitation events occurred during higher magnitude MEI periods in winter (Figure 11). Increased discharge was associated with higher MEI (both El Niño and La Niña) and summer La Niña conditions on Tonto Creek (Figure 12). Increased precipitation was associated with increased discharge in both seasons (Figure 13).

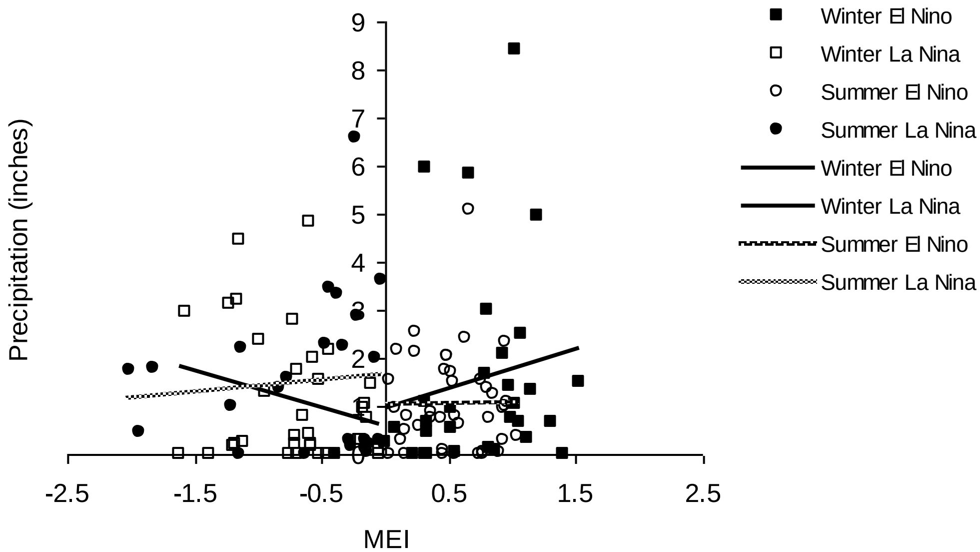

Figure 11. Total Monthly Precipitation at Gisela Rain Gage vs. MEI. Total monthly precipitation measured at WRCC Gisela Climate Station and MEI for preceding month. Time period is 2000 to 2010.

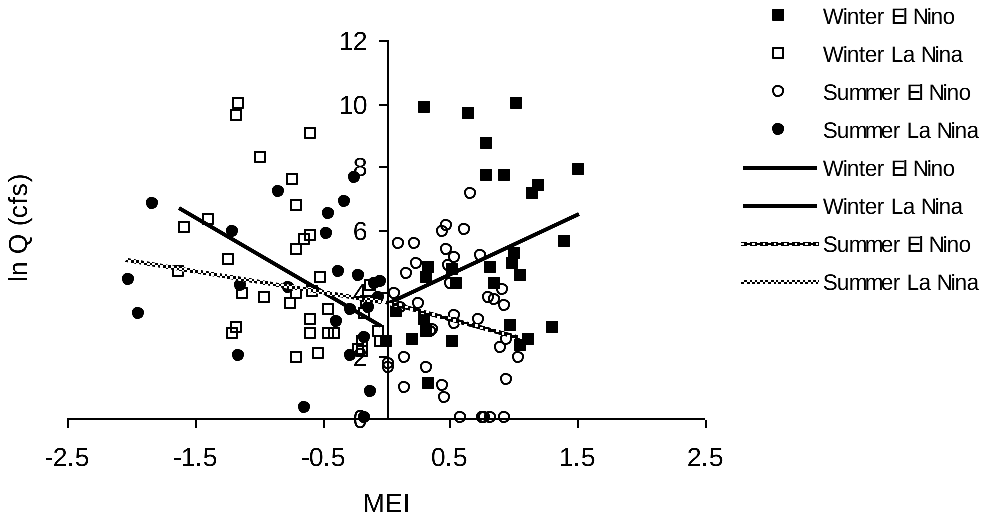

Figure 12. Natural Log of Maximum Daily Mean Discharge of Tonto Creek vs. MEI. Maximum daily mean discharge (per month) measured at USGS 09499000. Time period is 2000 to 2010.

