PRECIPITATION AND STREAMFLOW RESPONSES TO CLIMATE VARIABILITY IN THE ARKANSAS AND RED RIVER BASINS

By

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Abstract:

The Arkansas-Red River Basin (ARRB) features a steep east-west precipitation gradient ranging from 380 to 1420 mm. The objective of this study is to understand how precipitation (*P*) in different parts of the ARRB basin is connected to large-scale climate phenomena, mainly the Pacific Decadal Oscillation (PDO) and how streamflow (*Q*) responses to *P* differ in different phases of the PDO. Annual total *P* from 1932 to 2014 was significantly correlated with the PDO in all watersheds in the western and three watersheds in the central part of the basin ($p \leq 0.05$). On average, annual *Q* variability in the basin was high, with coefficient of variation of 0.72. The streamflow coefficient (*Q/P*) was 0.07, 0.14 and 0.29 in the western, central and eastern parts of the basin, respectively, meaning that 7, 14 and 29% of *P* translated to *Q*. During positive phase of the PDO, the western and central parts of the basin experienced the largest increase in annual *P* and *Q*. From negative to positive PDO, annual total *P* increased by 20.5 and 16.6% while *Q* increased by 50.4 and 52% in the western and central parts of the basin, respectively. Seasonally, *P* increased the most during winter for the western part of the basin and during spring for the central part. Also in the central and western parts of the ARRB, *Q* increased significantly in all seasons during positive PDO. *Q* increased by up to 53% during fall in the western part of the basin and up to 80% during winter in the central part of the basin. Grazing systems, such as winter wheat grazing can be managed to take advantage of the increased foraging production potential during positive PDO phase. Farmers, ranchers and farm insurance agents can also benefit from the knowledge of potential droughts associated with the negative phases of the PDO by planting drought resistant crops or reducing herd size and purchasing drought insurance. Finally, municipal utility authorities can make more effective middle and long range planning by considering the water availability during the positive and negative phases of PDO.

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CHAPTER I

ANNUAL PRECIPITATION AND STREAMFLOW RESPONSES TO CLIMATE VARIABILITY IN THE ARKANSAS RIVER AND RED RIVER BASIN

1.1 Abstract

The Arkansas-Red River Basin (ARRB) features a steep east-west precipitation gradient ranging from 380 to 1420 mm. To facilitate management and planning of water resources in the basin, it is important to understand how precipitation (*P*) in different parts of the basin is connected to the large-scale climate phenomena and how streamflow (*Q*) responses to *P* differ in different phases of each climate phenomenon.

We investigated the relationship of PDO, AMO and ENSO indices with annual precipitation in the ARRB and the effects of PDO on annual precipitation and streamflow in watersheds along the ARRB. Our results showed that annual total *P* from 1932 to 2014 was significantly correlated ($p \leq 0.05$) with the Pacific Decadal Oscillation (PDO) index in all watersheds in the western and three in the central parts of the basin, but not in any watershed in the eastern part of the basin. Atlantic Multidecadal Oscillation (AMO) was significantly correlated with annual *P* in three watersheds in the east basin. El-Niño Southern Oscillation (ENSO) was correlated with *P* in three western watersheds and in one central watershed. The coefficient of variation for *Q* was 0.72, and the *Q* coefficients (Q/P) were 0.07, 0.14 and 0.29 in the western, central and eastern parts of the basin, respectively, meaning that 7, 14 and 29% of *P* translated to *Q*. The positive PDO phase had

significant effects on annual *P* and *Q* in the western and central parts of the ARRB. Compared with the negative phase, the annual total *P* in positive phase of PDO increased by 20.5 and 16.6 while *Q* increased by 50.4 and 52% in the western and central parts of the basin, respectively.

The ARRB basin has a much greater variation in *Q* compared to many other streams and rivers in the U.S. These inter-annual variations have been amplified by the pacific decadal oscillation (PDO), especially for the central and western part of this basin. During the positive phase of PDO, precipitation in western and central parts of the basin increased by approximately 20%, resulting in proportionally larger increase in streamflow. Grazing system, such as winter wheat grazing can be managed to take advantage of the increased foraging production potential during positive PDO phase. Farmers, ranchers and farm insurance agents can also benefit from the knowledge of potential droughts associated with the negative phases of the PDO by planting drought resistant crops or reducing herd size and purchasing drought insurance. Finally, municipal utility authorities can make more effective middle and long range planning by considering the water availability during the positive and negative phases of PDO.

KEYWORDS: climate variability, large-scale climate phenomena, streamflow, precipitation gradient, Arkansas-Red River Basin.

1.2 Introduction

Improved understanding of the interactions between human and natural systems at the regional level in the context of global change is one of the greatest environmental challenges (Dooge, 1992; McCarthy, 2001; Seoane and López, 2007; Carey et al., 2010; Tingstad and MacDonald, 2010; Liu and Cui, 2011; Bai et al., 2014; Brikowski, 2015; Gao et al., 2016). Rivers and streams have been used to irrigate crops and nourish cities for thousands of years. With more and more people seeking to live in arid or semi-arid regions (Sorooshian, 2006), management actions to keep up with increasing water demand are often necessary (McCarthy, 2001). In Oklahoma, United States (U.S), a state located in the central of the Arkansas/Red River Basins (ARRB), 56% of the water used for all purposes comes from surface water, i.e., reservoirs, rivers and streams (Oklahoma Water Resources Board, 2015). Such demand is not likely to diminish since the state's population has been steadily increasing while the groundwater, another major source of water in the state and throughout the ARRB, has been steadily decreasing in some regions (Albrecht, 1988; Kustu et al., 2010; Konikow, 2015). While groundwater depletion directly affect water availability for agriculture, it can also reduce baseflow in streams and rivers (Brikowski, 2008; Kustu et al., 2010) necessary to supply population downstream, particularly under below average preciptation. To meet the societal demands of water with anticipated increase in frequency of drought, especially in the western and central parts of the basin, inter-basin water transfer from regions of historically high runoff depth such as eastern Oklahoma to regions of low runoff such as the metropolitan areas of Oklahoma City is under intensive discussion (Thornton, 2014).

To challenge local water managers in the ARRB even further, climate variability often provokes extreme hydrologic events such as droughts and floods, with direct impacts on irrigation, public water reserves and ecosystem vitality (Buckner and Kurklin, 1984; Dziegielewski et al., 1997; Nobre et al., 2016). While societies have learned how to overcome seasonal to inter-annual variations in precipitation through increasing surface water impoundments, such as reservoirs and farm ponds, the steady departure of precipitation to below average conditions can slowly deplete state-wide water reserves. For example, the drought in California during 1987-1992 was not felt for the first three years while the use of stored water was allowed, but as drought persisted, state water reserves depleted, impacting agriculture, public water storage and energy generation (Dixon et al., 1996; Dziegielewski et al., 1997). Like-wise in Sao Paulo, Brazil during 2014-2016, two years of extreme drought rapidly decreased reservoir storage state-wide, affecting water supply in the biggest mega-city in South-America (Nobre et al., 2016). In the ARRB, a region with a large east-west precipitation gradient, extreme hydrologic events can unfold differently from one watershed to the other (Buckner and Kurklin, 1984; Hong and Kalnay, 2000; Schubert et al., 2004b). In the western portion of the basin, droughts are known to have aggravated some of the greatest natural tragedies in the U.S, like the 1930's dust bowl (Schubert et al., 2004b; Nigam et al., 2011). To the east, protracted wet periods can cause floods, causing deaths and costing millions of dollars (Buckner and Kurklin, 1984). To adapt the socio-ecological systems to increased climate variability in the ARRB, it is important to understand how precipitation in different parts of the basin is connected to the large-scale climate phenomena and how streamflow responses to precipitation differ in different phases of each climate phenomenon. Understanding climate variability and its drivers is essential to the development of hydrologic models and hydrologic forecasting tools that will ultimately aid in decision making (Clark et al., 2001; Tootle and Piechota, 2006; Kalra and Ahmad, 2009; Oubeidillah et al., 2011; Switanek and Troch, 2011; Wei and Watkins, 2011; Joseph et al., 2012).

Climate variability in the U.S has been widely discussed and often attributed to planetary scale climate phenomena (Hong and Kalnay, 2000; Enfield et al., 2001; McCabe et al., 2004; Schubert et al., 2004b; Nigam et al., 2011; Pu et al., 2016). Information regarding large-scale climate phenomena is not usually downscaled to watershed levels (e.g. USGS HUC 8 or 10) where most management decisions are made. Climate variability can be explained as a natural or a non-anthropogenic variability spanning from years to decades. It is caused by interactions of variables such as variations in earth's orbit, sea level pressure, volcanic eruptions, and variation in wind speed (Ghil, 2002). Based on the pattern of these planetary-scale phenomena, scientists create climate indices, using different approaches (National Center for Atmospheric Research Staff, 2015). A climate index is a simple diagnostic quantity used to characterize these patterns. Examples of climate indices are the ones used to quantify deviations from mean sea surface temperatures (SSTs) (National Center for Atmospheric Research Staff, 2015). The SSTs are recurring patterns of ocean-atmosphere anomalies that are known to affect continental atmosphere pressure, temperature and precipitation throughout the world (Mantua et al., 1997; Enfield et al., 2001; Englehart and Douglas, 2003; Fye et al., 2004; McCabe et al., 2004; Schubert et al., 2004a; Knight et al., 2006; Lapp et al., 2013;). The most frequently discussed, large scale modes of climate variability affecting the continental U.S and the ARRB include the El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO).

ENSO is the most short-lived of the three, with phases typically persisting from 6 months to 5 years (Ghil, 2002). It is characterized by surface water temperature variations in the central Pacific Ocean. ENSO causes more severe impacts on climate along the Equator, with secondary effects in North America (Hare and Mantua, 2000). Across the central Great Plains, U.S, ENSO has been shown to affect winter precipitation and groundwater levels (Mauget and Upchurch, 1999; Kurtzman and Scanlon, 2007; Yang et al., 2007; Kuss and Gurdak, 2014).

The PDO persists longer than ENSO, presenting a decadal to multi-decadal pattern of occurrence and is characterized by variations in surface water temperatures along the North American Pacific Coast. The PDO has a stronger influence in North America with secondary effects in the tropics (Mantua et al., 1997; Zhang et al., 1997; Miles et al., 2000; Mantua and Hare, 2002). Like ENSO, the PDO has been shown to affect precipitation and groundwater levels across the Great Plains and Central U.S (Zume and Tarhule, 2006; Kurtzman and Scanlon, 2007; Kuss and Gurdak, 2014)

The AMO is a multi-decadal pattern of 65 to 85 years and is characterized by variations in surface water temperature on the Northern Atlantic Ocean (Enfield et al., 2001). Studies have shown its effects over precipitation in Europe, North and South America (Enfield et al., 2001; Knight et al., 2006). In central U.S, river flows have shown positive correlation with warm AMO

(Tootle and Piechota, 2006; Sagarika et al., 2015). Over the Great Plains, AMO was reported to exert profound influence on precipitation across decadal time-scales (Nigam et al., 2011).

While the hydroclimatology of the central U.S is clearly influenced by AMO, PDO, and ENSO (Tootle and Piechota, 2006; Sagarika et al., 2015), there are great differences in the spatial pattern of occurrence and effects of SSTs on streamflow and precipitation in this region (Tootle and Piechota, 2006; Sagarika et al., 2015). Nigam et al. (2011) found that AMO is more often tied to multi-year droughts than the PDO and ENSO over the Great Plains. Kuss and Gurdak (2014) showed that groundwater levels in the main aquifers of the central U.S are influenced by ENSO and PDO more so than AMO. In the proximity of the ARRB, adjacent basins to the west have manifested different responses to the PDO. The PDO has showed to be significantly correlated to streamflow and precipitation in the Puerco Rico basin, northwest New Mexico (Molnar and Ramirez, 2001) but not to three basins (Guadalupe, San Antonio and Nuances River basins) in southwest Texas (Joseph et al., 2012).

A knowledge gap exists between climate projection at local watershed scale to basin or even larger scale (Kurtzman and Scanlon, 2007). Considering the intricate relationships between SSTs and hydro-climatic factors in the ARRB, we hypothesize a transition in term of the influence of large climate phenomena on precipitation from PDO to AMO. This information is relevant and critical in long term water planning which is usually produced at watershed level such as the Watershed Planning Regions in Oklahoma (Board, 2011). In addition, such information can assist the planning and evaluation of potential interbasin water transfer project.

The overall objective of this study is to understand the effect of large-scale climate phenomena on precipitation and streamflow responses along the precipitation gradient of the ARRB. We have the following specific objectives in this study:

1. Investigate the relationship of PDO, AMO and ENSO indices with annual precipitation in the ARRB.
2. Determine the effects of PDO on annual precipitation and streamflow in watersheds along the ARRB.

