5-21-2017

# Multi-Scale Correlation Analyses between California Streamflow and ENSO/PDO

Kazi Ali Tamaddun
*University of Nevada, Las vegas*, tamaddun@unlv.nevada.edu

Ajay Kalra
*Southern Illinois University*, kalraa@siu.edu

Sajjad Ahmad
*University of Nevada, Las Vegas*, sajjad.ahmad@unlv.edu

# Multi-scale correlation analyses between California streamflow and ENSO/PDO

Kazi Ali Tamaddun[1], Ajay Kalra[2], Sajjad Ahmad[3]

[1]Department of Civil and Environmental Engineering and Construction, University of Nevada, 4505 S. Maryland Parkway, Las Vegas, NV 89154-4015, USA; Phone: (702) 490-1284; email: tamaddun@unlv.nevada.edu

[2]Department of Civil and Environmental Engineering, Southern Illinois University, 1230 Lincoln Drive, Carbondale, IL 62901-6603; Phone: (618) 453-7008; email: kalraa@siu.edu

[3]Department of Civil and Environmental Engineering and Construction, University of Nevada, 4505 S. Maryland Parkway, Las Vegas, NV 89154-4015, USA; Phone: (702) 895-5456; email: sajjad.ahmad@unlv.edu

## ABSTRACT

El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) are two of the most important climate indices that influence the western U.S. hydrology significantly. This study evaluated how these two indices have influenced California streamflow over the years and determined their correlation at multiple time-scales. Data were obtained from 14 unimpaired streamflow stations of California for a study period of 63 years (i.e., 1951 to 2013). The concept of continuous wavelet transform was applied to observe the variance in each time-series at multiple time-scale bands over the years. The correlation was found to be higher in the latter half of the study period. ENSO showed a higher correlation with California streamflow compared to PDO across the study period. The results of this study can be of assistance in determining the relationship between Pacific SST fluctuation and California streamflow. The findings may help understand the recent California drought as well.

## INTRODUCTION

Understanding the spatiotemporal relationship between hydro-climatic factors (i.e., precipitation, temperature, and streamflow) and climate variability (change in oceanic-atmospheric indices) has been of great interest to climate researchers (McCabe and Wolock, 2002; Durdu, 2010; Kalra and Ahmad, 2011). Studies suggest that the temporal change in climate patterns can potentially alter the behavior of hydrologic variables (Burn and Elnur, 2002; Carrier et al., 2013). Many of the recent studies have looked into change patterns of hydrologic variables along with climate variability (Kalra et al., 2008; Carrier et al., 2016; Tamaddun et al., 2016a; Choubin et al. 2014). Understanding of the relationship between hydrologic variables and climate variability has become important for water management since the water managers are facing the challenge of meeting the increasing population and energy demand with limited and diminishing resources (Kalra and Ahmad, 2012; Thakali et al., 2016; Qaiser et al. 2013; Shrestha et al. 2012; Dawadi and Ahmad 2013). Besides describing the potential impacts associated with a change in climate (IPCC, 2014; Dawadi and Ahmad 2012), studies have also emphasized the increasing importance of understanding the spatiotemporal change pattern (Weider and Boutt, 2010; Zhang et al., 2016; Kalra et al., 2013 a & b).

Climate indices, which represent the change behavior of oceanic-atmospheric systems, have been used as one of the input parameters in forecasting models. Out of many climate indices, El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) are two of the most important indices originating from the Pacific Ocean that influence the western US hydrology immensely (Beebee and Manga, 2004). ENSO (located in the Niño 3.4 zone of the Pacific Ocean) is a natural cycle that alters with a frequency of 2-7 years between a warm phase, known as El Niño, and a cold phase, known as La Niña. PDO, on the other hand, has a slightly larger area of influence in the northwestern Pacific and alters between a warm and a cold phase at every 25-50 years. A detailed discussion on how ENSO and PDO work and how they are associated with the western US hydrology can be found in the works of Cayan et al. (1999), Miles et al. (2000), Beebee and Manga (2004), and Tamaddun et al. (2016b).

Studies suggest that both ENSO and PDO have worked as influencing factors to alter the western US hydrology, especially in the Colorado River Basin (CRB) and California region (Kahya and Dracup, 1993; Hidalgo and Dracup, 2003; Sagarika et al., 2015a; Pathak et al., 2016a). The recent droughts in California have drawn the attention of many climate researchers (Griffin and Anchukaitis, 2014; Wei et al., 2016). Studies have concluded that different phases of ENSO and PDO have influenced the western US hydrology differently based on spatial and seasonal variation (Hamlet and Lettenmaier, 1999; McCabe et al., 2007; Sagarika et al., 2014). Hoerling and Kumar (1999) have discussed the theories behind the physical mechanism that cause the pressure and temperature fluctuations of the Pacific and how they influence the western US hydrology.