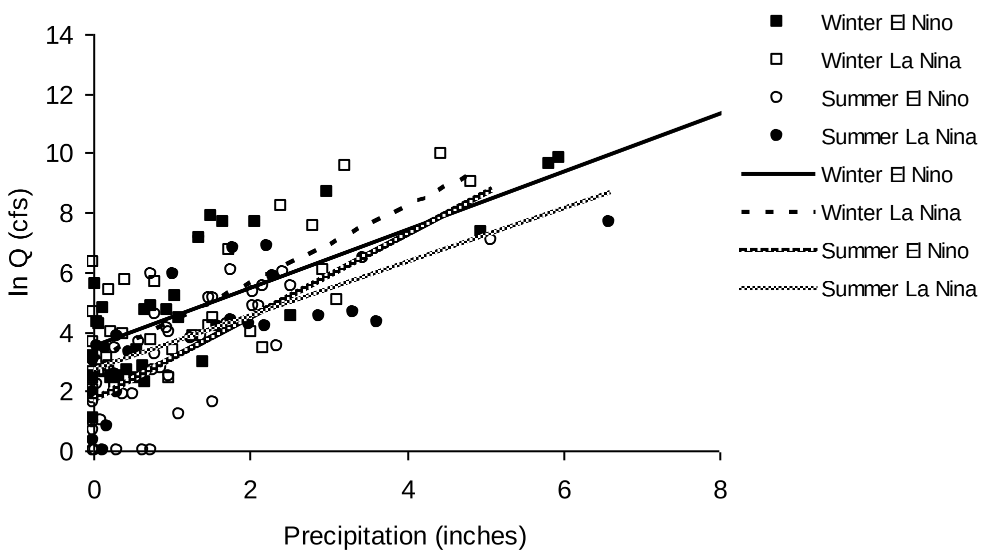

Figure 13. Natural Log of Maximum Daily Mean Discharge of Tonto Creek vs. Total Monthly Precipitation for Gisela Rain Gage. Discharge measured at USGS 09499000. Precipitation from WRCC Gisela Climate Station. Time period is 2000 to 2010.

Both the UM and RM for Tonto Creek were statistically significant (Table 4). The results of the LRT comparing the UM and the RM support rejecting H_0 – thus, the H_A that the coefficients in the UM are not zero is not rejected. Although the MEI/season factor in the UM was not significant as was for the case for the Salt River site (based on p-values), the results of the LRT were that the UM was a better fit than the RM for Tonto Creek.

Table 4. Regression Model Results for Tonto Creek. Dependent variable is natural log of discharge (cfs) for both models. Independent variables are PRECIP (precipitation in inches), MEI (absolute value of MEI) season (winter/summer), MEI/PRECIP (interaction between MEI and precipitation), MEI/season (interaction between magnitude of MEI and season), and PRECIP/season (interaction between precipitation and season). The two regression models are UM including all variables and RM with all coefficients other than precipitation held at zero. Adjusted R^2 values were 0.61 (UM) and 0.53 (RM). The LRT of the UM/RM X^2 value was 29.62 compared to the X^2 value 11.07 at 0.05 significance level for 5 degrees of freedom (see hypothesis test section 2.7).

Model	Coefficients:	Estimate(SE)	p-value	R^2
UM	(Intercept)	1.83(0.37)	0.00	0.61
	MEI	0.51(0.91)	0.46	
	PRECIP	1.19(0.18)	0.00	
	season	0.50(1.01)	0.51	
	MEI/PRECIP	-0.09(0.25)	0.71	
	MEI/season	1.00(0.60)	0.10	
	PRECIP/season	-0.09(0.20)	0.65	
RM	(Intercept)	2.68(0.18)	0.00	0.53
	PRECIP	1.12(0.09)	0.00	

3.3 Nutrients, Discharge, and MEI at Salt River Site

Overall, both TN and TP concentrations were positively correlated with discharge in the Salt River (Table 5). But neither TN nor TP concentrations were significantly correlated with the MEI based on p-values of linear regressions for TN and TP as functions of the magnitude of the MEI.

Both the UM and RM with TN concentration as a function of discharge were statistically significant and both discharge and season were significant factors. The UM better explained variability in TN concentration than did the RM. The results of the LRT comparing the UM and the RM support rejecting H_0 that the coefficients other than the discharge coefficient are zero. $H_{A,}$ that the coefficients in the UM are not zero is not rejected.