1.3 Material and Methods

1.3.1 Study Area

The Arkansas River Basin and the Red River Basin or the ARRB is located in the southwestern part of the Mississippi River basin (Figure 1.1). The combined area of the two basins is of 538,382 km^2 and covers part of the states of Colorado, New Mexico, Kansas, Missouri, Arkansas, Louisiana, Texas and the totality of Oklahoma. The basin presents a unique east-west gradient of climate, hydrology, and vegetation. It has a humid subtropical climate in the east and a cold semi-arid climate to the west (Kottek et al., 2006). The annual precipitation in the ARRB is as high as 1400 mm in the southeast and gradually decreases to as little as 330 mm in the northwest. A nearly reverse gradient of annual potential evapotranspiration exists ranging from 1000 mm in the southeast to 1700 mm in the northwest. The gradient in annual surface runoff is even steeper, ranging from as high as 500 mm in the east to only 2 mm in the west (Duan and Schaake, 2003). As a testimony to such climate diversity, twelve level III eco-regions (U.S EPA eco-region Framework) are contained within the basin. The large precipitation gradient and diverse ecosystems allied with long-term records of precipitation and streamflow make the ARRB an ideal basin for understanding streamflow responses to long-term climate variability.Sixteen watersheds across the ARRB were chosen as study units. Streamflow data were obtained from the USGS water-watch database (http://waterwatch.usgs.gov).

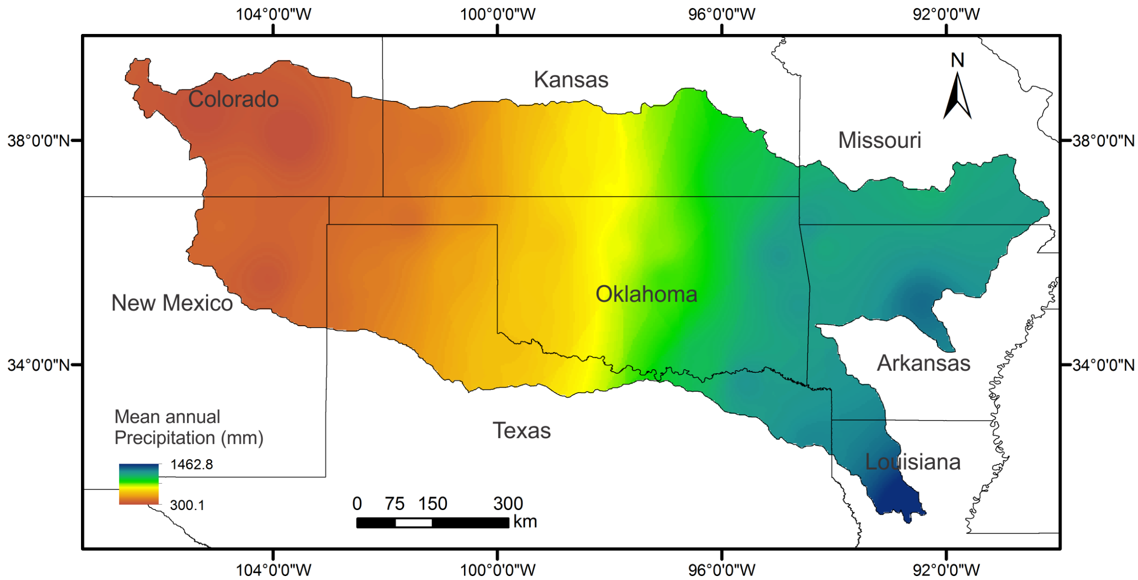

Figure 1.1. Arkansas River and Red River basin outline. The colors represent annual in the basins from 1932 to 2014.

Several factors were considered before selecting the watersheds suited to run our analysis. First, the selected watersheds have long-term (4 decades at least), non-regulated natural streamflow data. In other words, no large structure of surface water retention should be located upstream of the streamflow gauge. Second, it was a requisite that distance from streamflow gage to precipitation gauge should be no more than 20 km. Third, no significant ground water extraction record should exist in the watershed since it could alter streamflow (Brikowski, 2008; Kustu et al., 2010; Dale et al., 2015) and therefore the coefficient of streamflow to precipitation. Water withdrawal can be very significant in the dryer parts of the ARRB, where agriculture and human population rely heavily on streams and rivers (Petsch, 1980; Waltemeyer, 1989; Lewis and Esralew, 2009). Since each state regulates water records differently, exact water withdrawal amounts are difficult to obtain or calculate. Official records are usually limited to large rivers and streams along a period of a few decades. Therefore, there was no attempt to estimate and reconstruct streamflow where withdrawal occurred. Utilizing existing statistical summaries of streamflow and related publications (Petsch, 1980; Waltemeyer, 1989; Rasmussen and Perry, 2000; Funkhouser et al., 2008), we were able to identify and exclude rivers and streams that had any record of water subtractions for agriculture or city use, limiting our analysis to the smallest of rivers, creeks and streams. Based on those criteria, a total of 16 watersheds with sizes ranging from 37 km^2 to 2338 km^2 distributed across the states of Texas, Oklahoma, Arkansas, Kansas, Colorado and New Mexico were selected across the ARRB (Figure 1.2).

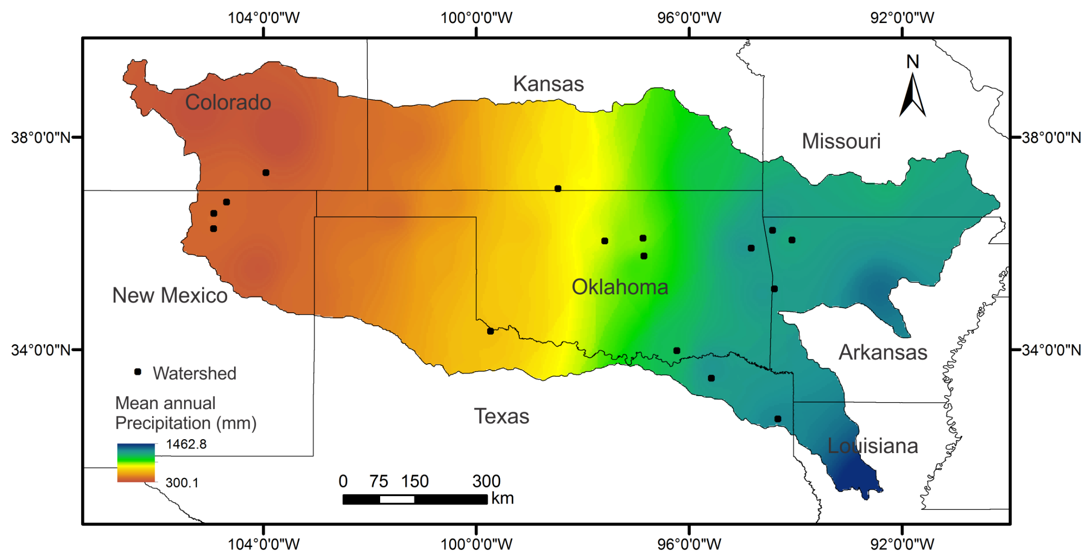

Figure 1.2 The annual precipitation for the Arkansas River and Red River basin. The black dots denote the locations of selected 16 watersheds.

The period of streamflow record ranges from 1931 to 2014. Mean annual precipitation ranged from 395 mm for the Van Bremer Arroyo Watershed in Colorado in the west to 1208 mm for the Litter Cypress Bayou Watershed in Texas in the east. To capture contrasting characteristics related to the transition in climate (subtropical humid to semi-arid climate) in the ARRB, we chose to categorize watersheds into three groups: western region, central region and eastern region (Table 1.1). Each categorized region is unique in terms of climate and vegetation. The western region has a semi-arid climate, where precipitation in watersheds ranged from 395 to 422 mm, and natural vegetation is predominantly short-grasses. The central region is a transition zone between a subtropical humid to a semi-arid climate, with mean annual precipitation ranging from 619 to 901 mm. Vegetation in the central region varies from hardwood forests and tall-grasses to mixed and short-grasses. The eastern region has a subtropical climate, with annual precipitation range of 1040 to 1208 mm and is mostly dominated by tall-grasses and pine/pine-hardwood forests.

Table 1.1. Name (including USGS gage station number), drainage area, altitude of gage station, annual precipitation, annual streamflow and length of record for 16 watersheds in the Arkansas River and Red River basins.

Watershed - USGS gage station number	Drainage area (km^2)	Gage altitude (m)	Mean annual precipitation (mm)	Mean annual flow (cfs)	Length of record
Western					
Van Bremer Ar, CO - 07126200	420	1512	395	1.6	1967-2009
Rayado Cr, NM - 07208500	168	2048	404	13.5	1931-2014
Vermejo R, NM - 07203000	780	1939	405	19.3	1928-2014
Ponil Crk, NM - 07207500	442	2021	422	11.5	1951-2014
Central					
Groesbeck Cr, TX - 07299670	784	435	619	23.8	1963-2014
Medicine Lodge R, KS - 07149000	2338	392	683	146	1938-2014
Skeleton Cr, OK - 07160500	1061	277	754	139	1950-2014
Council Cr, OK - 07163000	80	252	830	12	1934-1993
Dry Cr, OK - 07243000	178	250	901	25.9	1956-1994
Eastern					
Blue R, OK - 07332500	1235	153	1040	312	1936-2014
White R, AK - 07048600	1036	347	1113	535	1964-2014
Flint Cr, AK - 07195800	37	358	1159	14.8	1962-2014
James Fork Cr, AK - 07249400	381	140	1156	146	1959-2014
Sulphur R, TX - 07343000	714	112	1168	246	1950-2014
Baron Fork Cr, OK - 07197000	808	214	1161	324	1949-2014
Little Cypress B, TX - 07346070	1748	53	1208	521	1946-2014

Cr= Creek, R=River, B=Bayou, Ar=Arroyo

1.3.2 Precipitation, streamflow, evapotranspiration and the water-budget

Precipitation data was obtained from the National Historical Climatological Network (Menne et al 2015), the best available source of historical precipitation data in the U.S (Groisman and Legates, 1994). The length of precipitation record selected matches the length of streamflow record for the same watershed. Similar to some previous studies (Kibria et al., 2016), we required the selected precipitation gage to be located within 20 km in distance to the streamflow gage. Two precipitation gages in the western, three in the central and two in the eastern parts of the basin were selected beyond the 20 km stipulated radius. We chose not to use the average precipitation record for climatic division provided by the National Centers for Environmental Information like other studies did (Garbrecht et al., 2004; Kurtzman and Scanlon, 2007). The region averaged precipitation is delineated using state boundaries, separating homogeneous regions within different climatic zones (Guttman and Quayle, 1996). Within our spatial scale, several watersheds would fall under the same climatic zone, yielding same P amounts. In addition, in our study, precipitation gages within watershed boundaries have presented a poor correlation with climatic area averaged P ($r^2 < 0.5$).

Annual runoff depth (Q, mm) was calculated from annual flow (m^3/s) and associated contributing drainage area (m^2) for each watershed. Q includes surface and sub-surface runoff as well as baseflow from groundwater. Annual evapotranspiration was calculated based on a simplified water balance equation with only P, ET and Q components. Some assumptions were made to justify the use of this simplified equation. First, variation in soil water storage was considered to be negligible since net change of soil water storage in decadal time-scale is very small compared to cumulative P, Q and ET (Garbrecht et al., 2004). Secondly, watersheds selected were not located on major bedrock or alluvial aquifers and annual the groundwater recharge (G) was also considered negligible. The ET was considered the complement of runoff therefore was calculated as $ET = P - Q$, with all variables expressed in mm. The streamflow coefficient was calculated by dividing mean annual Q (mm) by mean annual P (mm). Simply put, the streamflow coefficient represented the portion of precipitation that was transferred to streamflow.

The coefficient of variation (Cv) grants an individual measure of P or Q variability. It allows comparing degree of oscillations in P and Q among watersheds in the ARRB and worldwide. The Cv is defined as the ratio between standard deviation of annual P or Q and the mean annual P or Q (Poff, 1996; Miles et al., 2000; Post and Jones, 2001; McMahon et al., 2007b). The coefficient of variation of precipitation ($Cv_{,P}$) is a measure of local climate variability (Post and Jones, 2001). In terms of streamflow, its coefficient of variation ($Cv_{,Q}$) indicates the combined effects of precipitation variation and watershed characteristics, which might amplify or attenuate variability in P inputs (Post and Jones, 2001). Large $Cv_{,P}$ indicates a large variability of annual P around the mean. In the same way, larger $Cv_{,Q}$ represents larger annual variation of Q around the mean.

1.3.3 PDO, AMO and ENSO

PDO, AMO and ENSO manifest themselves in a “warm”/positive phase or a “cold”/negative phase. For PDO, AMO and ENSO, such phases are negative PDO and positive PDO (Figure 1.3), negative AMO and positive AMO (Figure 1.4), and La Niña (negative) and El Niño (positive) (Figure 1.5), respectively. The positive and negative phase were associated with change in sea surface temperature at different part of the Pacific or Atlantic oceans and therefore different precipitation regime in the north hemisphere.

Researchers pointed out only two full PDO cycles in the past century, being negative or “cool” phases prevailing from 1890-1924 and 1947-1976 and positive or “warm” phases from 1925-1946 and from 1977 to at least middle 1990’s (Mantua et al., 1997; Mantua and Hare, 2002). However, growing evidence also suggests inter-decadal to decadal PDO behavior (White and Cayan, 1998; Mantua and Hare, 2002). Dramatic but less famous shifts occurred at different times, i.e., in 1957-58, not receiving the deserved emphasis by researchers (Zhang et al., 1997).

The PDO index was obtained from the Tokyo Climate Center (Japan Meteorological Agency website -http://ds.data.jma.go.jp/tcc/tcc/products/elnino/decadal/pdo.html).