Studies suggest that hydrologic variables and oceanic-atmospheric oscillations are usually non-stationary in nature and do not fall into normal probability distribution function (Jevrejeva et al., 2003; Grinsted et al., 2004; Sagarika et al., 2015b; Kalra et al., 2013c). Hence, understanding the change behavior and predicting the frequency patterns of such distributions have drawn the attention of climate researchers (Grinsted et al., 2004). A detailed literature review on how non-parametric methods can tackle non-stationary data distributions can be found in Pathak et al. (2016b) and Tamaddun et al. (2016b). Out of these, continuous wavelet transform (CWT) has been widely used as feature extraction tool as the method produces lower signal-to-noise ratio in a signal or a time series (Grinsted et al., 2004). In conjunction with CWT, cross wavelet transform and wavelet coherency (WTC) analysis have been used effectively to evaluate the association of multiple time series data distributions (Jevrejeva et al., 2003; Tang et al., 2014). Formation techniques and theory of XWT and WTC can be found in the works of Torrence and Compo (1998).

In the current study, streamflow variability of California was analyzed in association with its correlation with ENSO and PDO variations at multiple frequency bands using the concepts of CWT, XWT, and WTC analysis. The results of the study may help understand the change pattern of California streamflow variability in relation to Pacific Ocean climate variability.

## STUDY AREA AND DATA

According to the United States Geological Survey (USGS) hydrologic unit map, the continental U.S. is divided into 18 hydrologic regions (Figure 1). In this study, the California hydrologic region was selected. In 2012, USGS published the Hydroclimatic Data Network (HCDN) 2009, which enlisted 704 unimpaired streamflow stations across the continental United States.