TP concentration was also positively correlated with discharge. Both the UM and RM with TP load as a function of discharge were statistically significant. However, neither season nor the interaction factor between discharge and season were significant factors, suggesting that seasonality may not be an important factor when characterizing TP concentration. The results of the LRT comparing the UM and the RM support rejecting the H_0, that the coefficients other than the discharge coefficient are zero. Therefore $H_{A,}$ that the coefficients in the UM are not zero, is not rejected.

Table 5. Regression Results for TN and TP for Salt River. Dependent variables are N.conc (total nitrogen concentration in mg/L) and P.conc (total phosphorus concentration in mg/L). Independent variables are Q (discharge in cfs), season (summer/winter), season*Q (interaction between season and discharge), and MEI (magnitude of MEI). The two regression models are UM including all variables and RM with all coefficients other than discharge held at zero. The LRT X^2 values were 21.85 (N.conc) and 7.48 (P.conc) versus the X^2 value 5.99 at 0.05 significance level for 2 degrees of freedom (see hypothesis test section 2.8).

Model	Coefficients:	Estimate(SE)	p-value	R^2
UM	(Intercept)	$3.37x10^{-1}(1.50x10^{-1})$	0.03	0.19
N.conc	Q	$9.54x10^{-5}(3.19x10^{-5})$	0.00	
	season	$4.42x10^{-1}(2.18x10^{-1})$	0.05	
	season*Q	$6.45x10^{-4}(2.57x10^{-4})$	0.01	
RM	(Intercept)	$7.98x10^{-1}(1.02x10^{-1})$	0.00	0.02
N.conc	Q	$5.74x10^{-5}(3.23x10^{-5})$	0.00	
UM	(Intercept)	$1.69x10^{-2}(7.75x10^{-2})$	0.83	0.15
P.conc	Q	$6.99x10^{-5}(1.64x10^{-5})$	0.00	
	season	$1.62x10^{-1}(1.13x10^{-1})$	0.15	
	season*Q	$1.49x10^{-4}(1.32x10^{-4})$	0.26	
RM	(Intercept)	$1.62x10^{-1}(4.91x10^{-2})$	0.00	0.11
P.conc	Q	$5.73x10^{-5}(1.56x10^{-5})$	0.00	

3.4 Nutrients, Discharge, and MEI at Lake Sites

Regression analyses were done for TN and TP concentrations measured at the lake sample sites as functions of corresponding discharges (Table 6). Concentrations of TN were positively correlated with discharge at Lake Sites A and C. Concentrations of TP were positively correlated with discharge at Lake Site A. Regression analyses were also performed for TN and TP concentrations measured at the lake sample sites as functions of corresponding discharges (Table 6). TP was positively correlated with the magnitude of the MEI at Lake Site A while TN was negatively correlated with the magnitude of the MEI at Lake Site B.

Table 6. Regression results for TN and TP at Roosevelt Lake Sites. Dependent variables (Dep. Var.) and independent variable coefficient estimates with standard error (Estimate(SE)) for each regression are shown. Variables are Q (discharge in cfs), TN (total nitrogen in mg/L), TP (total phosphorus in mg/L), and MEI (magnitude of MEI). Lake sites are A (Dam), B (Salt River arm of lake), and C (Tonto Creek arm of the lake).

Lake Site	Dep. Var.	Coefficient	Estimate(SE)	p-value	R^2
A	TN	Q	$1.32x10^{-4}(5.13x10^{-5})$	0.02	0.15
A	TN	MEI	$1.59x10^{-1}(1.02x10^{-1})$	0.13	0.04
A	TP	Q	$1.93x10^{-5}(5.19x10^{-6})$	0.00	0.30
A	TP	MEI	$3.04x10^{-2}(1.04x10^{-2})$	0.01	0.20
B	TN	Q	$-9.51x10^{-5}(9.67x10^{-5})$	0.33	0.00
B	TN	MEI	$-2.82x10^{-1}(1.23x10^{-1})$	0.03	0.13
B	TP	Q	$9.31x10^{-6}(1.63x10^{-5})$	0.57	0.00
B	TP	MEI	$-1.67x10^{-2}(2.20x10^{-2})$	0.45	0.00
C	TN	Q	$1.25x10^{-3}(2.95x10^{-4})$	0.00	0.39
C	TN	MEI	$1.05x10^{-1}(9.90x10^{-2})$	0.30	0.00
C	TP	Q	$6.31x10^{-4}(9.28x10^{-4})$	0.50	0.00
C	TP	MEI	$3.76x10^{-1}(2.33x10^{-1})$	0.12	0.06