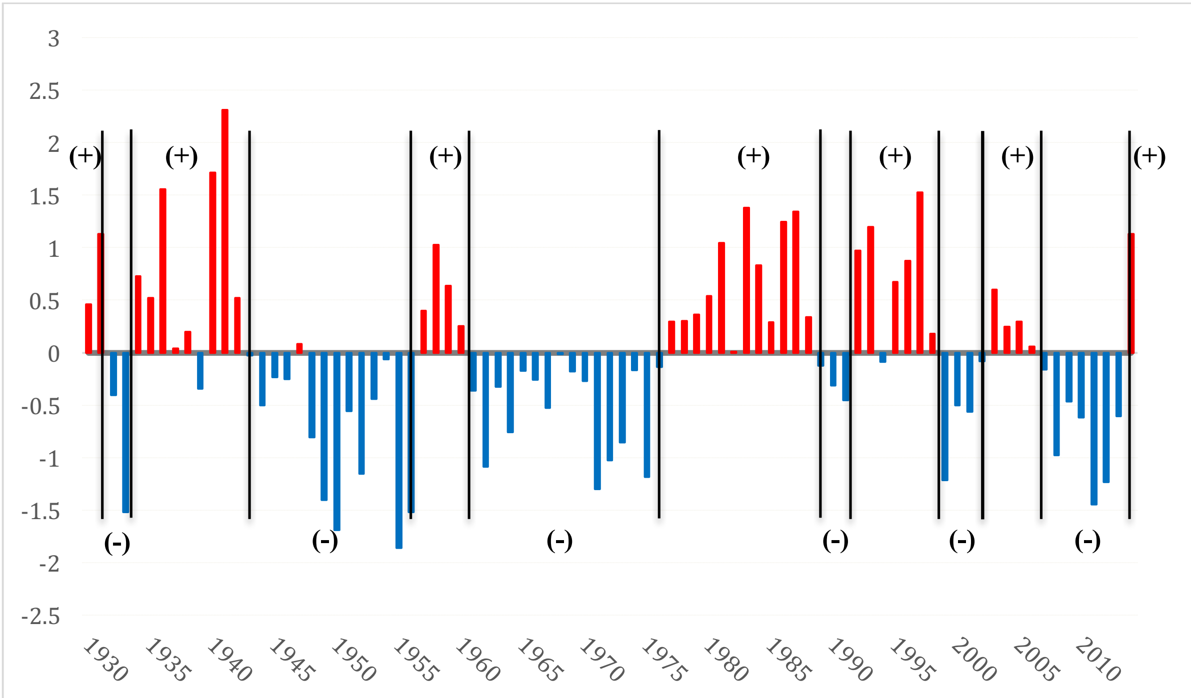

Figure 1.3. Time series of the Pacific Decadal Oscillation (PDO) index, 1930 to 2014. Values are annual PDO index summed over the months. Red bars represent the positive or "warm" years and the blue bars represent the negative or "cool" years of the PDO. The (+) and (-) signs represent the positive and negative phases adopted in this study.

Using the PDO index, each watershed data record was divided in positive and negative years. The negative phases include: 1932-33, 1943-56, 1961-76, 1989-91, 1999-02 and 2007-13. The positive phases include: 1934-42, 1957-60, 1977-88, 1992-98, 2003-06 and 2014.

AMO and ENSO indices were obtained from the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory.

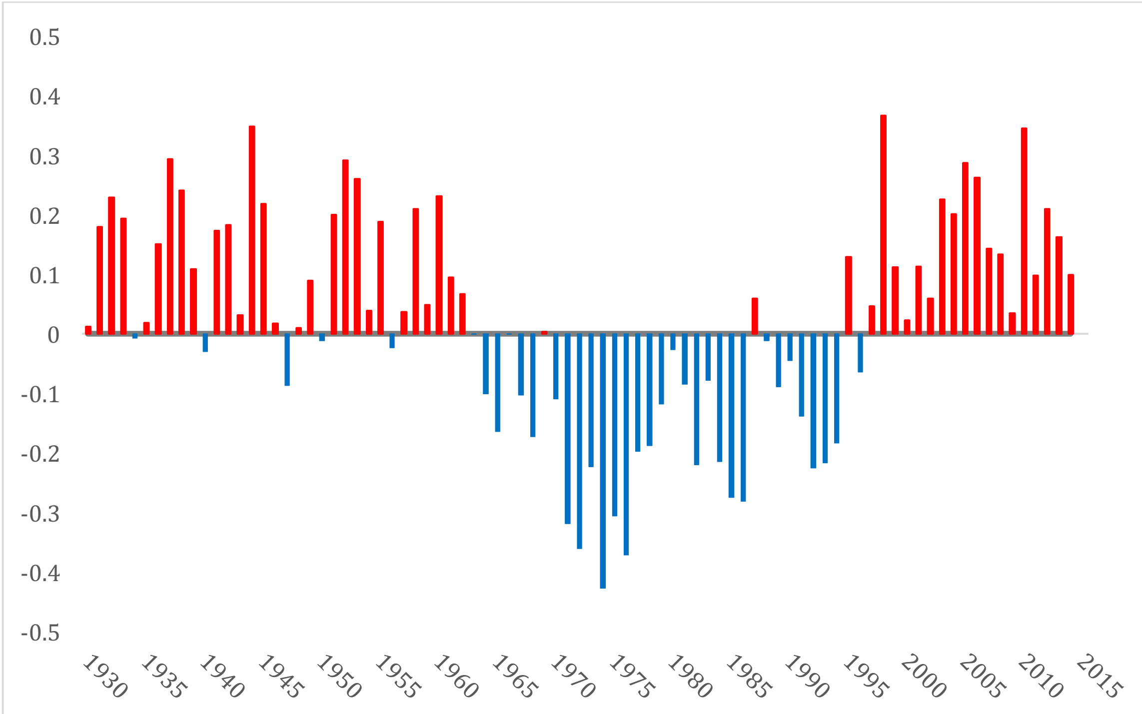

Figure 1.4. Time series of Atlantic Multidecadal Oscillation (AMO) index, 1930 to 2014. Values are annual AMO index summed over the months. Red bars represent the positive or "warm" years and the blue bars represent the negative or "cold" years of the AMO.

The multi-decadal behavior of the AMO and the almost seasonal behavior of ENSO did not allow us to divide positive and negative years evenly. AMO had long positive and/or negative phases, sometimes covering almost the entire period of the record. In the case of ENSO, dividing the analysis into multiple positive and negative phases could increase miscalculations caused by lagged effects of precipitation in inter-annual streamflow. Therefore, AMO and ENSO indices were only used in the correlation analysis.

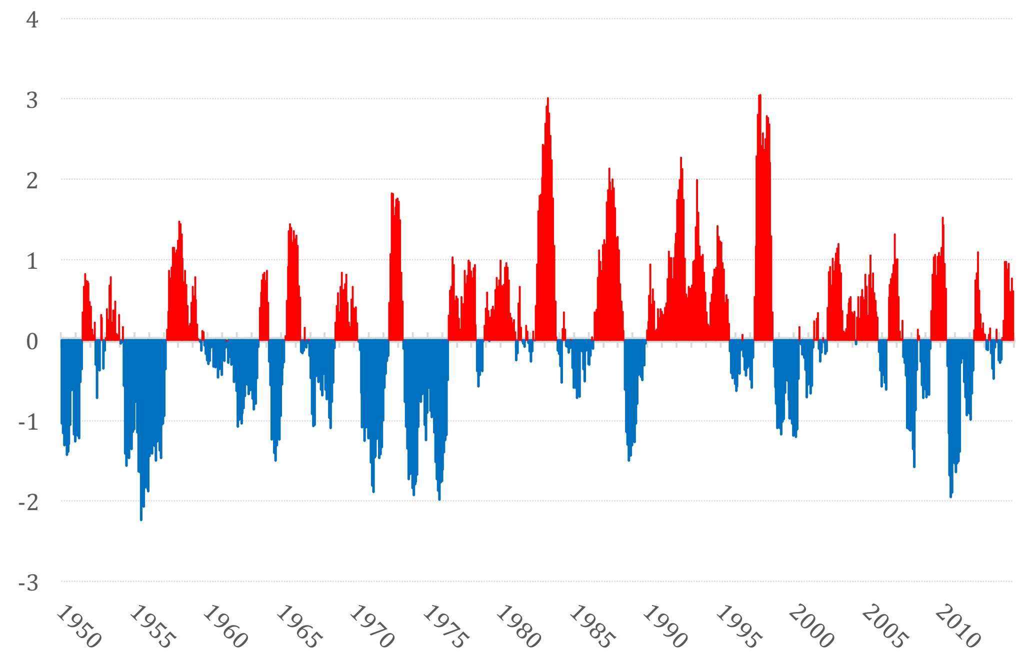

Figure 1.5. Time series of El-Niño Southern Oscillation index, 1950 to 2014. Values represent the monthly ENSO index. Red bars represent the positive or El Niño phase and the blue bars represent the negative or La Niña phase.

1.3.4 Sensitivity

While the *Cv* grants an individual measure of *P* or *Q* variability, sensitivity compares the relationship among *P*, *Q* and *ET*. Sensitivity can be regarded as the level in which a certain system will respond to changes in climatic conditions (Miles et al., 2000; McCarthy, 2001). Using varied approaches, sensitivity analysis is frequently employed in hydrological studies to evaluate sensitivity of hydro-climatic factors such as *Q* and ET to changes in *P* (Garbrecht et al., 2004; Chiew, 2006; Seoane and López, 2007; Harman et al., 2011; Amo-Boateng et al., 2014; Bai et al., 2014; Brikowski, 2015; Dale et al., 2015; Kibria et al., 2016;). Sensitivity is considered an intrinsic property of a watershed, which enables the establishment of a metric to compare responses among different watersheds at same time-scales (Chiew, 2006; Liu and Cui, 2011). In order to better understand the relationship between PDO phases and streamflow responses, we analyzed sensitivity of *Q* and *ET* to *P* changes during negative and positive PDO.

Sensitivity of *Q* or *ET* to *P* was calculated as the proportional change in *Q* or *ET* from negative to positive PDO years, divided by the proportional change in *P* for the same period of time (Garbrecht et al., 2004). In this case, if sensitivity of *Q* to *P* is 2, it means that for a 1% increase in *P*, there will be a 2% increase in *Q*.

1.3.5 Statistical analysis

We ran statistics using the software programs: R-studio version 0.99.473, Stat-plus for Mac version LE and JMP Pro version 13.0.0. Regression analyses were performed between each of the climate indices and mean annual P for the whole period of study in each watershed on annual time step. For the ENSO index, called Multivariate Enso Index (MEI), the data were provided monthly, so the correlation analysis was run between monthly P and MEI.

1.4 Results

1.4.1 Coefficient of variation

The average $Cv_{,P}$ of all watersheds was 0.24, with values ranging from 0.20 to 0.29 (Table 1.2).

Table 1.2. Coefficient of variation of P ($Cv_{,P}$) and Q ($Cv_{,Q}$) for 16 watersheds in the ARRB.

Watershed	$Cv_{,P}$	$Cv_{,Q}$
Western	0.2	1.45
Van Bremer Ar, CO		
Rayado Cr, NM	0.26	0.65
Vermejo R, NM	0.26	0.77
Ponil Cr, NM	0.25	0.81
AVERAGE	0.24	0.92
Central		
Groesbeck Cr, TX	0.29	0.8
Medicine Lodge R, KS	0.21	0.6

Skeleton Cr, OK	0.28	0.91
Council Cr, OK	0.25	0.98
Dry Cr, OK	0.25	0.86
AVERAGE	0.26	0.83
Eastern		
Blue R, OK	0.24	0.67
White R, AK	0.23	0.38
Flint Cr, AK	0.21	0.5
James Fork R, AK	0.22	0.52
Sulphur R, TX	0.23	0.55
Baron Fork Cr, OK	0.22	0.48
Little Cypress B, TX	0.21	0.58
AVERAGE	0.22	0.53

The ranges of $Cv_{,P}$ were 0.2 to 0.26, 0.21 to 0.29 and 0.21 to 0.24 for western, central and eastern regions, respectively. The central region had the largest average and range of $Cv_{,P}$ while the eastern had the smallest average and range of $Cv_{,P}$. Statistically, there was no difference in $Cv_{,P}$ values between regions in the ARRB (Figure 1.6) (Appendix C).