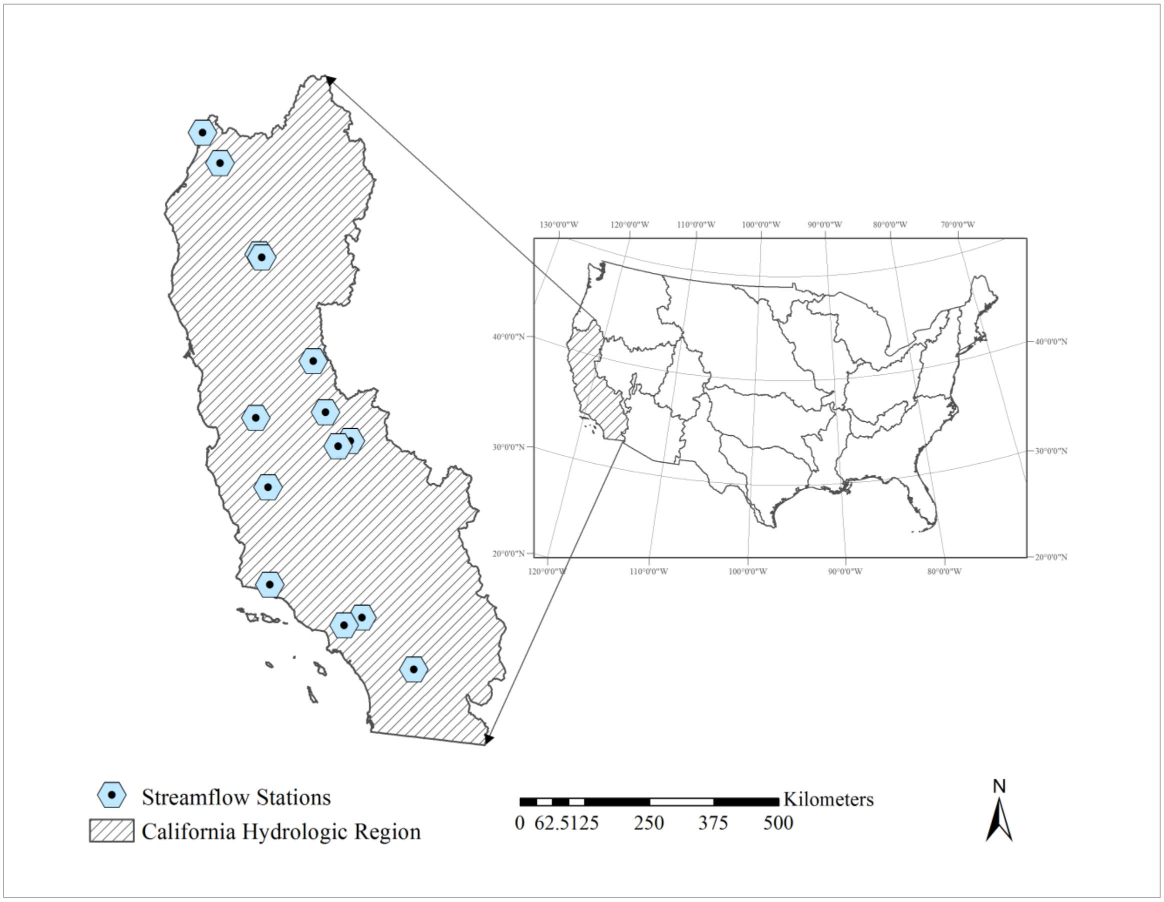


**Figure 1.** Map showing the selected streamflow stations in the California hydrologic region.

In this study, 14 stations from the California region were selected (Figure 1) with each station having continuous data of 63 years (from 1951 to 2013). The raw data were obtained on a monthly mean basis, which was averaged over the water year cycle (from previous year's October to current year's September). Both ENSO and PDO data were obtained for the same length as streamflow. ENSO (Niño 3.4) and PDO (OI SST, version 2) indices for the current year were obtained using a three-month moving average of the monthly indices. ENSO data were obtained from the U.S. National Oceanic and Atmospheric Administration (NOAA) online database, while PDO data were obtained from the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) online database. For both the indices, an increase refers to the warming of SST (warm phase) and decrease refers to cooling of SST (cold phase).

## METHODOLOGY

The current study followed three steps to complete the analyses. The first step consisted of obtaining the individual CWTs of each of the time series (i.e., streamflow, ENSO, and PDO). The second step was to construct XWTs from the CWTs. The third and final step was to run WTC analysis from the CWTs. A brief description of each of these steps has been provided below based on the works of Torrence and Compo (1998), Jevrejeva et al. (2003), Grinsted et al. (2004), Souza et al. (2007), and Beecham and Chowdhury (2009).

Wavelets, in general, have been favored over other traditional decomposition methods, such as the Fourier transform, as wavelets can be translated and scaled in both the time and the frequency domain (Jevrejeva et al., 2003). Use of wavelets has been suggested to be more appropriate for analyzing non-normal time-series, which are quite prevalent in non-stationary hydroclimatic data e.g., streamflow (Grinsted et al., 2004). Non-stationary data can be decomposed in multiple frequency power spectrums using CWT, which allows detection of change behavior (variance in data) at different time scales (frequencies) (Foufoula-Georgiou and Kumar, 1995). Out of many different wavelet functions, the Morlet wavelet has been most widely used in the field of geophysical signal analysis (Percival and Walden, 2000); hence, the current study chose the Morlet function as the mother wavelet type.

To represent the variability of all the streamflow stations, principal component analysis (PCA) was used as the dimensionality reduction technique. The first principal component (PC1) explained 94.52% variability of all the stations. This PC1 was used for further analyses and has been coined as "streamflow1" in the subsequent discussions.

An XWT is obtained from the complex conjugation of two CWTs. This process produces a cross wavelet power spectrum, where a high (low) common power refers to the high (low) covariance between the signals (time series) (Grinsted et al., 2004). XWT also produces the relative phase angle in the time-frequency space between the two time series, which can be used to obtain the lag response behavior between the two time series (Jevrejeva et al., 2003).

WTC analysis quantifies the correlation between the two time series in consideration and determines significant coherency (association) at lower common power, which makes it more useful than XWT alone (Grinsted et al., 2004). The current study used the Monte Carlo approach (Wallace et al., 1993) to calculate the confidence levels against red noise (Brownian noise). A 5% significance level was considered appropriate based on previous literature (Torrence and Compo, 1998).

## RESULTS

The study determined the association between the California hydrologic region streamflow (obtained from the PC1 of 14 different stations and named as streamflow1) variation and ENSO/PDO variation over the study period. Figure 2 shows how each of the time series has varied at multiple frequency bands over the study period using CWT power spectrums and global wavelet spectrums. Figure 3 (Figure 4) shows the XWT (WTC) common power spectrums between streamflow1 and ENSO/PDO.

### *Variance in individual time-series data*

The CWT power spectrum of streamflow1 revealed that significant variance in the California hydrologic region occurred in the 8-16 year time-scale band from 1968 to 2007, in the 2-3 year band around 1973, and in the 3-4 year band from 1971 to 1982 (Figure 2a). The highest variance in the 8-16 year band was also picked by the global wavelet spectrum as the spike suggested (Figure 2a). The 3-6 year average variance across the study period showed that the time series had a declining pattern after 2002.