4.0 Discussion

My hypothesis was that variation in the ENSO affects precipitation, discharge, and nutrient concentrations in the Upper Salt River Watershed. Based on this hypothesis, my predictions were: (1) discharge volumes on the Salt River and Tonto Creek will show significant correlation with precipitation and the ENSO, (2) nitrogen and phosphorus concentrations measured in the Upper Salt River Watershed are significantly correlated with discharge volumes of the two tributaries, and (3) nitrogen and phosphorus concentrations measured in the Upper Salt River Watershed are significantly correlated with the ENSO. Statistical analyses results supported predictions (1) and (2) while prediction (3) was weakly supported.

Consistent with prediction (1), discharge volumes on the Salt River and Tonto Creek were positively correlated with precipitation. While discharge was significantly correlated with the MEI/season for the Salt River, this relationship was not as strong for Tonto Creek based on p-values of the UMs and RMs. The magnitude of the MEI by itself was not a significant factor predicting discharge of the Salt River or Tonto Creek. However, the interaction factor of the magnitude of the MEI and season was statistically significant for the Salt River, supporting the observation of Karamouz and Zahraie (2004), that ENSO was significantly correlated with streamflow in the Salt River; discharge was strongly correlated with the MEI and season for the Salt River but only weakly correlated for Tonto Creek. Based the results of the LRTs, RM was the better model predicting discharge for the Salt River while the UM was the better model predicting discharge for Tonto Creek.

The Salt River MEI/precipitation/discharge analyses generally supported previous findings of the literature that the warm phase of the ENSO is associated with increased precipitation and streamflow in winter in the Western U.S. (Cayan *et. al*. 1999, Dettinger *et. al*. 2003, Kahya and Dracup 1994, Karamouz and Zahraie 2004, Rajagopalan *et. al.* 1998) However, in addition to large winter storms during strong El

Niño conditions, high MEI values during cool phases of the ENSO (La Niña) were positively correlated with precipitation and streamflow for the Salt River. High precipitation and discharge were recorded in the strong La Niña winter of 2007/2008. The results of the Tonto Creek MEI/precipitation/discharge analyses were similar with the exception of only a weak correlation of discharge with the magnitude of the MEI/season. While the p-value for the MEI/season factor in the UM for the Salt River was 0.04, which is less than the 0.05 significance level, the results of the LRT show that the UM did not better explain the variability in discharge than did the RM for the Salt River (R^2 of 0.40 vs. 0.38). The p-value for the MEI/season factor in the UM for Tonto Creek was not significant at the 0.05 level, but the results of the LRT showed the UM was a better fit than the RM (R^2 of 0.61 vs. 0.53). Since the average discharge volume of Tonto Creek is much less than the Salt River, increases in precipitation have a larger effect on predicted changes in discharge volumes for Tonto Creek. The same amount of rain on each tributary can increase the Salt River discharge by a small percentage and Tonto Creek by a large percentage. This is reflected in the difference in R^2 values between the two models and the better fit to data of the UM for Tonto Creek vs. the RM.

My analyses differ from previous studies in that the MEI values were for the month prior to the month in which precipitation and discharge were recorded, as suggested by Klaus Wolter on the NOAA website (http://www.esrl.noaa.gov/psd/enso/mei/table.html). Using different time lags between the MEI and discharge could yield different results. However, the observed increases in discharge in the Salt River and Tonto Creek immediately following rain events suggests that very little lag is necessary in this region when calculating the effects of precipitation on discharge.

Dettinger *et al*. (2003) compared the largest daily flow for the Salt River (from 1914-1995) in a year (October through September) to the December through

February SOI and found that the highest flows were associated with either an El Niño (SOI <-0.5) or neutral (-0.5<SOI<0.5) year. Following the same method, I compared the largest daily flows from the Salt River for each year (October through September) from 2000 to 2011 to the mean February through December SOI of the concurrent year. I found the two highest flows recorded from 2000 to 2011 were associated with both an El Niño year (SOI = -1-1, MEI = 1.1, discharge = 88,300 cfs in 2010) and a La Niña year (SOI = 2.0, MEI = -1.1, 81,300 cfs in 2008). This supports my finding that the magnitude of the MEI is important in addition the sign (positive or negative).