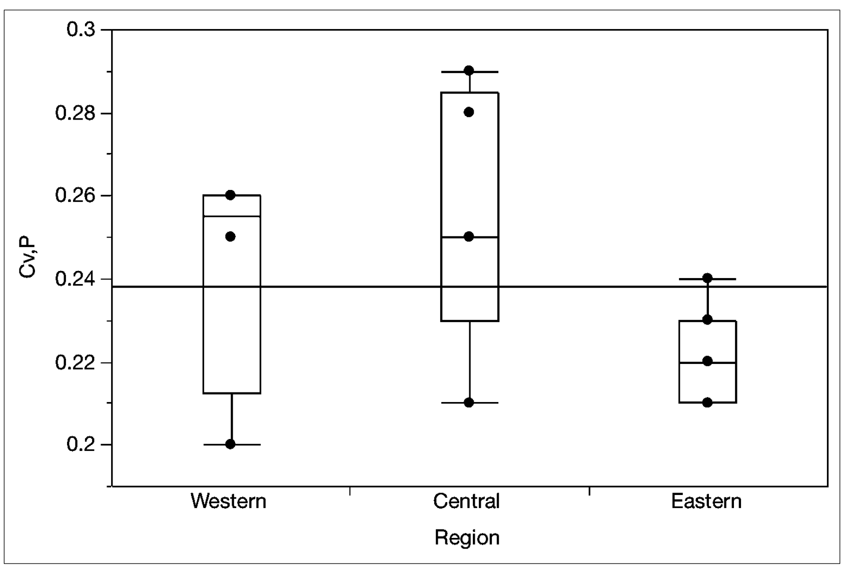

Figure 1.6. Box plot of a one-way Anova analysis of $Cv_{,P}$ between western, central and eastern regions in the ARRB

The average $Cv,_Q$ of all watersheds was 0.72, with the values ranging from 0.38 to 1.45. The ranges of $Cv,_Q$ were 0.65 to 1.45, 0.6 to 0.98 and 0.38 to 0.67 for western, central and eastern region, respectively. $Cv,_Q$ values in the western and central watersheds of the ARRB are statistically equal (Appendix D) while $Cv,_Q$ values in both regions are statistically different from $Cv,_Q$ values in the eastern region (Figure 1.7)

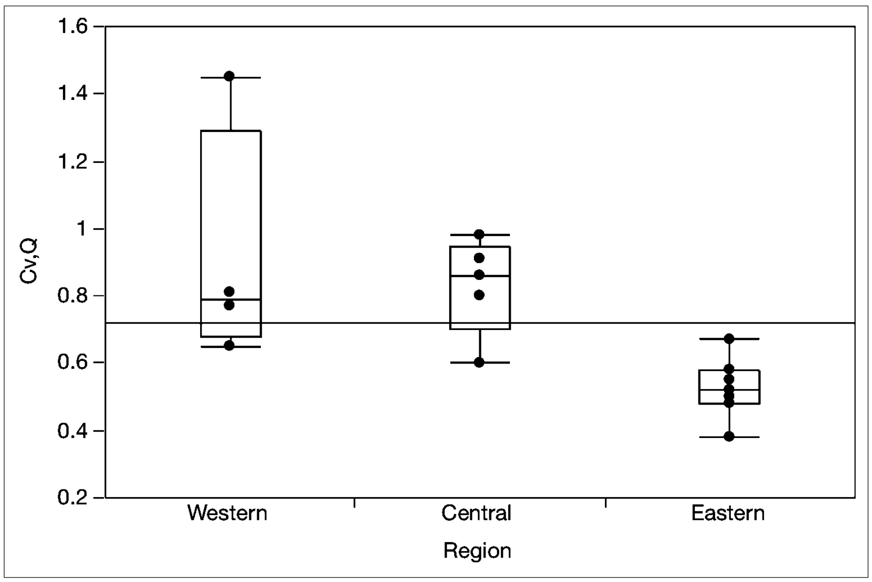

Figure 1.7. Box plot of a one-way Anova analysis of *$Cv,_Q$* between western, central and eastern regions in the ARRB

1.4.2 Correlation analysis

Mean annual P was significantly correlated with PDO index ($p<0.05$) for all watersheds in the western, for three watersheds in the central and for no watersheds in the eastern portion of the basin (Figure 1.8) (Appendix A).

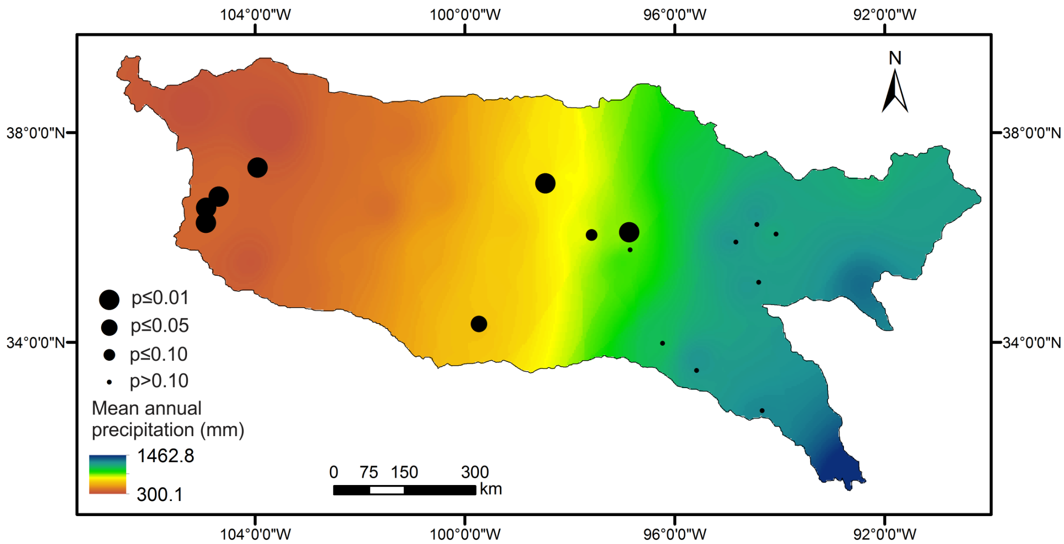

Figure 1.8. The annual precipitation map for the ARRB. The black bubbles denote the locations and the size of the bubbles denotes the significant level of correlation (p value) between annual precipitation and PDO index for each of the 16 selected watersheds.

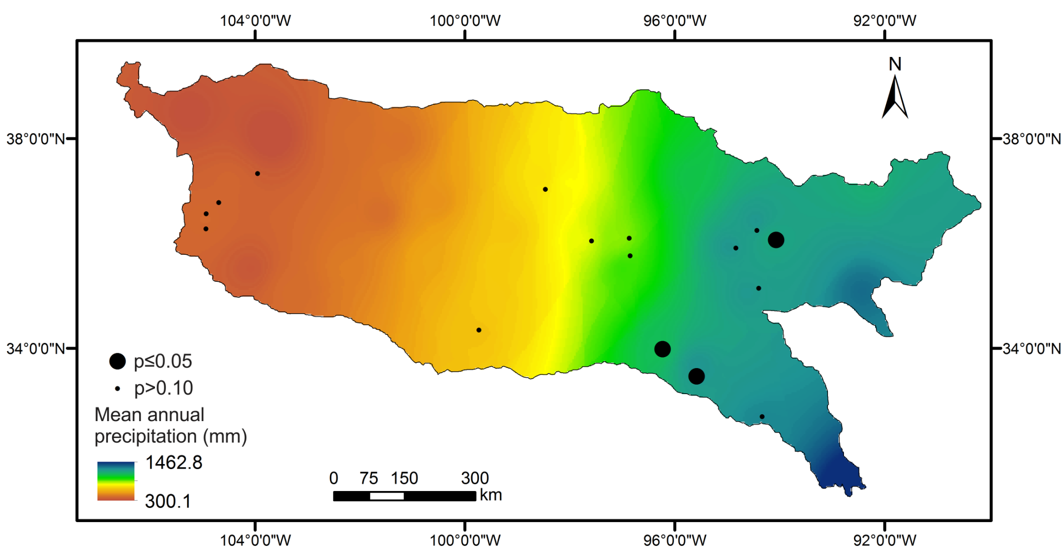

Figure 1.9. The annual precipitation map for the ARRB. The black bubbles denote the locations of watersheds and the size of the bubbles denotes the significant level of correlation (p value) between annual precipitation and AMO index for each of the 16 selected watersheds.

Mean annual *P* and AMO index were significantly correlated for three watersheds in the eastern portion of the basin (Figure 1.9). Mean annual *P* was significantly correlated with the ENSO index for three watersheds in the western region and one watershed in the central region (Figure 1.10)

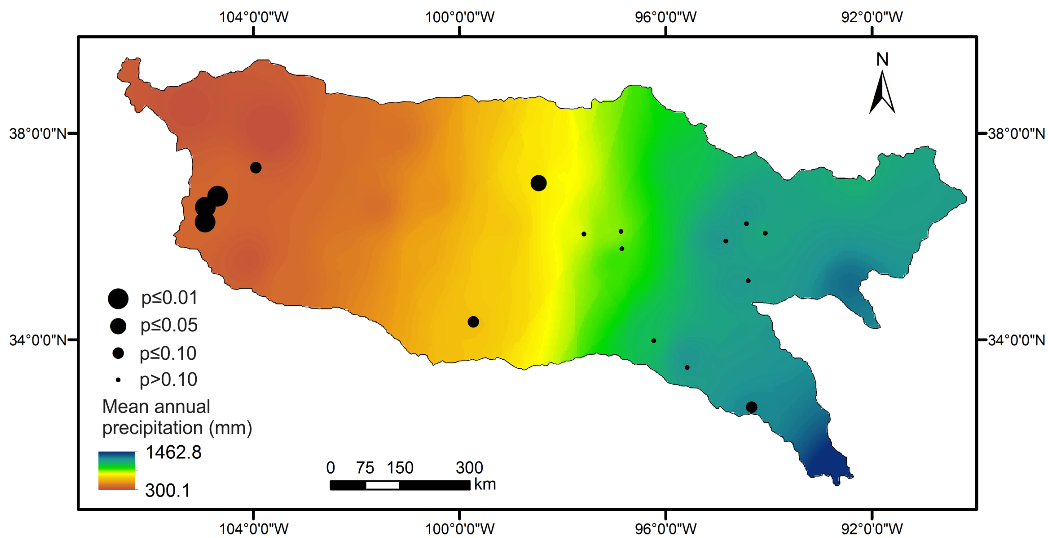

Figure 1.10 The annual precipitation map for the Arkansas River and Red River basins. The black bubbles denote the locations of watersheds and the size of the bubbles denotes the significant level of correlation (p value) between annual precipitation and ENSO index for each of the 16 selected watersheds.

1.4.3 Effects of PDO phases on P, Q and ET

Precipitation was numerically greater during the positive phase of PDO than the negative phase in 11 of the 16 watersheds, with greater differences for the western and central portion of the ARRB (Table 1.4). The increase in P from negative to positive PDO years was statistically significant (single tailed t-test given unequal variance and significance level of 0.1) in all but one western and central watersheds but was not statistically significant for any watershed in the eastern region. On average, from negative to positive years, there was a 20.5% increase in precipitation for watersheds in the western region, with values ranging from 17.8 to 26.4%. There was an average 16.6% increase in precipitation for watersheds in the central region, with values ranging from 7.8 to 27.6%. There was a 0.9% decrease in precipitation for the eastern region, with values ranging from - 6.4 to 4.4%.

Table 1.3. Annual total precipitation (P, mm) during the entire study period (Long term), the positive phase (+PDO), the negative phase (-PDO) of the Pacific Decadal Oscillation and percentage change from negative to positive phase (-PDO to +PDO) for 16 watersheds in the ARRB.

Watershed	*P* (mm)	*P* (mm) (+)PDO	*P* (mm) (-)PDO	*P* change (%) (-)PDO to (+)PDO	t-test (p value)
Western					
Van Bremer Ar, CO	395	441	349	26.4	**0.01**
Rayado Cr, NM	403	437	371	17.8	**0.01**
Vermejo R, NM	405	439	371	18.3	**0.01**
Ponil Cr, NM	422	460	385	19.5	**0.01**
AVERAGE	406	444	369	20.5	
Central					
Groesbeck Cr, TX	619	663	604	9.8	0.12
Medicine Lodge R, KS	683	706	655	7.8	**0.08**
Skeleton Cr, OK	754	820	685	19.7	**0.01**
Council Cr, OK	830	930	729	27.6	**0.01**
Dry Cr, OK	901	977	825	18.4	**0.02**
AVERAGE	757	819	700	16.6	
Eastern					
Blue R, OK	1040	1032	1047	-1.4	0.4
White R, AK	1113	1095	1131	-3.2	0.31
Flint Cr, AK	1159	1148	1170	-1.9	0.37
James Fork R, AK	1156	1118	1194	-6.4	0.14
Sulphur R, TX	1168	1158	1178	-1.7	0.39
Baron Fork Cr, OK	1161	1164	1119	4	0.26
Little Cypress B, TX	1208	1219	1168	4.4	0.2
AVERAGE	1144	1133	1144	-0.9	

Statistically significant values ($p \leq 0.1$) are highlighted in black.

The calculated mean annual *Q* was as little as 3.41 mm in the west to as much as 344.5 mm in the east (Table 1.5). Q increased from negative phase of PDO to positive phase of PDO for all watersheds in the western and central regions, but only for one watershed in eastern region. From negative phase of PDO to positive phase of PDO, mean annual Q increased by 50.4% ranging from 28.7 to 100.5% in the western region, increased by 52.3 % ranging from 6 to 104.8% in the central region, and had no significant change in the eastern region. The increase in Q from negative to positive PDO years was statistically significant (single tailed t-test given unequal variance and significance level of 0.1) for all watersheds in western and for four watersheds in the central region. The streamflow coefficient (*Q/P*) averaged 0.07, 0.14 and 0.29 for western, central and eastern respectively, indicating increasing efficiency of streamflow production from precipitation towards east. *Q/P* values in western and central regions are statistically equal (Appendix E) and both regions present statistically different *Q/P* values from the eastern region (Figure 1.11). No significant ($p \leq 0.05$) change in *Q/P* was found between negative and positive phases of PDO throughout the basin.

