SEARCHING FOR PREDICTIVE CLIMATE SIGNALS FOR RIVER FLOWS IN THE LOWER COLORADO RIVER BASIN OF TEXAS

Ronald Anderson, P.E., MBA, D. WRE[1]
Bob Rose[2]

ABSTRACT

The Highland Lakes are operated by the Lower Colorado River Authority (LCRA) in Texas to provide water supply to municipal, industrial, agricultural users and environmental flows for the river and Matagorda Bay. The Highland Lakes also provide for hydroelectric generation and recreation.

The catchment area is in the Texas Hill Country, a region classified as the Edwards Plateau. Subject to extended droughts interrupted by intense rainfall, the region has the nickname of Flash Flood Alley. Precipitation in the region is understood to be influenced by oceanic conditions in the Pacific, Atlantic, and Gulf of Mexico. While the behavior of these global climate patterns is climatologically understood, finding strong skill in prediction of streamflows has been challenging.

Identifying concurrent teleconnections, and to a lesser extend lagging indicators, is a critical first step for finding potential for predictors. Research efforts have often focused on predicting rainfall or climatic indexes. However, surface water managers need to relate predictions to streamflows. Climate indices can also be useful if they are hindcasted, enabling for relationships to the streamflow record to be established.

Persistence is one of the strongest predictive indicators in the region, primarily through the winter season. Persistence is useful in short term predictions because it directly relates to streamflows and indirectly is influenced by teleconnection patterns. Therefore explicitly considering teleconnection patterns adds less incremental short term skill but potential benefit for longer term prediction. Use of persistence and ENSO forecasts are currently being used in water supply forecasts at the LCRA.

INTRODUCTION

The Lower Colorado River Authority (LCRA) is a conservation and reclamation district created by the Texas Legislature in 1934. LCRA supplies electricity for Central Texas, manages water supplies and floods in the lower Colorado River basin, provides public parks, and supports community and economic development. LCRA manages water supplies for cities, farmers and industries along a 600-mile stretch of the Texas Colorado River between San Saba and the Texas Gulf Coast. The LCRA water supply includes a

[1] Chief Engineer, Lower Colorado River Authority, Ron.Anderson@lcra.org, member ASCE and AWWS P.O. Box 220, Mailstop R325, Austin, Texas 78767-0220, phone (512) 473-3572.
[2] Chief Meteorologist, Lower Colorado River Authority, Bob.Rose@lcra.org, American Meteorological Society (AMS), P.O. Box 220, Mailstop R325, Austin, Texas 78767-0220, phone (512) 473-3300.

combination of interruptible water for agricultural uses and firm water supply for municipal and industrial uses

LCRA operates six dams on the lower Colorado River in Central Texas: Buchanan, Inks, Wirtz, Starcke, Mansfield and Tom Miller. These dams form the six Highland Lakes - Buchanan, Inks, LBJ, Marble Falls, Travis and Austin as shown schematically in Figure 1. Two of these reservoirs, lakes Buchanan and Travis, are the only water supply reservoirs and only Lake Travis has flood control storage. The total combined storage in the Highland Lakes two water storage reservoirs, lakes Buchanan and Travis is approximately 2,010,000 acre-feet of water when at full conservation storage. LCRA regulates water discharges to manage floods, and releases water for sale to municipal, agricultural and industrial users. Installed hydropower generation at these reservoirs provides approximately 295 MW of electrical generation capacity.