In some studies, a time lag was used when comparing precipitation (in the form of rain and snow) to streamflow. In one such study, Cayan *et al*. (1999) compared precipitation in October through April to streamflow in January through July. This approach was used to capture the effects of snowmelt which is the primary source of runoff of the study area (Sierra Nevada). Kahya and Dracup (1994) used warm season ENSO indices to make predictions of the following cool season streamflow. The lag between the ENSO indices and precipitation and discharge used in those previous studies was several months, not just one month. Karamouz and Zahraie (2004) used ENSO signals to forecast snow budget and resulting streamflow. Keener *et al.* (2010) pointed out a three month lag when cross-correlating nitrate load and streamflow. This lag was used as the primary source of runoff on the Little River Watershed in Georgia was groundwater, not surface water, whereas the discharges in the Salt River and Tonto Creek in my study are primarily from surface water runoff.

In order to establish the effects of precipitation on streamflow, the best estimates of precipitation affecting each tributary were taken form weather stations with locations closest to the USGS stream gages. The Gisela rain gage was very close to the Tonto Creek USGS stream gage. The Roosevelt rain gage that was used for precipitation estimations for the Salt River was located at the elevation of Roosevelt Lake, downstream of the Salt River USGS Gage. This rain gage was the closest one found that maintained a continuous record with temporal coverage of the whole data set for the Salt River USGS stream gage. A precipitation gage installed near the USGS Salt River Gage would provide excellent information to explore the effects of precipitation and discharge on nutrient loads from both tributaries to Roosevelt Lake.

Consistent with prediction (2), both TN and TP concentrations were positively correlated with discharge the Salt River above the lake. For TN, the UM that included seasonality better explained the variability of concentration than did the RM (which held the season coefficient to zero). The p-values of variables for season and season/discharge were both significant at the 0.05 level. The LRT showed that the UM better explained the variability in TN concentration than did the RM. The p-values of the variables for season and season/discharge for the UM for TP were not significant at the 0.05 level. However, the LRT comparing the fit of the UM and RM for TP show that the UM better explained the variation in TP concentration compared to the RM. These results support previous studies that suggest P loading is tied to high discharge mobilizing phosphorus through hydrologic weathering (ADHS 1981). For N loading, long dry periods followed by periods with precipitation likely shift built-up nitrates in the soil into the tributary.

These results are further supported by comparing the overall mean of TN in the Salt River (0.88 mg/L) to the overall seasonal means of TN (0.58 mg/L, winter and 1.11 mg/L, summer) as well as the overall mean of TP (0.24 mg/L) to the seasonal means of TP (0.20 mg/L, winter and 0.28 mg/L, summer). By comparison, mean TN varies by season where mean TP varies little by season, while both vary with discharge. Due to stratification of the water column in summer, one might think that this same pattern would not be observed in the lake downstream. A comparison can be made of the seasonal means of TN and TP at sample site B to the overall mean (the lake sample site closest to the Salt River). The overall mean for TN for sample site B (0.64 mg/L) is lower than the summer mean (0.81 mg/L) and higher than the winter mean (0.56 mg/L). The overall mean for TP for sample site B (0.07 mg/L) is only slightly lower than the summer mean (0.08 mg/L) and slightly higher than the winter mean (0.06 mg/L). The TP measured in the lake differs from the TP measured in the Salt River by a decimal place where the TN does not. This pattern is expected due to P being attached to lithogenic particles that sink in water column.

Again, consistent with prediction (2), TN concentrations were correlated with discharge for Lake Sites A and C while TP concentration was correlated with discharge for Lake Site A. Seasonal variation in limnological conditions may result in seasonal variation in correlation between N and P concentrations by affecting the flow of tributary discharge in different seasons (i.e. summer stratification vs. winter). I would expect N and P concentrations measured when the lake is not stratified to be more influenced by discharge than those measured in the warm season when cool (bottom, or hypolimnion) and warm (top, or epilimnion) layers of the lake are thermally separated. Cooler water entering the lake sinks, taking its nutrient load with it. Lake data were not sufficiently resolved to compare shallow samples and deep samples during the warm season when lake stratification occurs. All lake samples used in this study were collected in the photic zone and not in the deeper part of the water column.