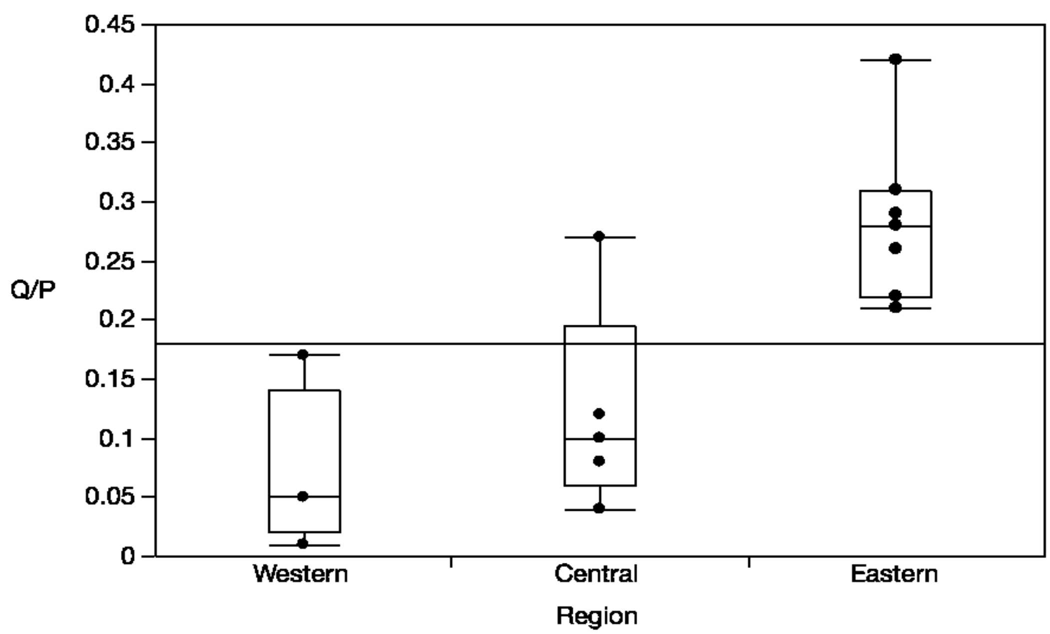

Figure 1.11. Box plot of a one-way Anova analysis of *Q/P* between western, central and eastern regions in the ARRB.

Table 1.4. Annual total streamflow (*Q*, mm) and streamflow coefficient (*Q* coef) during the positive phase, and the negative phase of the Pacific Decadal Oscillation for 16 watersheds in the ARRB. Percentage change of streamflow from the negative to the positive phase (*Q*,%). P value of single-tailed t-test for mean *Q* comparison between negative and positive PDO years.

Watershed	*Q* (mm)	*Q* (mm) (+)PDO	*Q* (mm) (-)PDO	*Q* change (%) (-)PDO to (+)PDO	t-test (p-value)	*Q* coef	*Q* coef (+)PDO	*Q* coef (-)PDO
Western								
Van Bremer Ar, CO	3.41	4.31	2.2	100.5	**0.07**	0.01	0.01	0.01
Rayado Cr, NM	71.4	81	62	30.6	**0.04**	0.18	0.19	0.17
Vermejo R, NM	22.1	26	18	41.8	**0.02**	0.05	0.06	0.05
Ponil Cr, NM	23.2	26	20	28.7	**0.10**	0.05	0.06	0.05
AVERAGE	30.0	34	25.7	50.4		0.07	0.08	0.07
Central								
Groesbeck Cr, TX	26.6	31	23	34.2	**0.10**	0.04	0.05	0.04
Medicine Lodge R, KS	56	58.4	55	6.0	0.37	0.08	0.08	0.08
Skeleton Cr, OK	115	145.5	85	71.0	**0.03**	0.14	0.17	0.1
Council Cr, OK	135	181.9	88.8	104.8	**0.01**	0.15	0.18	0.12
Dry Cr, OK	289	342	235	45.5	**0.10**	0.31	0.34	0.27
AVERAGE	124	152	97	52.3		0.14	0.16	0.12
Eastern								
Blue R, OK	226	219	232	-5.6	0.36	0.21	0.21	0.21
White R, AK	461	436	486	-10.3	0.21	0.41	0.40	0.42
Flint Cr, AK	360	342	376	-9.0	0.26	0.30	0.29	0.31
James Fork R, AK	344	793	830	-4.5	0.22	0.29	0.29	0.29
Sulphur R, TX	317	305	309	-1.3	0.46	0.28	0.27	0.26
Baron Fork Cr, OK	356	384	330	16.4	0.21	0.30	0.32	0.28
Little Cypress B, TX	276	251	264	-4.9	0.37	0.22	0.21	0.22
AVERAGE	334	390	404	-2.7		0.29	0.28	0.28

ET generally increased for years during the positive phase of PDO as compared to years during the negative phase of PDO (Table 1.6). The increase in *ET* was statistically significant (single tailed t-test given unequal variance and significance level of 0.1) for all watersheds in western, only three watersheds in central and no watershed in eastern regions.

Table 1.5. Annual total ET (mm) during the positive phase, and the negative phase of the PDO. Percentage change of ET from negative to positive phase (ET change, %). P-value of single-tailed t-test for mean ET comparison between negative and positive PDO years.

Watershed	*ET* (mm)	*ET* (mm) (+)PDO	*ET* (mm) (-)PDO	*ET* change (%) (-)PDO to (+)PDO	t-test (p-value)
Western					
Van Bremer Ar, CO	391	436	347	25.6	**0.01**
Rayado Cr, NM	332	356	310	14.8	**0.01**
Vermejo R, NM	383	413	353	17.0	**0.01**
Ponil Cr, NM	400	434	365	18.9	**0.01**
AVERAGE	377	410	344	19.1	
Central					
Groesbeck Cr, TX	593	635	584	8.7	0.14
Medicine Lodge R, KS	627	648	599	8.2	**0.07**
Skeleton Cr, OK	637	676	602	12.3	**0.05**
Council Cr, OK	694	748	640	16.9	**0.01**
Dry Cr, OK	613	634	590	7.5	0.29
AVERAGE	633	668	603	10.7	
Eastern					
Blue R, OK	812	812	815	-0.4	0.48
White R, AK	651	658	645	2.0	0.40
Flint Cr, AK	799	805	794	1.4	0.41
James Fork R, AK	811	793	830	-4.5	0.27
Sulphur R, TX	861	853	869	-1.8	0.41
Baron Fork Cr, OK	785	788	783	0.6	0.45
Little Cypress B, TX	942	968	903	7.2	0.13
AVERAGE	809	811	806	0.7	

The average increase of *ET* in the western region was 19.1% with values ranging from 14.8 to 25.6% for individual watershed. In the center, *ET* increased by 10.7% on average with values ranging from 7.5 to 16.9% for individual watershed.

1.4.4 Sensitivity

The sensitivity of *Q* to *P* averaged at 2.3 in the western region, compared with 2.8 in the central region (Table 1.6).

Table 1.6. Variations (%) in *P*, *Q* and *ET* from negative phase to positive phase of PDO and sensitivity of *Q* and *ET* to *P* for 16 watersheds in the ARRB.

Watershed	% change *P*	% change *Q*	% change *ET*	Sensitivity of *Q* to *P*	Sensitivity of *ET* to *P*
Western					
Van Bremer Ar, CO	26.4	100.5	25.6	3.8	1.0
Rayado Cr, NM	17.8	30.6	14.8	1.7	0.8
Vermejo R, NM	18.3	41.8	17.0	2.3	0.9
Ponil Cr, NM	19.5	28.7	18.9	1.5	1.0
AVERAGE	20.5	50.4	19.1	2.3	0.9
Central					
Groesbeck Cr, TX	9.8	34.2	8.7	3.5	0.9
Medicine Lodge R, KS	7.8	6.0	8.2	0.8	1.1
Skeleton Cr, OK	19.7	71.0	12.3	3.6	0.6
Council Cr, OK	27.6	104.8	16.9	3.8	0.6
Dry Cr, OK	18.4	45.5	7.5	2.5	0.4
AVERAGE	16.6	10.7	10.7	2.8	0.7

The mean value of sensitivity of *ET* to *P* was 0.9 in the western and 0.7 in the central.

1.5 Discussion

1.5.1 Coefficient of variation

The $Cv_{,P}$ range of 0.20 to 0.29 in the ARRB is relatively wide compared to other regions in the U.S. In the northern Great Plains, the range of $Cv_{,P}$ is 0.20 to 0.25 (Groisman and Legates, 1994). In the northeast, the range of $Cv_{,P}$ is 0.11 to 0.14 (Carey et al., 2010). A wider range of $Cv_{,P}$ in the ARRB is associated with the steep precipitation gradient. The relatively high values of $Cv_{,P}$ in the central part of the basin result from the high natural variability of precipitation. The creeks and rivers analyzed in our study presented an above average variability in $Cv_{,Q}$ as well, with mean annual $Cv_{,Q}$ of 0.72 for all watersheds. This value is approximately twice compared to a reported national average of 0.37 for 50 rivers in the U.S and the median of 0.31 reported for 1221 watersheds worldwide (McMahon et al., 2007a; McMahon et al., 2007b; McMahon et al., 2007c).

This illustrates that streamflow in tributary creeks and streams across the ARRB is highly variable (McMahon et al., 2007a; McMahon et al., 2007b; McMahon et al., 2007c). The exceptional high $Cv_{,Q}$ of 1.45 in the Van Bremer Arroyo Watershed was resulted from the very small mean annual streamflow (Poff, 1996). With the exception of Van Bremer Arroyo Watershed, CO. Even though the western and central regions are in different climatic region (semi-arid and subtropical humid) the $Cv_{,Q}$ values for watersheds in both regions are statistically equal. Watersheds in the central and eastern parts of the ARRB, belong to the same climate (subtropical humid) however had statistically different $Cv_{,Q}$ values. $Cv_{,Q}$ values from western and eastern watersheds are also statistically different.

1.5.2 Climate indices and precipitation

The correlation analysis revealed significant PDO influence on annual precipitation for the western and central parts of the ARRB. Interesting to note is that while precipitation was strongly correlated with PDO index ($0.001 \leq p \leq 0.005$), the strength of the correlation weakens along the west to east gradient. There was no significant relationship between *P* and PDO found for watersheds located in the southeastern part of the basin. The decrease in PDO influence from west to east was also observed in adjacent basins in New Mexico and Texas (Joseph et al., 2012). The reasons for weakened influence from PDO might be associated with the increasing influence from the AMO. The AMO index and *P* were significantly correlated ($p < 0.05$) in three watersheds in the east. Considering the multi-decadal pattern of occurrence of AMO, the influence of AMO on precipitation was less likely to be captured in an inter-annual correlation analysis and deserved further study, especially for the eastern region of the ARRB. There were significant correlations between ENSO and *P* in the western region. These results suggest that additional studies considering combined effects of the PDO and ENSO in the ARRB are necessary, especially considering similar impact on *P* from both PDO and ENSO were reported in Central U.S (Mauget and Upchurch, 1999; Kurtzman and Scanlon, 2007).

1.5.3 Effects of PDO phases on precipitation, streamflow and evapotranspiration

The *P*, *Q* and *ET* all increased during the PDO positive phase. The changes in *P*, *Q* and *ET* from negative phase to positive phase of PDO in the western and central are similar to trends observed by Garbrecht et al. (2004). In their study, the periods of 1961 to 1980 and 1981 to 2001 were classified as "dry" and "wet" respectively and *P*, *Q* and *ET* in 11 watersheds across Nebraska, Kansas and Oklahoma were compared and reported a 12% increase in *P*, a 64% increase in *Q* and a 5% increase in *ET* in "wet" period (PDO positive phase). In our analysis, the period from 1961 to 1980 included 16 negative PDO years (1961 to 1976) and three positive PDO years (1977-1980) while the period 1981 – 2001 had 15 positive PDO years (1981-1988, 1992-1998) and three negative years (1999-2002). In our study, compared to Garbrecht et al. (2004), the contrast between negative and positive PDO had similar effects in *P*, *Q* and *ET* partitioning in the western and central parts when considering our sensitivity analysis. The sensitivity of *Q* to *P* in the ARRB was on average 2.3 and 2.8 for western and central parts of the basin, meaning that for a given 1% increase in P, there was a 2.8% increase in *Q* for the same period. The sensitivity of *ET* to *P* averaged 0.9 and 0.7 for western and central parts of the ARRB, meaning that a 1% increase in P generated a 0.7% increase in *ET*. Winter precipitation variation is consistent with the results by Garbrecht et al. (2004). PDO phases have been shown to affect winter precipitation among other regions in the southern Great Plains (Kurtzman and Scanlon, 2007). Our results, although lacking a seasonal approach, emphasize the strong relationship between PDO and *P*, *Q* and *ET* in the central and western parts of the ARRB. There was no strong correlation between the AMO index and annual *P* in the western and central region of the ARRB, however significant correlation between the AMO index and annual P was found in three watersheds in the east basin. Previous studies suggested that the AMO effects on *P* are more often seen in summer rainfall over the U.S (Enfield et al., 2001; Sutton and Hodson, 2005; Knight et al., 2006). Further study focusing on the correlation between the AMO index and summer P in the ARRB basin is needed.