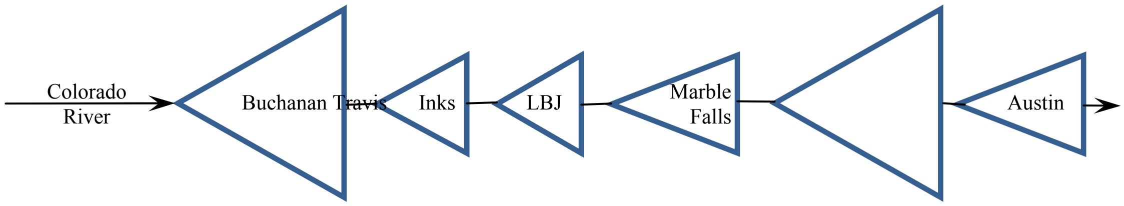

Figure 1. The Highland Lakes Chain of the Colorado River in Texas

Long lead time prediction of streamflows in the Colorado River basin could provide many opportunities for better resource planning and management including water supply, physical facilities, flood management, hydropower generation and scheduling, and environmental provisions. While general long lead time meteorological predictions such as drier than normal or wetter than normal are useful and improving, these do not lend themselves to directly quantifiable forecasts of streamflows or evaporation that can be readily used by surface water supply managers. Even the relationships between rainfall, if it could be accurately predicted, and streamflow, which is a reasonably well understood physical process, have significant variability. For the catchment of the Highland Lakes, statistical regression of the monthly of streamflows, precipitation only partially explains the variations in streamflows. This is likely due to the spatial and temporal variation of rainfall as well as issues such as surface and groundwater interactions and soil moisture conditions which are less easily quantified. Piechota & Dacup (1996) found that while strong relationships between the lagging indices of Southern Oceanic Index (SOI) and Palmer Drought Severity Index (PDSI) could be found, the same was not true for SOI and streamflows. Unfortunately, streamflows are necessary for surface water resource managers in evaluating supply.

There are many contributing factors to the difficulty in long lead time streamflow prediction in central Texas. First the lack of snow pack precludes one of the most helpful predictions available to our counterparts in the Southwest, Pacific-Northwest, and Atlantic Northeast states. Additionally weather patterns are influenced by Pacific generated fronts, Arctic influences, Atlantic influences, Gulf of Mexico influences, tropical disturbances, and even the influences from Canadian cold fronts can have a profound effect. Theses stalled fronts can sometimes be the source for large rain storms such as the Memorial Day Flood of 1981.

Other complications are influences from the north and southward displacement of the Hadley Cell over the southern US. If the cell is displaced further to the north or to the south, it could lead to more convection in Central Texas thus producing more precipitation. Researchers and water managers alike have employed a variety of methods to relate these climatic indicators to streamflow ranging from simple statistical relationships, advanced multivariate methods, and even hydrodynamic modeling.

> The term "teleconnection pattern" refers to a recurring and persistent, large-scale pattern of pressure and circulation anomalies that spans vast geographical areas. Teleconnection patterns are also referred to as preferred modes of low-frequency (or long time scale) variability. Although these patterns typically last for several weeks to several months, they can sometimes be prominent for several consecutive years, thus reflecting an important part of both the interannual and interdecadal variability of the atmospheric circulation. (source: National Weather Service, Climate Prediction Center)

Of the thirteen prominent teleconnection patterns, several have been investigated for use as long lead indicators of hydrology in the area. These include Pacific Decadal Oscillation (PDO), Northern Atlantic Oscillation (NAO), El Niño/Southern Oscillation (ENSO), and Atlantic Multidecadal Oscillation (AMO). Of these indicators, the ENSO is perhaps the best understood and the best quantified indicator for the streamflows in the lower Colorado River basin. ENSO is measured by several indicators including the Sothern Oscillation Index (SOI), the Oceanic Niño Index (ONI), and the Multivariate ENSO Index (MEI). Both ONI and MEI have been computed for long historical periods lending them to be easily correlated with the gaged surface water record.

EL NIÑO/SOUTHERN OSCILLATION EFFECTS ON CENTRAL TEXAS WEATHER

The meteorological influences of the ENSO cycle on Texas weather are rather well understood. In the negative phase, often referred to as La Niña, easterly trade winds increase in strength across equatorial Pacific, causing colder than normal waters to spread west from the coast of South America to near the International Date Line. A "cold tongue" of water develops across central and eastern equatorial regions, leaving a zone of warmer than normal water across across the western Pacific and Indian Ocean. The warmer than normal waters fuel the development of thunderstorms across the western Pacific. Rising air currents associated with the area of thunderstorms tend to sink across the central and eastern parts of the equatorial Pacific, creating a closed area of circulation. The sinking air causes the development of a broad high pressure area across the eastern half of the Pacific. As the Pacific circulation strengthens, the area of high pressure across the eastern Pacific expands to the north. Eventually, the area of high pressure gains enough strength to cause the Polar Jet Stream to shift from southern

California to the Pacific Northwest and western Canada. As the storm track shifts to the north in connection with the Jet Stream, drier than normal weather conditions develop across the southern US, including Texas. This drier than normal pattern often leads to the development of drought. The influence of La Niña can be seen in Figure 2.