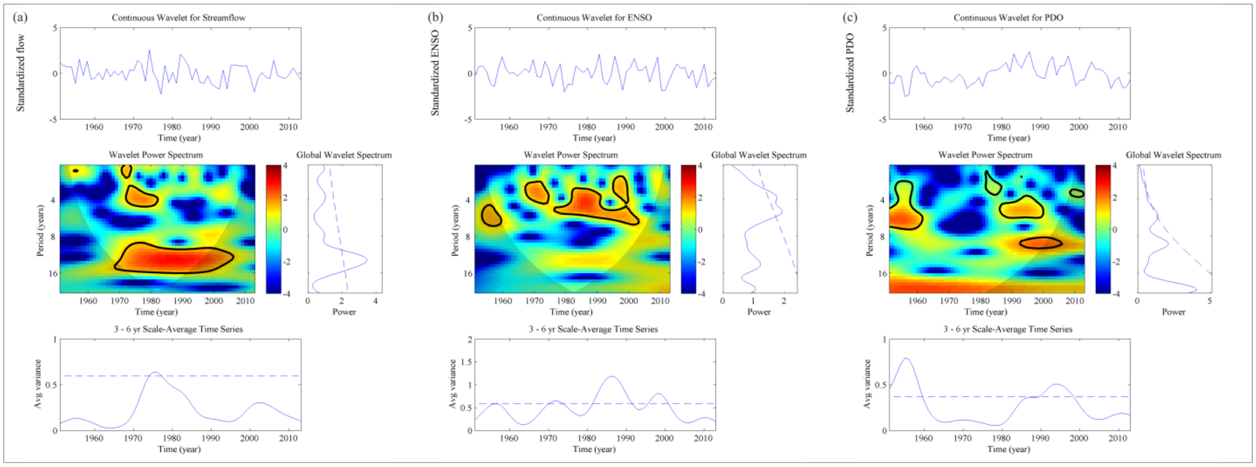


**Figure 2.** Time-series variation, CWT power spectrum, global wavelet spectrum, and average variance over the study period for (a) streamflow1, (b) ENSO, and (c) PDO. The thick black contour lines mark the regions of 5% significance level against the red noise.

The CWT power spectrum of ENSO showed that high variance was prevalent at multiple intervals along the study period in the 3-8 year band. The highest variance was observed in the 3-6 year band from 1975 to 2004, which was also picked by the global wavelet spectrum (Figure 2b). The average variance showed the periodic nature of the ENSO cycle with a periodicity of 2-7 years.

The CWT power spectrum of PDO showed significant variance in the 3-8 year band from 1951 to 1963, in the 2-4 year band from 1981 to 1987, in the 4-6 year band from 1984 to 1999, in the 8-10 year band from 1993 to 2006, and around the 4 year band from 2008 to 2013 (Figure 2c). The presence of high variance was observed across the entire study period in the 16-year band and beyond, which was also picked by the global wavelet spectrum but was not found to be significant at a 5% significance level. The average variance over the study period echoed the decadal nature PDO cycle.

***Covariance between the time series***

From the XWT between streamflow1 and ENSO, high common power (covariance) was observed around the 6-year scale from 1953 to 1958, in the 2-5 year band from 1968 1988, in the 8-16 year band from 1969 to 2005, and in the 3-4 year band from 1994 to 2000 (Figure 3a). The arrows indicating the relative phase relationship in the 2-6 year band did not show any uniform pattern, as the arrows were observed to point both towards right (in-phase relationship) and left (anti-phase relationship). An in-phase (anti-phase) relationship implies a change in the same (opposite) direction. In the 8-16 year band, the arrows were found to be pointing vertically upwards. Vertically upward arrows indicate that ENSO led streamflow1 by 90°, or in other words, there was a lag of one quarter between change in ENSO and streamflow1.