1.6 Conclusion

The watersheds in Arkansas River and Red River basin have a much greater variation in Q compared to many other streams and rivers in the U.S. These inter-annual variations have been amplified by the pacific decadal oscillation (PDO), especially for the central and western part of this basin. During the positive phase of PDO, P in western and central parts of the Arkansas River and Red River basin increased by approximately 20%, resulting in proportionally larger increase in streamflow even though the streamflow coefficient does not differ between the positive and negative phase of PDO. Grazing system, such as winter wheat grazing can be managed to take advantage of the increased foraging production potential during positive PDO phase. Increased precipitation during positive PDO events can be also beneficial to non-agricultural sectors due to smaller agricultural use and increased streamflow. Farmers, ranchers and farm insurance agents can also benefit from the knowledge of potential droughts associated with the negative phases of the PDO by planting drought resistant crops or reducing herd size and purchasing drought insurance. Finally, municipal utility authorities can make more effective middle and long range planning by considering the water availability during the positive and negative phases of PDO.

CHAPTER II

PRECIPITATION SEASONALITY AND STREAMFLOW RESPONSES TO CLIMATE VARIABILITY IN THE ARKANSAS RIVER AND RED RIVER BASIN

2.1 Abstract

The Pacific Decadal Oscillation (PDO) affects the inter-annual variability of precipitation in the Arkansas-Red River Basin (ARRB). However, it is unknown whether and how PDO affects the seasonality of precipitation (*P*) and streamflow(*Q*), which are critical information for agricultural water management and flood control in this region. We correlated the monthly P and Q with PDO index in the ARRB basin and compared seasonal P and Q at the positive and the negative phase of the PDO for each watershed in the basin. Our results showed that PDO has significantly affected the *P* during winter and spring in the western and central regions of the ARRB. During the positive phase of PDO, *P* for winter, spring, summer and fall increased by 4, 36, 17 and 19%, respectively, in the western part and increased by 25, 22, 12 and 7% in the central part of the basin. Even though *P* increase occurred mainly during winter and spring, the increase in *Q* was significant during all seasons in central and western watersheds of the ARRB. Compared with the negative phase of PDO, the *Q* for winter, spring, summer and fall increased by 17, 37, 43 and 53%, respectively, in the western part and increased by 80, 52, 32 and 43%, respectively, in the central part of the basin. During positive phase of PDO, increased spring *P* in the western part of the basin will benefit foraging and crop yields. Higher water demands from agriculture and urban areas in summer could benefit from increased *Q* following winter and

spring P increase. This information can be used for water resource planning and effective operation of reservoirs considering drought risks associated with the negative phase of PDO.

KEYWORDS: PDO, seasonal precipitation, evapotranspiration, watershed, the Great Plains

2.2 Introduction

Seasonal distributions of precipitation (P) and streamflow (Q) have long been observed and studied to serve human needs. In arid and semi-arid regions of the United States U.S, timely management actions are often necessary to meet the ever-growing demands of water from agriculture, urban population and energy generation (Petsch, 1980; Waltemeyer, 1989; McCarthy, 2001; Sorooshian, 2006). These actions require consideration of the differences between water supply and demand throughout the whole year. This is particularly important for reservoir operation in the Great Plains. Effective operation of reservoirs permit the retention of storm water during extreme precipitation events and allow later release and use during summer when peak demand of water for agriculture irrigation and urban use occurs (Garbrecht et al., 2004). However, a recent study showed that the south-central Great Plains has one of the highest natural variability in annual streamflow (Rahal; 2016). For example, in the western part of the Arkansas/Red River Basin (ARRB), multi-year, abnormally dry summers have caused severe human and natural disaster during the 30's Dust Bowl (Schubert et al., 2004b; Nigam et al., 2011). In other parts of the ARRB, specifically in southern Oklahoma and northern Texas, extreme rain events have caused floods, taking lives and amassing millions of dollars in damage (Buckner and Kurklin, 1984). Extreme hydrologic events are often linked to large-scale climatic phenomena such as the Pacific Decadal Oscillation (PDO), the Atlantic Multidecadal Oscillation (AMO) and the El Niño Southern Oscillation (ENSO) (Hong and Kalnay, 2000; Enfield et al., 2001; McCabe et al., 2004; Sutton and Hodson, 2005; Knight et al., 2006; McPhaden et al., 2006; Nigam et al., 2011;). In the ARRB, our most recent studies have shown that PDO strongly affects precipitation and streamflow in the central and western parts of the basin. Effects of the PDO on seasonal streamflow in the ARRB are especially important to know since the effect of precipitation on streamflow could be doubled or even tripled depending on the timing of precipitation in a year. Further studies are needed to fully comprehend the effects of the PDO phases on precipitation and how the change in precipitation will trickle down to affect the streamflow seasonally and unfold spatially across the basin. Effects of the PDO on precipitation vary by season in the central U.S., with significant changes seen during both summer and winter (Kurtzman and Scanlon, 2007; Pu et al., 2016). While previous studies do cast some light on the effects of the PDO on precipitation, to facilitate water management in the ARRB, a finer spatial resolution study is needed. Therefore, to better prepare water managers and state officials to adapt to climate variability in the ARRB, it is our goal to unravel seasonal responses of *P* and *Q* to the PDO at watershed scale.

The overall objective of this study is to understand the effects of PDO on seasonal precipitation, streamflow and evapotranspiration along the precipitation gradient of the Arkansas River and Red River basin. The specific objectives include:

1. Understand how PDO affects *P* and *Q* on monthly/seasonal scale in the ARRB.
2. Quantify and compare seasonal *P* and *Q* at the positive and the negative phase of the PDO for each watershed.

2.3 Material and Methods

2.3.1 Study Area

The ARRB is located in the southwest part of the Mississippi River basin. The Arkansas and Red River basins combined have an area of 538,382 km^2 and cover part of the states of Colorado, New Mexico, Kansas, Missouri, Arkansas, Louisiana, Texas and the whole state of Oklahoma. In the ARRB, an expressive east-west gradient of climate, hydrology, and vegetation can be found.

In the east, by the Köppen classification, humid subtropical and continental humid climate dominates, while in the west, a semi-arid climate predominates (Kottek et al., 2006). The total annual *P* is over 1300 mm in the southeast and decreases gradually to less than 350 mm in the west. Annual potential evapotranspiration ranges from 1000 mm in the south to 1700 mm in the center and parts of the west. Decreasing from east to west, annual surface runoff ranges from as high as 500 mm in the east to less than 2 mm in the west (Duan and Schaake, 2003). As a result of the high natural variability in climate, there are a total of twelve different eco-regions (level III, U.S EPA Eco-region Framework) in the ARRB basin.

2.3.2 Watersheds

A total of 16 watersheds with size ranging from 37 km^2 to 2338 km^2 encompassing the states of Texas, Oklahoma, Arkansas, Kansas, Colorado and New Mexico were selected in the ARRB (Figure 2.1).

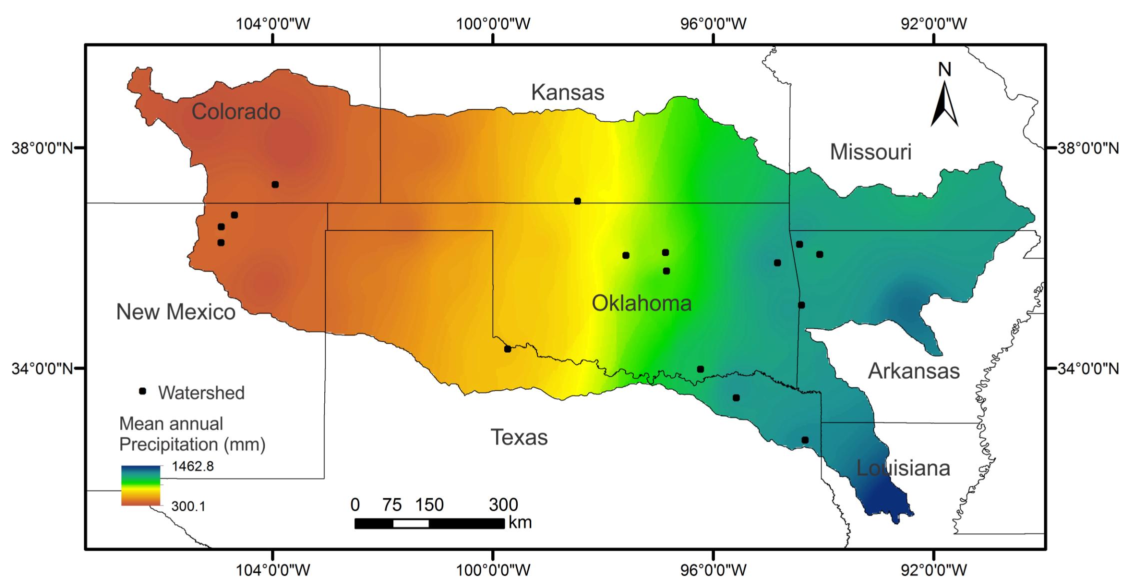

Figure 2.1 The annual precipitation for the Arkansas River and Red River basin. The black dots denote the locations of the 16 selected watersheds.

Factors considered prior to selecting the watersheds included: i) presence of at least four decades of streamflow records to capture decadal climate variability, ii)absent of dams upstream from the streamflow gage, iii) close to a precipitation gage (less than 25 km), and iv) absent of major groundwater or surface water withdrawals in the watershed (Petsch, 1980; Waltemeyer, 1989; Rasmussen and Perry, 2000; Funkhouser et al., 2008), which could alter *Q* (Brikowski, 2008; Kustu et al., 2010; Dale et al., 2015). Mean annual *P* of selected watersheds ranged from 395 mm for the Van Bremer Arroyo watershed in Colorado to 1208 mm for the Litter Cypress Bayou watershed in Texas (Table 2.1).

Table 2.1 Watershed name (including USGS gage station number), drainage area, altitude of gage station, annual precipitation, annual streamflow and length of record for 16 watersheds in the Arkansas River and Red River basins.

Watershed - USGS gage station number	Drainage area (km^2)	Gage altitude (m)	Mean annual precipitation (mm)	Mean annual flow (cfs)	Length of record
Western					
Van Bremer Ar, CO - 07126200	420	1512	395	1.6	1967-2009
Rayado Cr, NM - 07208500	168	2048	404	13.5	1931-2014
Vermejo R, NM - 07203000	780	1939	405	19.3	1928-2014
Ponil Crk, NM - 07207500	442	2021	422	11.5	1951-2014
Central					
Groesbeck Cr, TX - 07299670	784	435	619	23.8	1963-2014
Medicine Lodge R, KS - 07149000	2338	392	683	146	1938-2014
Skeleton Cr, OK - 07160500	1061	277	754	139	1950-2014
Council Cr, OK - 07163000	80	252	830	12	1934-1993
Dry Cr, OK - 07243000	178	250	901	25.9	1956-1994
Eastern					
Blue R, OK - 07332500	1235	153	1040	312	1936-2014
White R, AK - 07048600	1036	347	1113	535	1964-2014
Flint Cr, AK - 07195800	37	358	1159	14.8	1962-2014
James Fork Cr, AK - 07249400	381	140	1156	146	1959-2014
Sulphur R, TX - 07343000	714	112	1168	246	1950-2014
Baron Fork Cr, OK - 07197000	808	214	1161	324	1949-2014
Little Cypress B, TX - 07346070	1748	53	1208	521	1946-2014

Cr= Creek, R=River, B=Bayou, Ar=Arroyo

The entire basin was further categorized by the precipitation and the geographic locations into three regions. The annual total *P* ranged from 395 to 422 mm, 619 to 901 mm and from 1040 to 1208 mm for the west, central and eastern region, respectively.

2.3.3 Precipitation and streamflow

Monthly *P* data was obtained from the National Historical Climatological Network website (http://cdiac.ornl.gov/epubs/ndp/ushcn/ushcn_map_interface.html), the best available source of historical *P* data in the U.S (Groisman and Legates, 1994). Streamflow data was obtained from the USGS water-watch database (http://waterwatch.usgs.gov). The length of *P* record selected matches the length of *Q* record for the same watershed. Like previous studies within the Great Plains (Kibria et al., 2016), the selected precipitation gage should be located within 20 km in distance to the streamflow gage. Considering there are only a few unregulated, and undisturbed rivers in watersheds of the central and western regions, two *P* gages in the western, three in the central and two in the eastern parts of the basin were selected beyond the 20 km stipulated radius.

2.3.4 PDO

The PDO is divided into positive phase (warm phase) and negative phase (cold phase). We utilized the PDO index (Table 2.2) obtained from the Tokyo Climate Center (Japan Meteorological Agency website - http://ds.data.jma.go.jp/tcc/tcc/products/elnino/decadal/pdo.html). Years with negative PDO index were classified as negative years, and years with positive PDO index were classified as positive years. To avoid bias, in a few cases, negative or positive PDO years were truncated to balance the number of negative years with positive years. The PDO index was used in correlation analysis using the R programming software. PDO years used were those with presence of *Q* record. The negative phases include: 1932-33, 1943-56, 1961-76, 1989-91, 1999-2002 and 2007-13. The positive phases include: 1934-42, 1957-60, 1977-88, 1992-98, 2003-06 and 2014.

2.3.5 Seasonal distribution

Monthly *P*, *Q* and *ET* data was divided in winter, spring, summer and fall, according to the astronomical separation for the northern hemisphere. The data from December, January and February were averaged and considered as winter, March, April and May were considered as spring, June, July and August were considered as summer and September, October and November as fall.