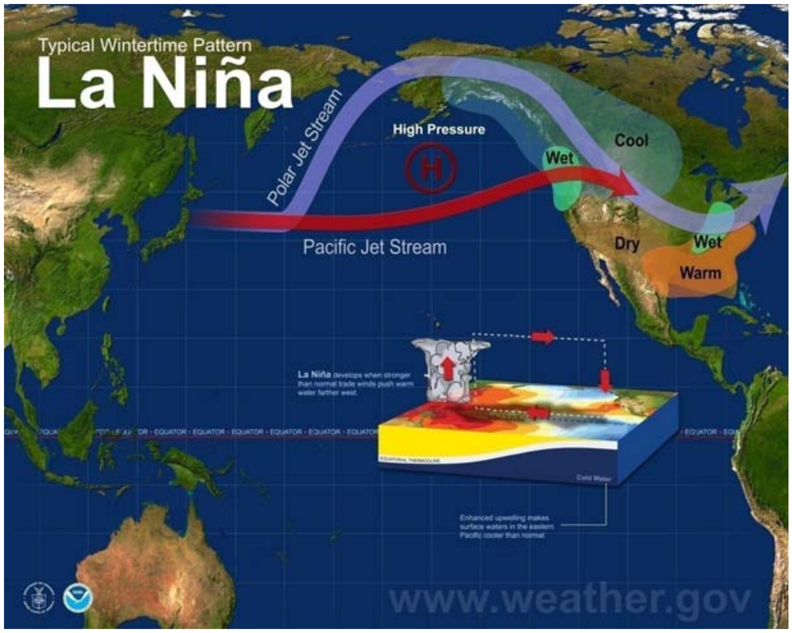

Figure 2. Typical Wintertime La Niña Pattern

The National Climatic Data Center has compiled a set of charts based on the historical record showing the anomalous influence of El Niño and La Niña on precipitation across the US by month. These charts, shown in Figures 3 and 4, also show the departures and percent frequency of occurrence. In the Central Texas region during November to January influence is a 60 to 70% increased frequency of 10 to 70 mm less precipitation as show in Figure 3. The effect is only slightly weaker during the December to February period shown in Figure 4.

In the positive phase of ENSO, often referred to as El Niño, the easterly trade winds diminish and are replaced by westerly trades. These westerly winds pull the very warm waters residing across the western Pacific all the way east to the coast of South America. Eventually a tongue of warmer than normal water develops across the central and eastern equatorial Pacific. These warm waters fuel the development thunderstorms across the central and eastern Pacific, leading to rising air currents, creating a broad area of low pressure. As the broad area of low pressure strengthens, circulation around the low helps focus the storm track across the southern US.

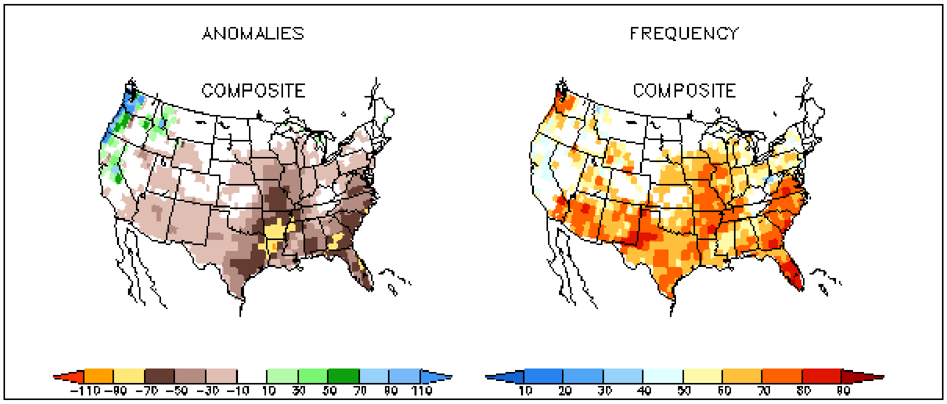

Figure 3. U.S. Precipitation Departures (mm)
Frequency of Occurrence (%) for La Niña during Nov.-Jan.