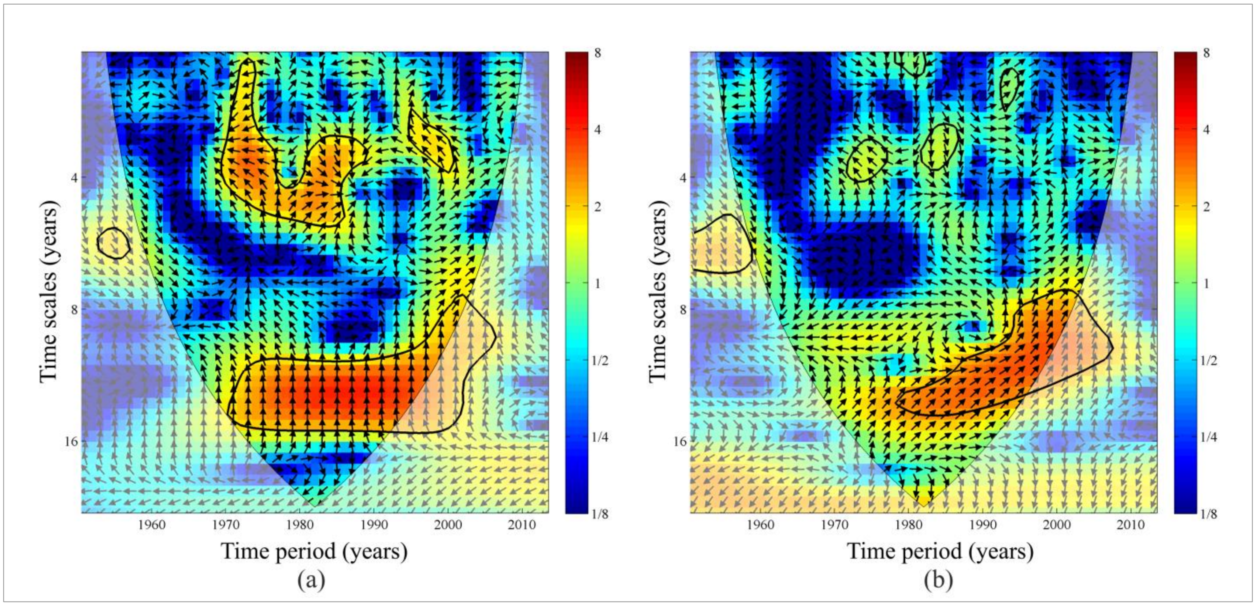


**Figure 3.** XWT common power spectrum between (a) streamflow1 and ENSO and (b) streamflow1 and PDO. The thick black contour lines mark the regions of 5% significance level against the red noise. The relative phase relationships are represented by the arrows, where the right (left) pointed arrows indicate an in-phase (anti-phase) relationship. Arrows pointing vertically upward show that ENSO (PDO) led streamflow1 by 90° (one quarter).

From the XWT between streamflow1 and PDO, significant covariance was observed in the 6-7 year band from 1951 to 1960, at multiple intervals from 1970 to 1993 in the 2-4 year band, and in the 8-16 year band from 1979 to 2008 (Figure 3b). The arrows indicating relative phase relationship in the lower bands did not show any specific pattern as the arrows were found to be pointing both in towards the right and the left. The arrows in the 8-16 year band were found to be pointing towards the right with inclinations of pointing straight up. This indicates that PDO and streamflow changed in the same direction from 1979 to 2008 with PDO leading streamflow by few months to approximately one quarter.

***Correlation between the time series***

From the WTC analysis between streamflow1 and ENSO, it was observed that in the 8-16 year band, from 1955 to 2013, streamflow1 and ENSO were highly correlated: the modified $R^2$, calculated based on Torrence and Webster (1999), was found to be as high as 1.0. Higher correlation with an $R^2$ of 0.7 was observed around the 6-year band from 1957 to 1963 (Figure 4a). There were other instances of high correlation in the lower as well higher time-scale bands but they were not found to be statistically significant. The arrows indicating the relative phase relationship were mostly found to be pointing vertically straight up, indicating a 90° (one quarter) lag between ENSO and streamflow1.

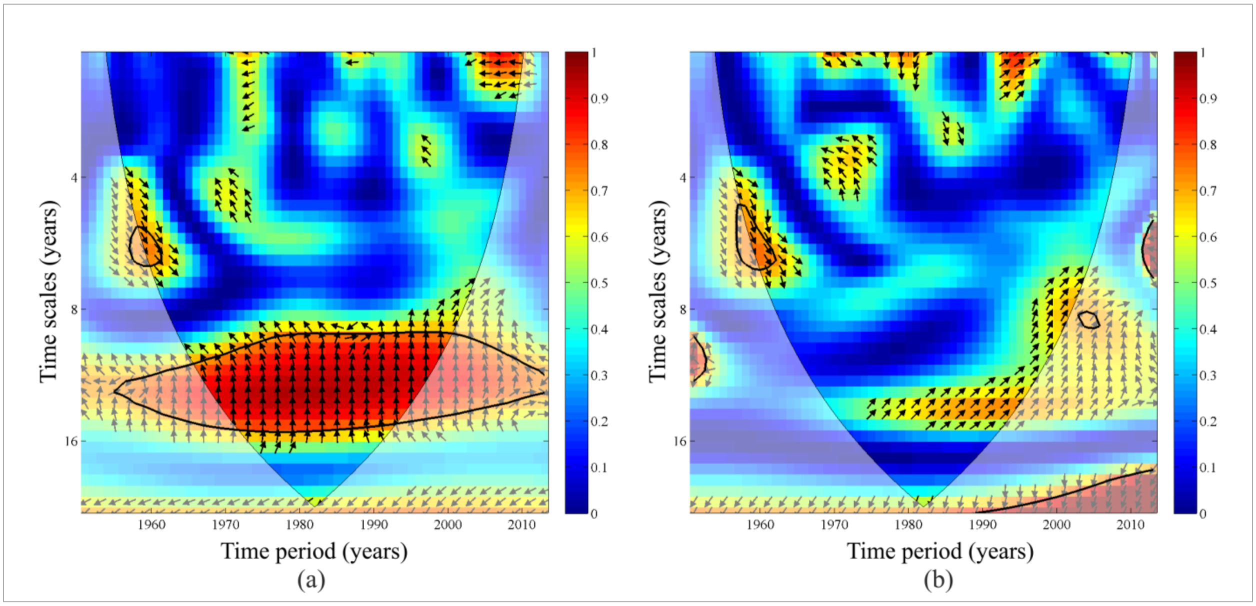


**Figure 4.** WTC common power spectrum between (a) streamflow1 and ENSO and (b) streamflow1 and PDO. The thick black contour lines mark the regions of 5% significance level against the red noise. The relative phase relationships are represented by the arrows, where the right (left) pointed arrows indicate an in-phase (anti-phase) relationship. Arrows pointing vertically upward show that ENSO (PDO) led streamflow1 by 90° (one quarter).