Inconsistent with prediction (3), TN and TP concentrations observed on the Salt River were not significantly correlated with the magnitude of the MEI, even though the discharge of the Salt River was correlated with high MEI events in winter, and both N and P loads were correlated with discharge. As stated by Ellis *et al.* (2008), discharge is affected by soil moisture. It is reasonable to expect that saturated soil moisture due to wet winters result in larger discharge events following summer storms. This increased summer discharge would increase both N and P loading into Roosevelt Lake from the Salt River.

TN and TP concentrations measured in Roosevelt Lake were correlated with the magnitude of the MEI but these correlations were inconsistent. TP concentration was correlated with the magnitude of the MEI at Lake Site A but TN concentration was correlated with the magnitude of the MEI at Lake Site B. Although direct comparison of nutrients and MEI suggest some significant relationships, the true relationships may be masked by internal lake nutrient loading which has seasonal variability due to stratification and remixing of the water column (Tarrant *et al*. 2010).

Keener *et al.* (2010), who found correlation between the ENSO signal and nitrate concentration, suggested that a model based on “the 3-7 periodicity of ENSO” could be used as a predictor for nitrate loads in the Little River Watershed in Georgia. Correlations in the Upper Salt River watershed between the magnitude of the MEI and TN and TP measurements varied by sample site, with stronger correlations found in the lake and no correlation found in the Salt River. In the Upper Salt River watershed, a similar approach as that used by Kenner *et al*. (2010) might be effective using the magnitude of the ENSO signal as a predictor of high discharge events in the Salt River and Tonto Creek, which carry increased nutrient loads to Roosevelt Lake. Although the studies are similar, Keener *et al.* (2010) used nitrate whereas TN was used in this investigation. Nitrate is only a fraction of the pool of total N. Separating out nitrate from TN, which was not possible in this case, might have yielded different results.

5.0 Conclusion

The goal of this study was to investigate if and how ENSO was correlated to precipitation, discharge, and nutrient concentrations in the Upper Salt River Watershed. The state and magnitude of the MEI were compared to precipitation and discharge events and then to nutrient concentrations at three sites on Roosevelt Lake and one site located upstream of the lake on the Salt River, as well as discharge on the Salt River and Tonto Creek.

It was found that, during the years of 2000-2010, higher winter MEI values were positively correlated with higher precipitation and discharge in the Upper Salt River Watershed. However, the same pattern was not evident in summer. Regression model equations supported what was observed in plotting discharge measurements vs. MEI values: large discharge events were positively correlated with large precipitation events in winter as was expected. Discharge was positively correlated with the MEI and with season for the Salt River. The same correlation was less strong for Tonto Creek. However, the UM better fit the data for Tonto Creek and the UM was not a better fit for the Salt River. Thus, the value of the MEI should be considered in addition to precipitation data when forecasting discharge on the Salt River and Tonto Creek.

N concentrations in the Salt River were correlated with discharge and season while P concentrations were correlated to discharge but not season. N and P concentrations in Roosevelt Lake were correlated with discharge: N at sites A and C and P at site A. Relationships of Salt River and Tonto Creek discharges with Roosevelt Lake nutrient concentrations were not easily defined and are influenced by the effects of lake nutrient cycling.

Direct comparison of nutrient concentrations to temporally corresponding MEI index values did not yield the strong relationship that was predicted. Although the direct effects of the ENSO on nutrient concentrations were not demonstrated, predictions (1) and (2) point toward the relationship of the ENSO to nutrient concentrations. If ENSO affects precipitation and discharge, and discharge affects nutrient concentrations, then the link between ENSO and nutrient concentrations should be recognized.

A reasonable predictor of probability of large storm events in winter in the Upper Salt River watershed is the MEI. High magnitude MEI in winter is associated with higher magnitude discharge events in the Salt River, which accounts for approximately 85% of discharge to Roosevelt Lake. With the established relationship between discharge and nutrient loading, it is reasonable to conclude that ENSO affects the discharge and nutrient loading into Roosevelt Lake via the Salt River and Tonto Creek. According to model predictions compiled by Ellis *et al*. (2008), precipitation and streamflow for the Upper Salt River Watershed might decrease in the coming years. While Ellis *et al*. (2008) did not include ENSO data in developing his predictive model, data on the state of the ENSO can be used to in combination with such a model to forecast if and when these events might occur. By association, forecasts that suggest reduced precipitation and discharge also have implications for nutrient loading.