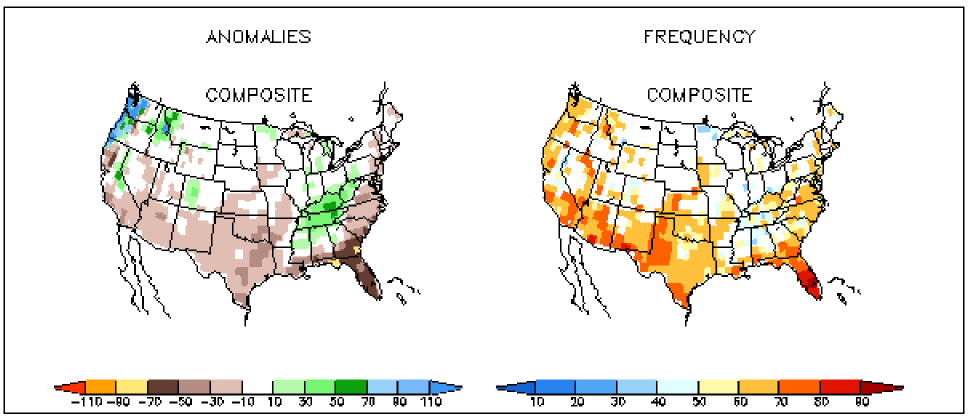

Figure 4. U.S. Precipitation Departures (mm)
and Frequency of Occurrence (%) for La Niña during Dec- Feb.

The flow of moisture off the Pacific Ocean, in combination with a flow of moisture off the Gulf of Mexico, creates frequent periods of storms, resulting in above normal rainfall. A recent summary of ENSO model predications is show in Figure 5 which shows a period of relatively long range consensus among predictions. While the horizon of consensus of the ENSO predictions is often longer than streamflow persistence, it is still short relative to multi-year water supply system operations.

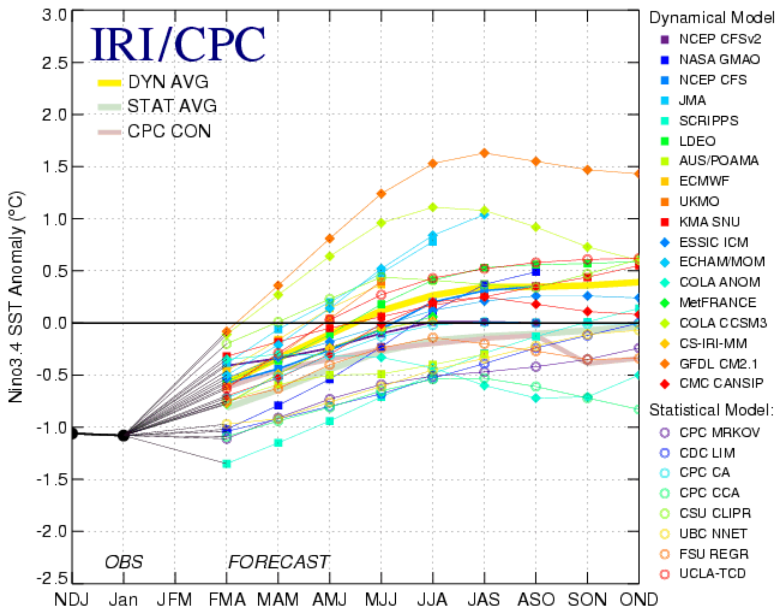

Figure 5. ENSO Model Predictions for February 2012

SUMMARY OF PREDICTION STUDIES INVOLVING CENTRAL TEXAS

O'Connell (2002) focused on the longer term indicators of ENSO and the NAO, noting that the PDO cycle was too long to be of much management use as a indicator. She examined correlation coefficients between streamflow in lower Colorado River basin and the indicators for the period of 1940 to 1999 on an annual time step. While she found good correlation between concurrent data, leading indicators showed only minor correlations. She found the indicators to be capable of improving annual forecasts by 11-13% over persistence alone, and an optimal linear combination used SOI and NAO to gain a 49% improvement" but noted "skill inflation may have occurred, as forecasts were not tested on an independent data set." Interestingly, she identified the strong month to month persistence that often exits in the streamflow data sets apart from teleconnections. However that was not directly useful for the modeling approach. Furthermore, at the time, she suggested that without strong lead correlations, the indictors were not useful as predictors. However, now a decade later, we have easy access to good dynamic and statistical prediction models, at least for ENSO, which can make concurrent relationships useful for several months in the future even where leading predictions by indicators may not be established.