The WTC between streamflow1 and PDO showed that they were highly correlated in the 8-10 year band from 1951 to 1953, in the 4-8 year band from 1957 to 1963, in the bands beyond 16 years from 1990 to 2013, and around the 6-year band from 2010 to 2013. There were other instances of high correlation along the study period at multiple frequency bands but they were not found to be statistically significant. The arrows indicating the relative phase relationship did not show any uniform pattern in the regions of significance. However, there was a higher tendency of the arrows to be pointing downwards indicating a negative lag between PDO and streamflow1.

## DISCUSSIONS AND CONCLUSION

In this study, 14 streamflow stations from the California hydrologic region were selected and data were obtained over a study period of 63 years (from 1951 to 2013) to evaluate the association between California streamflow variation and two of the most significant oceanic-atmospheric indices of the Pacific Ocean that highly influence the western US hydrology, namely ENSO and PDO. Using the concepts of CWT, followed by XWT and WTC, the study evaluated the correlation between California streamflow variation and ENSO/PDO at multiple frequency bands over the study period.

The results revealed that both ENSO and PDO have influenced California streamflow variation over the years at multiple frequency bands, though ENSO showed a much higher association. For ENSO, the most significant time-scale band was found to the 8-16 year band, where ENSO and California streamflow were found to be directly correlated with a lag of one quarter (three months) between them. PDO was found to be highly correlated with California streamflow at bands beyond 16 years. The limitation of the record length did not allow the current study to evaluate the association between the time series beyond the 16-year band with certainty.

But the association between PDO and California streamflow suggested the presence of high correlation beyond the 16-year band. In the case of ENSO, which alters over a cycle of 2-7 years, higher correlation with California streamflow at the 8-16 year band suggested that every ENSO cycle (both the warm and the cold phases) may have influenced the streamflow variation over the years. The relative phase relationship also suggested the lag response behavior between ENSO and California streamflow. In the case of PDO, which is decadal in nature and alters every 25-50 years, association with California streamflow at time-scale bands beyond 16 years provided important insight into how PDO might have been correlated to California streamflow variation. An extension of the record length may allow the study to evaluate correlation at higher time-scale bands.

The major contributions of the current study are:

- Using data from unimpaired streamflow stations of the California hydrologic region to observe the variability over the years at multiple frequency bands.
- Determining the covariance and evaluating the correlation between California streamflow variation and ENSO/PDO at significant intervals at multiple frequency bands.
- Observing the relative phase relationship between California streamflow and ENSO/PDO at different intervals of significant correlation.

The findings of the study may be helpful in understanding the nature of California streamflow change patterns in association with the temporal change of ENSO and PDO.

**REFERENCES**


Beebee, R. A., Manga, M. (2004). “Variation in the relationship between snowmelt runoff in Oregon and ENSO and PDO.” *Journal of the American Water Resources Association* 40 (02099), 1011–1024. doi:10.1111/j.1752-1688.2004.tb01063.x.

Beecham, S., Chowdhury, R. K. (2009). “Temporal characteristics and variability of point rainfall: a statistical and wavelet analysis.” *International Journal of Climatology* 30, 458–473. doi:10.1002/joc.1901.

Burn, D. H., Elnur, M. A. H. (2002). “Detection of hydrologic trends and variability.” *Journal of Hydrology* 255 (1), 107–122.

Carrier, C., Kalra, A., & Ahmad, S. (2013). “Using Paleo Reconstructions to Improve Streamflow Forecast Lead Time in the Western United States.” *Journal of the American Water Resources Association*, 49(6), 1351–1366. doi:10.1111/jawr.12088

Carrier, C., Kalra, A., & Ahmad, S. (2016). “Long-range precipitation forecast using paleoclimate reconstructions in the western United States.” *Journal of Mountain Science* 13 (4), 614–632. doi:10.1007/s11629-014-3360-2.

Choubin, B., Khalighi-Sigaroodi, S., Malekian, A., Ahmad, S., & Attarod, P. (2014). “Drought forecasting in a semi-arid watershed using climate signals: a neuro-fuzzy modeling approach.” *J. Mt. Sci*. 11(6): 1593–1605, doi: 10.1007/s11629-014-3020-6.

Cayan, D. R., Redmond, K. T., & Riddle, L. G. (1999). “ENSO and hydrological extreme in the western United States.” *Journal of Climate* 12, 2881–2893. doi:10.1175/1520-0442(1999) 012<2881:EAHEIT>2.0.CO;2.

Dawadi, S., & Ahmad, S. (2012). “Changing climatic conditions in the Colorado River Basin: Implications for water resources management.” *Journal of Hydrology, 430–431*, 127–141. http://doi.org/10.1016/j.jhydrol.2012.02.010

Dawadi, S., & Ahmad, S. (2013). "Evaluating the impact of demand-side management on water resources under changing climatic conditions and increasing population." *Journal of Environmental Management*, *114*, 261–75. http://doi.org/10.1016/j.jenvman.2012.10.015

Durdu, Ö. F. (2010). "Effects of climate change on water resources of the Büyük Menderes River basin, western Turkey." *Turkish Journal of Agriculture and Forestry* 34 (4), 319–332.