References

Araghinejad, S., D. H. Burn, and M. Karamouz (2006), Long-lead probabilistic forecasting of streamflow using oceanatmospheric and hydrological predictors, Water Resour. Res., 42, W03431, doi:10.1029/2004WR003853.

Arizona Administrative Code (A.A.C.), Title 18, Chapter 11. Water Quality Standards.

Arizona Department of Environmental Quality (ADEQ). Mission Statement and Core Responsibilities (2011). http://www.azdeq.gov/environ/water/index.html

Arizona Department of Health Services (ADHS). Nutrient Levels in the Salt River Basin with Recommended Standards for Phosphorus and Nitrogen. Ambient Water Quality Unit (1981).

Bates, B.C., Kundzewicz, Z.W., Wu, S., Palutikof, J.P. (Eds.), 2008. Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp.

Cayan, Daniel R., Redmond, Kelly, and Riddle, Laurence G., ENSO and Hydrologic Extremes in the Western United States. *Journal of Climate*, 12, 2881(1999)

Chiew, Francis H.S. and McMahon, Thomas A. Global ENSO-streamflow Teleconnection, Streamflow Forecasting and Interannual Variabillity. *Hydrological Sciences*. 43(3) June (2002).

Dettinger, Michael *et al*., United States Streamflow Probabilities and Uncertainties Based on Anticipated El Nino, Water Year 2003. http://meteora.ucsd.edu/cap/elnino_fcast.pdf

Downing, John A. and McCauley, Edward. 1992. The Nitrogen: Phosphorus Relationship in Lakes. *Limnology and Oceanography*, 37(5), 936-945.

Dubrovsky, N.M., Burow, K.R., Clark, G.M., Gronberg, J.M., Hamilton P.A., Hitt, K.J., Mueller, D.K., Munn, M.D., Nolan, B.T., Puckett, L.J., Rupert, M.G., Short, T.M., Spahr, N.E., Sprague, L.A., and Wilber, W.G., 2010, The quality of our Nation's waters—Nutrients in the Nation's streams and groundwater, 1992–2004: U.S. Geological Survey Circular 1350, 174 p. Additional information about this study is available at http://water.usgs.gov/nawqa/nutrients/pubs/circ1350

Ellis, Andrew W., Hawkins, Timothy W., Balling, Robert C., and Gober, Patricia. Estimating Future Runoff Levels for a Semi-arid Fluvial System in Central Arizona, USA. *Climate Research*, 35, 227-239 (2008).

Elser, James J., Bracken, Matthew E.S., Cleland, Elsa E., Gruner, Daniel S., Harpole, W. Stanley, Hillebrand, Helmut, Ngai, Jacqueline T., Seabloom, Eric W., Shurin, Jonathan B., Smith, Jennifer E. Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. Ecology Letters (2007) 10: 1–8.

Fisher, S. G. and Minckley, W. L. 1978. Chemical Characteristics of a Desert Stream in Flash Flood. *Arid Environments*, Vol 1, pp. 25-33.

Grimm, Nancy B. and Fisher, Stuart G. 1986. Nitrogen limitation in a Sonoran Desert stream. *Am. Benthol. Soc.*, 1986, 5(1):2-15

Gruber, Nicolas and Galloway, James N. 2008. An Earth-system Perspective of the Global Nitrogen Cycle. *Nature*, 451(17), 293-296.

Hamlet, Alan F. and Lettenmaier, Dennis P. Columbia River Streamflow Forecasting Based on ENSO and PDO Climate Signals. *Water Resources Planning and Management*, 125 (6) Nov/Dec (1999).

Kahya, Ercan and Dracup, John A. The Influences of Type 1 El-Niño and La-Niña Events on Streamflows in the Pacific Southwest of the United States. Journal of Climate. 7(6): 965-976.

Karamouz, M., and B. Zahraie (2004), Seasonal streamflow forecasting using snow budget and El Nin˜o– Southern Oscillation climate signals: Application to the Salt River Basin in Arizona, J. Hydrol. Eng., 9(6), 523– 533.