> *Hydrological Persistence: The characteristic of hydrologic conditions to remain in wet or dry cycles. Interactions between global climate process and the hydrological cycle can result in rainfall and stream flow data clustering into wetter and drier conditions.*

In hindsight, the prediction skill may have been improved through classification of ENSO into El Niño, Neutral, or La Niña rather than a continuous variable, since the strength of the condition seems to have less impact than the condition alone. Similarly the streamflows and the ENSO indexes are highly correlated so the lack of additional information from the ENSO index may be due to the fact that the ENSO signal is already largely incorporated into the antecedent conditions. LCRA now uses both the persistence and the ENSO forecasts for aiding prediction (Anderson and Walker, 2010) of streamflows and subsequently lake contents.

Dr. James Tolan (2006) also investigated ENSO impacts in Texas but with a focus on salinity along the Texas Gulf Coast. However, this is still of interest since, in some areas, salinity can be related to streamflow with potentially less error than precipitation (Anderson, Wedig, and Tyagi, 2009). Dr. Tolan analyzed the period of 1982 to 2004 using seasonally standardized salinity. He found major cross correlations between both ENSO and PDO while also finding minor correlations with NAO and yearly season cycles. Dr. Tolan also identified five frequencies associated with the variation in salinity that correspond to ENSO but the period of salinity record is short in relation to the patterns.

Slade and Chow (2011) focused their study on the Texas Hill Country using the period of 1950 to 2009. While they looked at precipitation, flood flows, and streamflows, our interest here is streamflows. Their results confirmed the meteorological understanding of ENSO influences. They found for each gage in the region that the mean streamflow during El Niño periods exceeds the mean streamflow during La Niña periods. While this exceedence was only slight in the San Saba River, Llano River, and Johnson Creek; the exceedence was substantial at the more southerly gages of such as the Pedernales, Guadalupe, and Blanco Rivers. The focus of their work was diagnostic rather than predictive, therefore they only looked at concurrent conditions or lagging indicators rather than leading indicators such as was done by O'Connell.

NOAA Operational Definitions for El Niño and La Niña Episodes

- El Niño: characterized by a positive ONI greater than or equal to +0.5°C.
- La Niña: characterized by a negative ONI less than or equal to -0.5°C.

CPC considers El Niño or La Niña conditions to occur when the monthly Niño3.4 OISST departures meet or exceed +/- 0.5°C along with consistent atmospheric features. These anomalies must also be forecasted to persist for three consecutive months.

Quan et. al. (2011) looked at the ability to reproduce the historical standard precipitation index (SPI) for the period of 1982 to 2002 using dynamic atmospheric climate simulations across the United States. While SPI is not easily related to streamflows, the results of the research echo findings of other research in the central Texas area. They note that inherent drought persistence alone provides considerable seasonal skill. Furthermore, they note that dynamic sea surface temperature (SST) models do improve predictive skill, and that ENSO is believed to be the preponderance of the skill source in the Southern US.

Wei, W. and Watkins (2011) evaluated ENSO, PDO, and NAO specifically related to flows in the Lower Colorado River. They conducted an ordinal polytomous logistic regression approach to forecasting streamflows. Of all the indicators they evaluated, they found that only hydrologic persistence and ENSO or PDO provided any skill over mean seasonal streamflow patterns.

ANALYSIS USING NON-PARAMETRIC-METHODS

As has been shown in the literature, persistence and ENSO are skillful in predicting streamflows in central Texas for up to several months. While other indicators may be shown to be good predictors of climate indices, further research is needed to quantify the impacts of PDO and NAO to central Texas streamflows. Past research suggests that additional indicators may only provide marginal additional prediction skill but continued advances in the understanding and simulation of teleconnection patterns may prove otherwise.

The gaged record of the Highland Lakes for the period of 1940 to 2011 was analyzed and computed for the month to month persistence of streamflows for conditions of El Niño, La Niña, neutral, or unspecified. The computed persistence is the basis for transitional probabilities used to constrain chaining Marcov forecasts. Monthly streamflows are grouped into lower quartile, inner quartile range, and upper quartile bins for dry, medium, and wet conditions respectively. The three antecedent classes, three transitional classes, and 12 months a year result in 108 potential combinations of prior distributions for describing transitional probabilities. Furthermore, considering the four ENSO classifications results in 424 combinations.