Foufoula-Georgiou, E., Kumar, P. (1995). "Wavelets in Geophysics." Academic Press, San Diego, CA, USA, p. 373.

Griffin, D., Anchukaitis, K. J. (2014). "How unusual is the 2012–2014 California drought?" *Geophys. Res. Lett*., 41, 9017–9023, doi:10.1002/2014GL062433.

Grinsted, A., Moore, J. C., & Jevrejeva, S. (2004). "Application of the cross wavelet transform and wavelet coherence to geophysical time series." *Nonlinear Processes in Geophysics* 11, 561–566. doi:10.1002/etep.

Hamlet, A. F., Lettenmaier, D. P. (1999). "Columbia river streamflow forecasting based on ENSO and PDO climate signals." *Journal of Water Resources Planning and Management* 125 (6), 333–341.

Hidalgo, H. G., Dracup, J. A. (2003). "ENSO and PDO effects on hydroclimatic variations of the Upper Colorado River Basin." *Journal of Hydrometeorology* 4,5–23.

Hoerling, M. P., Kumar, A. (2000). "Understanding and predicting extratropical teleconnections related to ENSO." In: El Niño and the Southern Oscillation: Multi-scale Variations and Global and Regional Impacts (H. F. Diaz & V. Markgraf, eds). Cambridge University Press, Cambridge, United Kingdom, pp. 57-88.

Intergovernmental Panel on Climate Change, IPCC. (2014). "AR5 - Working Group 3, Mitigation of Climate Change – Contribution of Working Group III." Available at: http://report.mitigation2014.org/spm/ipcc_wg3_ar5_summary-for-policymakers_approved.pdf.

Jevrejeva, S., Moore, J. C., & Grinsted, A. (2003). "Influence of the arctic oscillation and El Niño-Southern Oscillation (ENSO) on ice conditions in the Baltic Sea: the wavelet approach." *Journal of Geophysical Research* 108 (D21), 4677. doi:10. 1029/2003JD003417.

Kahya, E., Dracup, J. A. (1993). "U.S. streamflow patterns in relation to the El Niño/ Southern Oscillation." *Water Resources Research* 29 (8), 2491–2503. http://dx.doi.org/ 10.1029/ 93WR00744.

Kalra, A., Piechota, T. C., Davies, R., & Tootle, G. A. (2008). "Changes in US streamflow and western US snowpack." *Journal of Hydrologic Engineering*, 13(3), 156-163.

Kalra, A., & Ahmad, S. (2011). "Evaluating changes and estimating seasonal precipitation for the Colorado River Basin using a stochastic nonparametric disaggregation technique." *Water Resour. Res.* 47, W05555. http://dx.doi.org/10.1029/ 2010WR009118.

Kalra, A., Ahmad, S. (2012). "Estimating annual precipitation for the Colorado River Basin using oceanic-atmospheric oscillations." *Water Resources Research* 48, W06527. http://dx.doi.org/10. 1029/2011WR010667.

Kalra, A., Li, L., Li, X., & Ahmad, S. (2013a). "Improving streamflow forecast lead time using oceanic-atmospheric oscillations for Kaidu river basin, Xinjiang, china." *J. Hydrological Eng*. 18 (8), 1031–1040.

Kalra, A., Miller, W. P., Lamb, K. W., Ahmad, S., & Piechota, T. (2013b). "Using large-scale climatic patterns for improving long lead time streamflow forecasts for Gunnison and San Juan River Basins." *Hydrological Processes*, 27(11), 1543–1559. doi:10.1002/hyp.9236.

Kalra, A., Ahmad, S., & Nayak, A. (2013c). "Increasing streamflow forecast lead time for snowmelt-driven catchment based on large-scale climate patterns." *Advances in Water Resources*, 53, 150–162. doi:10.1016/j.advwatres.2012.11.003.

McCabe, G. J., Wolock, D. M. (2002). "A step increase in streamflow in the conterminous United States." *Geophysical Research Letters* 29 (24), 2185. doi:10.1029/2002GL015999.

McCabe, G. J., Betancourt, J. L., & Hidalgo, H. G. (2007). "Associations of decadal to multidecadal sea-surface temperature variability with Upper Colorado river flow." *Journal of the American Water Resources Association* 43 (1), 183–192.

Miles, E. L., Snover, A. K., Hamlet, A. F., Callahan, B., & Fluharty, D. (2000). "Pacific northwest regional assessment: the impacts of climate variability and climate change on the water resources of the Columbia River Basin." *Journal of the American Water Resources Association* 36 (2), 399–420.

Pathak, P., Kalra, A., & Ahmad, S. (2016a). "Temperature and precipitation changes in the Midwestern United States: implications for water management." *International Journal of Water Resources Development*, 1–17. http://doi.org/10.1080/07900627.2016.1238343.