Keener, V.W., Feyereisen, G.W., Lall, U., Jones, J.W., Bosch, D.D., Lowrance, R.R. 2010. El-Niño Southern Oscillation (ENSO) influences on monthly NO3 load and concentration, stream flow and precipitation in the Little River Watershed, Tifton, GA. Journal of Hydrology. 381(3-4):352-363.

Menne, M. J., C. N. Williams, Jr., and R. S. Vose, 2010. United States Historical Climatology Network Daily Temperature, Precipitation, and Snow Data. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee. http://cdiac.ornl.gov/epubs/ndp/ushcn/ushcn_map_interface.ht ml

National Oceanic and Atmospheric Administration (NOAA). Multivariate ENSO Index. 2011. http://www.esrl.noaa.gov/psd/enso/mei/

National Weather Service, Climate Prediction Center, Monthly Atmospheric and SST Indices, http://www.cpc.ncep.noaa.gov/data/indices/soi

Pagano, T.C and Garen, D.C., 2005. Climate Variations, Climate Change, and Water Resources Engineering. Chapter, Integration of Climate Information and Forecasts into Western US Water Supply Forecasts.

Piechota, T.C., Dracup, J.A., 1999. Long-range streamflow forecasting using El Niño–Southern Oscillation indicators. Journal of Hydrologic Engineering 4 (2), 144–151.

Rajagopalan, B. and Lall, U. 1998. Interannual Variability in Western Us Precipitation. Journal of Hydrology 210 (1998), 51-67.

Reynolds, Richard, Dettinger, Michael, Cayan, Daniel, Stephens, Doyle, Highland**,** Lynn, and Wilson, Raymond, 2003. Effects of El Nino on Streamflow, Lake Level, and Landslide Potential. U.S. Geological Survey.

Salt River Project (SRP). Daily water report. http://www.srpwater.com/dwr/report.aspx?dt=1/7/2012

Schmidt, N., Lipp, E.K., Rose, J.B., Luther, M., 2001. ENSO influences on seasonal rainfall and river discharge in Florida. Journal of Climate 14 (4), 615–628.

Scott, D., J. Harvey, R. Alexander, and G. Schwarz (2007), Dominance of organic nitrogen from headwater streams to large rivers across the conterminous United States, Global Biogeochem. Cycles, 21, GB1003, oi: 10.1029/2006GB002730.

Seefeld, Kim and Linder, Ernst. Statistics Using R with Biological Examples. 2007. University of New Hampshire, Durham, NH Department of Mathematics & Statistics.

Sterner, R. W. and Elser, J. J. Ecological Stoichiometry: The Biology of Elements from Molecules to the Biosphere (Princeton Univ. Press, Princeton, NJ, 2002).

Tarrant, P. E., Amacher, J. A., and Neuer, Susanne (2010), Assessing the potential of Medium Resolution Imaging Spectrometer (MERIS) and Moderate Resolution Imaging Spectroradiometer (MODIS) data for monitoring total suspended matter in small and intermediate sized lakes and reservoirs, Water Resour. Res., 46, W09532, doi: 10.1029/2009WR008709.

Tarrant, P. and S. Neuer (2009), Monitoring Algal Blooms in a Southwestern U.S. Reservoir System,*Eos Trans. AGU*, *90*(5), 38, doi:10.1029/2009EO050002.

Trenberth, K.E., 1997. The definition of El Niño. Bulletin of the American Meteorological Society 78 (12), 2771–2777.

U.S. Environmental Protection Agency (EPA) National Eutrophication Survey. Report on Theodore Roosevelt Lake, Gila County, Arizona. EPA Region IX. Working Paper No. 735 (1977).

United States Geological Survey (USGS), Peak Streamflow for Arizona, USGS 09498500 Salt River Near Roosevelt, AZ, http://nwis.waterdata.usgs.gov/az/nwis/peak?site_no=09498500&agency_cd=USGS&format=html

United States Geological Survey (USGS), Water-Data Report 2010, 09498500 Salt River Near Roosevelt, Arizona.

United States Geological Survey (USGS), Water-Data Report 2010, 0949900 Tonto Creek Above Gun Creek, Near Roosevelt, Arizona.

United States Geological Survey (USGS). Water Watch webpage (2011). http://waterwatch.usgs.gov/new/?m=real&r=az&w=map

Western Regional Climate Center (WRCC), accessed periodically throughout 2011, http://www.wrcc.dri.edu/