These prior distributions capture both the persistence and ENSO impacts as the supported by the literature. An example of the transitional probabilities for the condition of unspecified ENSO is shown in Table 1.

Table 1. Transitional Probability of Persistent Quartiles for Unspecified ENSO Condition

Last Mon	This Mon	**Persist Dry**	Dry to Medium	Medium to Wet	Medium to Dry	**Persist Medium**	Medium to Wet	Wet to Dry	Wet to Medium	**Persist to Wet**
12 1		**76.47%**	23.53%	0.00%	14.29%	**65.71%**	20.00%	0.00%	42.11%	**57.89%**
1 2		**77.78%**	22.22%	0.00%	11.11%	**75.00%**	13.89%	0.00%	27.78%	**72.22%**
2 3		**61.11%**	27.78%	11.11%	19.44%	**72.22%**	8.33%	0.00%	27.78%	**72.22%**
3 4		**72.22%**	27.78%	0.00%	13.89%	**61.11%**	25.00%	0.00%	50.00%	**50.00%**
4 5		**33.33%**	55.56%	11.11%	33.33%	**52.78%**	13.89%	0.00%	38.89%	**61.11%**
5 6		**38.89%**	50.00%	11.11%	27.78%	**44.44%**	27.78%	5.56%	61.11%	**33.33%**
6 7		**66.67%**	27.78%	5.56%	11.11%	**69.44%**	19.44%	11.1%	33.33%	**55.56%**
7 8		**50.00%**	38.89%	11.11%	25.00%	**55.56%**	19.44%	0.00%	50.00%	**50.00%**
8 9		**55.56%**	27.78%	16.67%	19.44%	**66.67%**	13.89%	5.56%	38.89%	**55.56%**
9 1	0	**61.11%**	11.11%	27.78%	16.67%	**58.33%**	25.00%	5.56%	66.67%	**27.78%**
10 11		**72.22%**	27.78%	0.00%	11.11%	**66.67%**	22.22%	0.00%	38.89%	**61.11%**
11 12		**77.78%**	22.22%	0.00%	11.11%	**72.22%**	16.67%	0.00%	33.33%	**66.67%**

The observed transitional probabilities in Table 1 have been compared to random probabilities. The transitional probabilities which cannot be rejected at a 95% confidence as randomly occurring are shaded in the table. Only six of the 36 persistent states appear to be random. These are predominantly during the April to May and May to June transitions. This is reasonable since this is the period of spring rainfall also known as the 'barrier period'. The majority of the transition probabilities reflect statistically significant month to month persistence. Said another way, the odds of switching out of a condition, or even more so from wet to dry or dry to wet conditions, rarely follow random probabilities.

Table 2 presents the observed transition likelihoods under La Niña conditions. The average increase in the likelihood of remaining in dry conditions or transitioning to the next dryer condition than under the unspecified condition is 12%.

Table 2. Transitional Probability of Persistent Quartiles for La Niña Condition

Last Mon	This Mon	Persist Dry	Dry to Medium	Medium to Wet	Medium to Dry	Persist Medium	Medium to Wet	Wet to Dry	Wet to Medium	Persist Wet
12 1		72.73%	27.27%	0.00%	0.00%	77.78%	22.22%	0.00%	50.00%	50.00%
1 2		88.89%	11.11%	0.00%	16.67%	75.00%	8.33%	0.00%	0.00%	100.0%
2 3		77.78%	11.11%	11.11%	37.50%	50.00%	12.50%	0.00%	20.00%	80.00%
3 4		90.00%	10.00%	0.00%	16.67%	66.67%	16.67%	0.00%	60.00%	40.00%
4 5		37.50%	37.50%	25.00%	55.56%	44.44%	0.00%	0.00%	33.33%	66.67%
5 6		57.14%	42.86%	0.00%	25.00%	75.00%	0.00%	33.33%	33.33%	33.33%
6 7		60.00%	20.00%	20.00%	14.29%	42.86%	42.86%	0.00%	0.00%	100.0%
7 8		0.00%	66.67%	33.33%	37.50%	37.50%	25.00%	0.00%	50.00%	50.00%
8 9		100.0%	0.00%	0.00%	40.00%	50.00%	10.00%	0.00%	33.33%	66.67%
9 1	0	71.43%	14.29%	14.29%	18.18%	63.64%	18.18%	0.00%	50.00%	50.00%
10 11		85.71%	14.29%	0.00%	23.08%	69.23%	7.69%	0.00%	28.57%	71.43%
11 12		88.89%	11.11%	0.00%	18.18%	72.73%	9.09%	0.00%	50.00%	50.00%

In Table 3 we see the likelihood under El Niño conditions. During El Niño conditions, we observe an average increase of 28% likelihood of transitioning out of dry conditions to moderate conditions throughout the year and an annual average of 7% increase in the likelihood of staying either medium or wet.