2.3.6 P, Q, ET and the water-budget

Monthly runoff depth (*Q*, mm) was calculated from monthly flow (m^3/s) and associated contributing drainage area (m^2) for each watershed. Runoff depth includes surface and sub-surface runoff and groundwater channel recharge. The assumptions that justify a water-budget equation with only *P*, *ET* and *Q* components (no variation in soil water storage and negligible groundwater recharge) are somewhat less applicable seasonally. Therefore, *ET* results will only reflect general tendencies and its shortcomings will be considered in the discussion. *ET* was considered the complement of *Q* therefore was calculated as $ET = P - Q$, with all variables expressed in mm.

2.3.7 Correlation analysis

Correlation analysis between monthly *P* and *Q* was conducted for the whole length of record for each watershed using R-studio version 0.99.473 and Stat-plus for Mac version LE.

2.4 Results

2.4.1 PDO impact on seasonal P, Q and ET

Winter had the lowest precipitation for the entire region (Table 2.3). For the western and central watersheds, summer was the wettest season followed by spring and fall. In the eastern part, the wettest season was spring followed by fall and summer.

Table 2.2. Seasonal distribution of P during long-term, positive and negative PDO phases for 16 watersheds in the Arkansas River and Red River basins.

	Long-term *P* (mm)[1]				*P* (mm), Positive PDO				*P* (mm), Negative PDO			
Watershed	**Win**	**Spr**	**Sum**	**Fall**	**Win**	**Spr**	**Sum**	**Fall**	**Win**	**Spr**	**Sum**	**Fall**
Western												
Van Bremer Ar, CO	36	105	174	82	35	124	198	87	37	85	150	78
Rayado Cr, NM	35	100	184	86	31	114	191	96	33	86	177	75
Vermejo R, NM	35	99	183	86	37	116	191	96	34	85	174	76
Ponil Cr, NM	36	101	200	86	39	113	217	91	33	89	182	81
AVERAGE	36	101	185	85	35	117	199	92	34	86	171	78
STD	0.5	2.5	10.7	1.8	3.5	5.2	12.3	4.6	1.6	1.9	14.4	2.6
Central												
Groesbeck Cr, TX	74	174	212	176	81	188	221	173	66	161	203	180
Medicine Lodge R, KS	67	205	258	159	64	211	262	167	67	198	253	150
Skeleton Cr, OK	75	233	257	215	82	265	278	221	67	203	236	209
Council Cr, OK	96	253	265	218	109	283	299	234	84	225	234	203
Dry Cr, OK	117	292	243	250	142	333	246	257	93	251	239	243
AVERAGE	85	231	247	203	96	256	261	210	75	208	233	197
STD	21	45	21	36	30	58	30	39	12	34	18	34
Eastern												
Blue R, OK	183	324	252	282	185	322	251	282	179	333	254	281
White R, AK	184	325	285	304	170	312	299	317	196	336	273	293
Flint Cr, AK	203	344	293	319	194	331	288	332	212	354	298	307
James Fork R, AK	213	360	259	324	213	329	255	322	213	392	263	327
Sulphur R, TX	231	359	273	316	237	329	263	330	224	368	284	302
Baron Fork Cr, OK	185	350	301	305	176	347	319	323	194	353	284	288
Little Cypress B, TX	231	349	273	316	237	329	263	330	224	382	284	302
AVERAGE	204	344	277	309	202	328	277	319	206	360	277	300
STD	21	15	18	14	28	11	26	17	17	22	15	15

[1]Represents the full length of record available for each watershed
STD= Standard Deviation
Win = winter, Spr = spring, Sum = summer

Compared with negative phase, *P* in winter increased significantly (p ≤ 0.1, single-tailed t-test, considering unequal variance) in four central watersheds in the positive phase of PDO (Table 2.4).

Table 2.3. Percentage change (%) in *P* from negative to positive PDO per season and p-values for single-tailed t-test given unequal variance between PDO phases for 16 watersheds in the Arkansas River and Red River basins.

Watershed	Win	p-value[1]	Spr	p-value	Sum	p-value	Fall	p-value
Western								
Van Bremer Ar, CO	-5	0.38	46	**0.00**	33	**0.01**	11	0.15
Rayado Cr, NM	-7	0.24	33	**0.01**	8	0.16	28	**0.02**
Vermejo R, NM	8	0.27	37	**0.01**	10	0.11	26	**0.03**
Ponil Cr, NM	18	0.15	27	**0.05**	19	**0.02**	12	0.24
AVERAGE	4		36		17		19	
Central								
Groesbeck Cr, TX	23	**0.10**	17	0.12	9	0.12	-4	0.26
Medicine Lodge R, KS	-4	0.42	6	0.28	4	0.35	11	0.18
Skeleton Cr, OK	22	**0.09**	31	**0.05**	18	**0.08**	5	0.35
Council Cr, OK	29	**0.02**	25	**0.04**	28	**0.02**	16	0.16
Dry Cr, OK	53	**0.01**	33	**0.01**	3	0.42	6	0.35
AVERAGE	25		22		12		7	
Eastern								
Blue R, OK	3	0.32	-3	0.28	-1	0.43	1	0.47
White R, AK	-13	0.14	-7	0.19	9	0.23	8	0.25
Flint Cr, AK	-8	0.22	-6	0.23	-3	0.37	8	0.23
James Fork R, AK	0	0.49	-16	**0.03**	-3	0.38	-1	0.44
Sulphur R, TX	6	0.26	-11	**0.10**	-8	0.25	9	0.23
Baron Fork Cr, OK	-9	0.19	-2	0.41	12	0.13	12	0.14
Little Cypress B, TX	11	0.14	-15	**0.03**	9	0.22	20	**0.03**
AVERAGE	-2		-9		2		8	

The *P* in spring increased significantly in all western watersheds, in three central watersheds and decreased significantly in three eastern watersheds in the positive phase of PDO. Summer *P* increased in two western watersheds and in two central watersheds. Fall *P* increased in half western watersheds and in one central watershed. From negative to positive phase of the PDO, spring had the largest increase in precipitation (by 46%) for western part of the basin but the largest increase (by 56%) in precipitation occurred in winter for the central part. There was no significant PDO impact on seasonal precipitation for the eastern part of the basin.

The spring season had the highest *Q* irrespective of PDO phase and region in the basin (Table 2.5).

Table 2.4. Seasonal distribution of *Q* during long-term, positive and negative PDO for 16 watersheds in the Arkansas River and Red River basins.

	Long-term *Q*(mm)[1]				*Q*(mm) Positive PDO				*Q*(mm) Negative PDO			
Watershed	**Win**	**Spr**	**Sum**	**Fall**	**Win**	**Spr**	**Sum**	**Fall**	**Win**	**Spr**	**Sum**	**Fall**
Western												
Van Bremer Ar, CO	0.1	0.5	2.2	0.6	0.1	0.5	3.1	0.7	0.1	0.5	1.3	0.4
Rayado Cr, NM	5.0	39.2	19.3	7.9	5.4	46.7	20	8.9	4.7	32	18.6	6.9
Vermejo R, NM	1.6	7.5	9.4	3.2	1.8	9.5	11	3.8	1.4	6	7.9	2.6
Ponil Cr, NM	1.0	13.2	6.7	2.1	1.2	15.2	7.5	2.3	0.9	11	6.0	1.9
AVERAGE	1.9	15.1	9.4	3.4	2.1	18.0	10.4	3.9	1.8	12	8.4	2.9
STD	2.2	16.9	7.2	3.2	2.3	20	7.1	3.6	2.0	14	7.3	2.8
Central												
Groesbeck Cr, TX	3	7	10	8	4	8	11	9	2	5	8	8
Medicine Lodge R, KS	11	21	14	12	11	21	15	12	11	21	14	11
Skeleton Cr, OK	11	40	29	27	13	53	35	35	9	28	23	20
Council Cr, OK	15	49	34	33	22	57	43	48	9	41	25	19
Dry Cr, OK	21	56	27	23	30	72	23	20	12	41	27	26
AVERAGE	12	35	23	20	16	42	26	24	9	27	19	17
STD	7	20	10	10	10	27	14	16	4	15	8	7
Eastern												
Blue R, OK	50	96	39	40	50	94	31	41	48	103	44	40
White R, AK	138	219	44	76	124	206	39	77	149	231	48	75
Flint Cr, AK	94	121	71	73	93	112	60	75	94	129	81	71
James Fork R, AK	110	152	31	54	111	128	30	54	109	176	32	53
Sulphur R, TX	87	117	42	60	90	114	38	58	85	120	47	62
Baron Fork Cr, OK	93	161	50	58	98	161	56	66	88	162	44	51
Little Cypress B, TX	90	119	25	21	98	108	26	21	83	129	24	20
AVERAGE	94	141	43	54	95	132	40	56	94	150	46	53
STD	26.4	41	14.7	19	23	39	13	19.8	31	43.7	18	19

Impact of PDO primarily affected the streamflow of watersheds in the western and central parts of the basin. Compared with the negative phase of PDO, the *Qs* in both winter and spring seasons of the positive phase significantly increased in three western and four central watersheds, and decreased in one eastern watershed (Table 2.6). The *Q* in summer season increased in two eastern and three central watersheds and decreased in one eastern watershed. The *Q* in fall increased in two western and two central watersheds.

Table 2.5. Percentage change (%) in *Q* from negative to positive PDO per season and p-values for single-tailed t-test given unequal variance between PDO phases for 16 watersheds in the Arkansas River and Red River basins.

Watershed	Win	p-value[1]	Spr	p-value	Sum	p-value	Fall	p-value
Western								
Van Bremer Ar, CO	-10	0.16	0	0.45	138	**0.07**	75	0.12
Rayado Cr, NM	15	**0.01**	46	**0.01**	7	0.37	29	**0.03**
Vermejo R, NM	29	**0.001**	67	**0.02**	39	**0.003**	46	**0.004**
Ponil Cr, NM	34	**0.001**	36	**0.09**	26	0.15	22	0.18
AVERAGE	17		37		53		43	
Central								
Groesbeck Cr, TX	55	**0.001**	57	**0.04**	34	**0.04**	11	0.21
Medicine Lodge R, KS	1	0.42	-4	0.38	13	0.26	5	0.38
Skeleton Cr, OK	43	**0.1**	89	**0.03**	53	**0.06**	70	**0.09**
Council Cr, OK	143	**0.02**	40	**0.09**	75	**0.04**	155	**0.05**
Dry Cr, OK	159	**0.08**	77	**0.01**	-14	0.45	-26	0.21
AVERAGE	80		52		32		43	
Eastern								
Blue R, OK	6	0.3	-8	0.2	-29	0.12	3	0.45
White R, AK	-17	**0.1**	-11	0.16	-18	0.27	3	0.45
Flint Cr, AK	-1	0.46	-13	0.15	-26	**0.09**	5	0.38
James Fork R, AK	1	0.46	-28	**0.01**	-4	0.44	1	0.48
Sulphur R, TX	7	0.36	-5	0.4	-20	0.36	-6	0.4
Baron Fork Cr, OK	11	0.24	0	0.48	28	0.11	31	0.15
Little Cypress B, TX	19	0.11	-16	0.19	10	0.36	3	0.44
AVERAGE	4		-12		-9		6	

In the western region of the basin, the increase of *Q* in PDO positive phase was relatively uniform across the seasons with the highest increase of 53% during the summer. In the central region, the highest percentage increase (80%) occurred in winter. *Q* coefficient was higher for winter season in the central and eastern regions and higher for spring season in the western region (Table 2.7).

Table 2.6 Seasonal distribution of *Q/P* during long-term, positive and negative PDO for 16 watersheds in the Arkansas River and Red River basins.

	Long-term *Q/P*				*Q/P* Positive PDO				*Q/P* Negative PDO			
Watershed	Win	Spr	Sum	Fall	Win	Spr	Sum	Fall	Win	Spr	Sum	Fall
Western												
Van Bremer Ar, CO	0.003	0.01	0.01	0.01	0.003	0.004	0.01	0.01	0.004	0.01	0.01	0.01
Rayado Cr, NM	0.27	0.44	0.11	0.11	0.33	0.45	0.11	0.11	0.22	0.43	0.10	0.11
Vermejo R, NM	0.08	0.08	0.05	0.05	0.11	0.09	0.06	0.05	0.06	0.07	0.04	0.04
Ponil Cr, NM	0.05	0.14	0.03	0.03	0.06	0.14	0.04	0.03	0.04	0.13	0.03	0.03
AVERAGE	0.10	0.17	0.05	0.05	0.13	0.17	0.06	0.05	0.08	0.16	0.05	0.05
Central												
Groesbeck Cr, TX	0.14	0.04	0.04	0.04	0.22	0.05	0.04	0.04	0.07	0.03	0.04	0.04
Medicine Lodge R, KS	0.24	0.1	0.05	0.07	0.25	0.1	0.06	0.06	0.24	0.11	0.05	0.08
Skeleton Cr, OK	0.15	0.14	0.11	0.1	0.18	0.17	0.14	0.11	0.11	0.11	0.09	0.08
Council Cr, OK	0.13	0.17	0.1	0.09	0.16	0.19	0.12	0.12	0.1	0.16	0.09	0.07
Dry Cr, OK	0.15	-0.19	0.12	0.08	0.18	0.22	0.13	0.05	0.12	0.16	0.11	0.1
AVERAGE	0.16	0.05	0.08	0.08	0.20	0.15	0.10	0.08	0.13	0.11	0.08	0.07
Eastern												
Blue R, OK	0.27	0.27	0.15	0.13	0.27	0.27	0.15	0.13	0.26	0.27	0.15	0.12
White R, AK	0.79	0.66	0.14	0.21	0.7	0.64	0.12	0.22	0.87	0.67	0.16	0.2
Flint Cr, AK	0.48	0.34	0.24	0.22	0.47	0.33	0.21	0.21	0.48	0.34	0.27	0.22
James Fork R, AK	0.49	0.61	0.11	0.13	0.5	0.37	0.11	0.13	0.49	0.4	0.11	0.13
Sulphur R, TX	0.34	0.3	0.13	0.15	0.35	0.31	0.13	0.14	0.33	0.3	0.14	0.16
Baron Fork Cr, OK	0.47	0.45	0.16	0.15	0.52	0.45	0.18	0.17	0.42	0.44	0.15	0.13
Little Cypress B, TX	0.34	0.3	0.13	0.15	0.31	0.36	0.09	0.06	0.27	0.34	0.09	0.06
AVERAGE	0.45	0.42	0.15	0.16	0.45	0.39	0.14	0.15	0.45	0.39	0.15	0.15

Q coefficient increased from negative to positive PDO for both winter and spring seasons for the western and central regions with the exception of the Van Bremer Arroyo watershed in CO and the Medicine Lodge river watershed in KS (Table 2.8).