Pathak, P., Kalra, A., Ahmad, S., & Bernardez, M. (2016b). "Wavelet-Aided Analysis to Estimate Seasonal Variability and Dominant Periodicities in Temperature, Precipitation, and Streamflow in the Midwestern United States." *Water Resources Management*, 30(13), 4649–4665. http://doi.org/10.1007/s11269-016-1445-0.

Percival, D.B., Walden, A.T. (2000). "Wavelet Methods for Time Series Analysis." Cambridge University Press, Cambridge, p. 594.

Qaiser, K., Ahmad, S., Johnson, W., & Batista, J. R. (2013). "Evaluating water conservation and reuse policies using a dynamic water balance model." *Environmental Management*, *51*(2), 449–58. http://doi.org/10.1007/s00267-012-9965-8

Sagarika, S., Kalra, A., & Ahmad, S. (2014). "Evaluating the effect of persistence on long-term trends and analyzing step changes in streamflows of the continental United States." *Journal of Hydrology* 517,36–53. doi:10.1016/j.jhydrol.2014.05.002.

Sagarika, S., Kalra, A., & Ahmad, S. (2015a). "Interconnection between oceanic-atmospheric indices and variability in the US streamflow." *Journal of Hydrology* 525, 724–736. doi:10. 1016/j.jhydrol.2015.04.020.

Sagarika, S., Kalra, A., & Ahmad, S. (2015b). "Pacific Ocean and SST and Z500 climate variability and western U.S. seasonal streamflow." *International Journal of Climatology* 36, 1515– 1533. doi:10.1002/joc.4442.

Shrestha, E., Ahmad, S., Johnson, W., & Batista, J. R. (2012). "The carbon footprint of water management policy options." *Energy Policy*, *42*, 201–212. http://doi.org/10.1016/j.enpol.2011.11.074

Souza, E. M. P., Echer, E., Nordemann, D. J., Rigozo, N. R., & Prestes, A. (2007). "Wavelet analysis of a centennial (1895–1994) southern Brazil rainfall series (Pelotas, 31°46'19"S 52°20'33"W)." *Climatic Change* 87 (3–4), 489–497. doi:10.1007/ s10584-007-9296-6.

Tamaddun, K., Kalra, A., & Ahmad, S. (2016a). "Identification of Streamflow Changes across the Continental United States Using Variable Record Lengths." *Hydrology*, 3(2), 24. http://doi.org/10.3390/hydrology3020024.

Tamaddun, K. A., Kalra, A., & Ahmad, S. (2016b). “Wavelet analysis of western U.S. streamflow with ENSO and PDO.” *Journal of Water and Climate Change*, 1–15. http://doi.org/10.2166/wcc.2016.162.

Tang, C., Chen, D., Crosby, B. T., Piechota, T. C., & Wheaton, J. M. (2014). “Is the PDO or AMO the climate driver of soil moisture in the Salmon River Basin, Idaho?” *Global and Planetary Change* 120,16–23. doi:10.1016/j.gloplacha.2014.05.008.

Thakali, R., Kalra, A., & Ahmad, S. (2016). “Understanding the Effects of Climate Change on Urban Stormwater Infrastructures in the Las Vegas Valley.” *Hydrology*, 3(4), 34. http://doi.org/10.3390/hydrology3040034.

Torrence, C., Compo, G. P. (1998). “A practical guide to wavelet analysis.” Bulletin of the American Meteorological Society 79 (1), 61–78. doi:10.1175/1520-0477(1998)079<0061: APGTWA>2.0.CO;2.

Torrence, C., Webster, P. (1999). “Interdecadal changes in the ENSO–monsoon system.” *Journal of Climate* 2679–2690. Available at: http://journals.ametsoc.org/doi/abs/10.1175/1520-0442(1999)012%3C2679:ICITEM%3E2.0.CO;2.

Wallace, J.M., Zhang, Y., & Lau, K.H. (1993). “Structure and seasonality of interannual and interdecadal variability of the geopotential height and temperature-fields in the northern-hemisphere troposphere.” *Journal of Climate* 6 (11), 2063–2082.

Wei, J., Jin, Q., Yang, Z., & Dirmeyer, P. A. (2016). “Role of ocean evaporation in California droughts and floods. *Geophysical Research letters* 6554–6562. doi:10.1002/grl.54627.

Weider, K., Boutt, D. F. (2010). “Heterogeneous water table response to climate revealed by 60 years of ground water data.” *Geophysical Research Letters* 37 (24), 10–15. doi:10. 1029/2010GL045561.

Zhang, F., Ahmad, S., Zhang, H., Zhao, X., Feng, X., & Li, L. (2016). “Simulating low and high streamflow driven by snowmelt in an insufficiently gauged alpine basin.” *Stochastic Environmental Research and Risk Assessment*, 30(1), 59–75. http://doi.org/10.1007/s00477-015-1028-2.