Table 3. Transitional Probability of Persistent Quartiles for El Niño Condition

Last Mon	This Mon Pe	sist Dry	Dry to Medium	Medium to Wet	Medium to Dry	Persist Medium	Medium to Wet	Wet to Dry	Wet to Medium	Persist Wet
12	1	100.0%	0.00%	0.00%	15.38%	69.23%	15.38%	0.00%	75.00%	25.00%
1	2	25.00%	75.00%	0.00%	8.33%	75.00%	16.67%	0.00%	14.29%	85.71%
2	3	nd	nd	nd	9.09%	81.82%	9.09%	0.00%	14.29%	85.71%
3	4	0.00%	100.0.%	0.00%	11.11%	44.44%	44.44%	0.00%	50.00%	50.00%
4	5	0.00%	100.0.%	0.00%	16.67%	83.33%	0.00%	0.00%	66.67%	33.33%
5	6	50.00%	50.00%	0.00%	18.18%	45.45%	36.36%	0.00%	25.00%	75.00%
6	7	66.67%	33.33%	0.00%	0.00%	87.50%	12.50%	0.00%	42.86%	57.14%
7	8	50.00%	50.00%	0.00%	14.29%	71.43%	14.29%	0.00%	33.33%	66.67%
8	9	50.00%	50.00%	0.00%	22.22%	66.67%	11.11%	0.00%	50.00%	50.00%
9	10	75.00%	25.00%	0.00%	8.33%	50.00%	41.67%	0.00%	50.00%	50.00%
10	11	50.00%	50.00%	0.00%	11.11%	44.44%	44.44%	0.00%	28.57%	71.43%
11	12	75.00%	25.00%	0.00%	11.11%	88.89%	0.00%	0.00%	20.00%	80.00%

* nd = no data

As the data is binned into further classifications, the number of observations gets small. As seen in Table 3, there is one state of transition that has not yet been observed in the gaged record. This posses a technical issue in using non-parametric methods if more indicator variables were to be incorporated.

CONCLUSIONS

Researchers have investigated climate predictive indicators in Texas and specifically in the lower Colorado River catchment for many years. Efforts focused on predicting streamflow, rainfall or climatic indexes. Surface water managers need to relate predictions to streamflows either by dynamical or statistical methods for use in supply management. Qualitative or classification indicators can be useful if they are also hindcasted so they can be related to the streamflow record with a statistical methods and the prediction uncertainty can be characterized. Month to month persistence is recognized as one of the most skillful indicators, primarily through the winter season. Persistence is useful in short term predictions because it directly relates to streamflows and indirectly is influenced by teleconnection patterns. Therefore explicitly including teleconnection patterns adds less incremental short term skill but still offers potential benefit for longer term prediction.

> A **hindcast** is a way of testing a mathematical model. Known or closely estimated inputs for past events are entered into the model to see how well the output matches the known results. Hindcasting is also known as backtesting.
>
> An example of hindcasting would be entering climate forcings (events that force change) into a climate model. If the hindcast accurately showed weather events that are known to have occurred, the model would be considered successful. - Wikipeda

Even though most research has focused on concurrent indicators rather than leading indicators, concurrent relationships may still be useful in prediction as global circulation models provide better and further outlooks into future climate. Use of lagging climate indicators may also help identify driving climate indicators but pose more challenges for prediction of streamflow. Use of persistence and, concurrent ENSO relationships, and ENSO forecasts are currently being used in water supply forecasting at the LCRA. Additional skill may be achieved through future research with AMO interactions with ENSO forecasts (Nielsen-Gammon, 2011) as long as the historical record is reasonably long for use in providing confidence in the streamflow relationships and understanding of the prediction uncertainty. Finally, even when additional indicators prove to be statistically significant they still need to provide substantively better projections over existing indicators to be of benefit to water managers.

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