The seasons with relatively high *ET* were spring and summer for western and central regions and summer and fall for the eastern region (Table 2.9).

Table 2.7. Percentage change (%) in *Q/P* from negative to positive PDO per season and p-values for single-tailed t-test given unequal variance between PDO phases for 16 watersheds in the Arkansas River and Red River basins.

Watershed	Win	p-value[1]	Spr	p-value	Sum	p-value	Fall	p-value
Western								
Van Bremer Ar, CO	-25	0.32	-60	0.32	0	0.11	0	0.2
Rayado Cr, NM	50	0.15	5	0.36	10	0.17	0	0.32
Vermejo R, NM	83	**0.08**	29	**0.09**	50	**0.008**	25	0.29
Ponil Cr, NM	50	**0.1**	8	0.34	33	0.14	0	0.25
AVERAGE	39.5		-4.5		23.25		6.25	
Central								
Groesbeck Cr, TX	214	0.19	67	**0.04**	0	0.22	0	0.3
Medicine Lodge R, KS	4	0.43	-9	0.28	20	0.26	-25	0.23
Skeleton Cr, OK	64	**0.08**	55	**0.04**	56	**0.1**	38	0.19
Council Cr, OK	60	**0.07**	19	0.19	33	0.17	71	0.12
Dry Cr, OK	50	**0.09**	38	0.12	18	0.32	-50	**0.1**
AVERAGE	78.4		34		25.4		6.8	
Eastern								
Blue R, OK	4	0.31	0	0.42	0	0.31	8	0.39
White R, AK	-20	0.12	-4	0.31	-25	**0.09**	10	0.36
Flint Cr, AK	-2	0.43	-3	0.37	-22	0.12	-5	0.4
James Fork R, AK	2	0.43	-8	0.28	0	0.46	0	0.46
Sulphur R, TX	6	0.37	3	0.43	-7	0.33	-13	0.32
Baron Fork Cr, OK	24	**0.06**	2	0.35	20	0.17	31	**0.1**
Little Cypress B, TX	15	0.2	6	0.34	0	0.49	0	0.46
AVERAGE	4.1		-0.57		-4.9		4.43	

Compared with the negative phase of PDO, the ET during the positive phase of PDO generally increased ($p \leq 0.1$, single-tailed t-test, considering unequal variance) primarily for the western and central regions with the largest percentage increase of 34% and 18% during spring for the western and the central region, respectively (Table 2.10). The PDO had very limited impact on *ET* for the eastern region of the basin.

Table 2.8. Seasonal distribution of *ET* during long-term, positive and negative PDO for 16 watersheds in the Arkansas River and Red River basins.

Watershed	Long-term *ET*(mm)				*ET*(mm) Positive PDO				*ET*(mm) Negative PDO			
	Win	Spr	Sum	Fall	Win	Spr	Sum	Fall	Win	Spr	Sum	Fall
Western												
Van Bremer Ar, CO	36	104	172	82	35	124	195	86	37	85	148	77
Rayado Cr, NM	30	61	164	78	32	67	171	87	29	54	158	68
Vermejo R, NM	34	92	173	82	35	106	180	92	33	79	167	74
Ponil Cr, NM	35	88	192	84	38	98	210	88	32	76	176	79
AVERAGE	34	86	175	81	35	99	189	88	33	73	162	75
STD	2.5	18.4	12	2.6	2.6	23.6	17	2.6	3	13.4	12	5
Central												
Groesbeck Cr, TX	71	168	202	168	78	180	210	164	64	156	195	172
Medicine Lodge R, KS	55	184	243	147	54	191	247	156	56	177	240	139
Skeleton Cr, OK	64	193	228	188	69	212	243	186	61	175	213	189
Council Cr, OK	81	204	232	185	87	226	256	187	78	185	209	184
Dry Cr, OK	96	236	215	227	112	261	218	237	81	210	212	217
AVERAGE	73	197	224	183	80	214	235	186	68	181	214	180
STD	16	25	16	29	21.5	32	20	32	10	20	16	28
Eastern												
Blue R, OK	134	228	213	241	134	227	214	242	132	231	210	241
White R, AK	47	106	241	228	46	107	260	239	47	105	226	218
Flint Cr, AK	109	223	223	246	101	221	229	257	117	225	216	236
James Fork R, AK	103	209	228	271	103	202	224	268	104	216	231	274
Sulphur R, TX	143	232	231	256	147	215	225	272	139	248	237	241
Baron Fork Cr, OK	92	189	251	247	78	186	263	257	106	192	240	238
Little Cypress B, TX	143	232	231	256	147	215	225	272	139	248	237	241
AVERAGE	110	202	231	249	108	196	234	258	112	209	228	241
STD	34	45	12	13	38	42	19	14	32	50	11	16

Table 2.9. Percentage change (%) in *ET* from negative to positive PDO per season and p-values for single-tailed t-test given unequal variance between PDO phases for 16 watersheds in the Arkansas River and Red River basins.

Watershed	Win	p-value[1]	Spr	p-value	Sum	p-value	Fall	p-value
Western								
Van Bremer Ar, CO	-5	0.38	46	**0.001**	32	**0.01**	11	0.15
Rayado Cr, NM	10	0.28	25	**0.09**	8	0.37	28	**0.03**
Vermejo R, NM	7	0.3	35	**0.09**	8	0.16	25	**0.04**
Ponil Cr, NM	18	0.16	30	**0.08**	19	**0.02**	11	0.24
AVERAGE	8		34		17		19	
Central								
Groesbeck Cr, TX	22	0.12	15	0.14	8	0.14	-5	0.27
Medicine Lodge R, KS	-5	0.41	8	0.25	3	0.37	12	0.17
Skeleton Cr, OK	13	0.13	21	**0.09**	14	0.12	-2	0.45
Council Cr, OK	11	0.12	22	**0.05**	22	**0.03**	2	0.46
Dry Cr, OK	38	**0.02**	24	**0.04**	3	0.42	9	0.27
AVERAGE	16		18		10		3	
Eastern								
Blue R, OK	2	0.38	-1	0.41	2	0.41	0	0.49
White R, AK	-2	0.48	2	0.46	15	0.11	10	0.23
Flint Cr, AK	-14	0.16	-2	0.42	6	0.31	9	0.23
James Fork R, AK	-1	0.46	-6	0.25	-3	0.39	-2	0.41
Sulphur R, TX	6	0.27	-13	**0.05**	-5	0.27	13	0.15
Baron Fork Cr, OK	-26	**0.01**	-3	0.39	10	**0.2**	8	0.24
Little Cypress B, TX	6	0.27	-13	**0.09**	-5	0.22	13	**0.02**
AVERAGE	-4		-5		3		7	

2.4.2 Responses of monthly Q to P

Correlation coefficient (r) between monthly P and Q in the ARRB ranged from 0.31 in the western to 0.74 in the central regions (Table 2.11). Stronger correlation was for the central region (r = 0.62).

Table 2.10. Correlation coefficients between monthly *P* and *Q* during the entire study period for 16 watersheds in the Arkansas River and Red River basins.

Watershed	*r*
Western	
Van Bremer Ar, CO	0.47
Rayado Cr, NM	0.31
Vermejo R, NM	0.45
Ponil Cr, NM	0.31
Central	
Groesbeck Cr, TX	0.63
Medicine Lodge R, KS	0.52
Skeleton Cr, OK	0.72
Council Cr, OK	0.66
Dry Cr, OK	0.57
Eastern	
Blue R, OK	0.65
White R, AK	0.52
Flint Cr, AK	0.57
James Fork R, AK	0.63
Sulphur R, TX	0.62
Baron Fork Cr, OK	0.57
Little Cypress B, TX	0.45

P-values are all smaller than 0.01

2.5 Discussion

2.5.1. Effects of PDO phases on seasonal P, Q and ET

Effects of PDO on seasonal *P* varied along the ARRB. For the western watersheds, significant increases were found in spring, summer and fall. Spring received the larger portion of *P* increase, with a 36% increase from negative to positive PDO. In the central part, significant increases were found mainly in winter. On average in the central region, monthly *P* had a 32% increase in winter and a 30% increase in spring from negative to positive PDO. In the eastern, no significant increase occurred in monthly *P* in any watershed. On average, a 14% decrease in monthly *P* occurred during spring. The results found in the central and western watersheds were similar to trends observed by Garbrecht et al. (2004) from 1961 to 2001 in the Great Plains. In their study, the first two decades analyzed were considered “dry years” and the two last decades “wet years”. During the “dry years (from 1961 to 1981), PDO was predominantly negative. While during the “wet years” (1982 to 2001), PDO was predominantly positive. The largest change from the dry years to the wet years was also reported for spring season. Kurtzman and Scanlon (2007) using data from the NCDC climatic divisions from 1905 to 2014 found that *P* during positive PDO phase in contrast to negative phase was significantly greater during the months of October to March (fall, winter and spring) in parts of Oklahoma, Texas, Arkansas and Missouri. In other regions such as the western U.S, positive PDO was also associated with increased *P* during winter in 80% of 250 climatic divisions analyzed (Goodrich and Walker, 2011). Positive PDO coinciding with El-Niño (warm or positive) phase in the U.S Great Plains have been reported to increase wet conditions mainly in spring season (Hu and Huang, 2009).

Analyzing the seasonal responses of *Q* to PDO, it is very important to consider the lag effects between *P* inputs and *Q* generation. Despite the fact that inside the ARRB the overall changes in monthly *P* in response to the PDO were concentrated around spring, monthly *Q increase* was in general evenly distributed throughout the year across the basin. In the west, even though *P* changed little during winter, *Q* had a significant increase. The increase in *Q* during winter is likely to be associated with increase of precipitation during fall. In the center, as the correlation analysis suggested, there was a higher correlation between *P* and *Q* and increase in *P* was always followed an increase in *Q* for the same season. In the central region, lagged response of *Q* to *P* occurred from summer to fall in two watersheds. Overall, for western and central watersheds, an increase in *P* always resulted in larger proportional increase in *Q*. No significant change in *Q* was observed in eastern part of the basin due to lack of PDO impact for precipitation.

In the western and central region, *ET* closely followed *P* for summer and fall season, and almost all increase in *P* was turned into *ET*, suggesting high atmospheric demand and the nature of water limiting watersheds. In the center, winter *ET* did not increase significantly despite the average 32% increase in *P*. Atmospheric demands were much lower during winter and spring months; therefore, the streamflow coefficients were generally higher during these two seasons. These explained the proportionally larger increase in *Q* for most central and western watersheds during winter and spring, during the positive phase of PDO. *ET* values here only represent trends and directions and do not make justice to the complex inter-play between watershed characteristics and hydro-climatic variables in a seasonal scale.

2.5.2 P and Q relationship

A higher correlation between *P* and *Q* suggests that alterations in *P* are more readily transferred to *Q*. The eastern region on average had the highest correlation coefficient between *P* and *Q*. In contrast, the correlation between *P* and *Q* was relatively low in the western part of the basin, specifically for Rayado and Ponil Creek watersheds in New Mexico, the only two watersheds above 2000 meters of altitude. This might be due to the fact that a large portion of *P* for these two watersheds were from snow, resulting spring *Q* from winter *P*, a lag between *P* and *Q* on seasonal scale (Carey et al., 2010).

2.6 Conclusion

There are strong PDO effect on the seasonal *P*, *Q*, and *ET* in the ARRB. Increased spring *P* in the western part of the basin during positive PDO will benefit foraging and crop yields and reduce reliance on groundwater withdrawal. Also in the western part of the basin, during positive PDO summers, higher water demands from agriculture and urban areas could benefit from increased *Q* following winter *P* increase. In the center, especially in watersheds around Stillwater and Oklahoma City, OK, *Q* increased on average 115% in winter, 69% in spring, 38% in summer and

66% during fall. This information is very important to water reservoir managers, who can more wisely release or hold flows between seasons, especially considering drought risks associated with negative PDO and its effects on *Q*. Ongoing inter-basin water transfer from southeast Oklahoma to metropolitan areas in the central region can incorporate such information to adapt and adjust regional transfer volume. Further studies are needed to analyze combined effects of ENSO and PDO especially in the central and western regions, where La Nina has shown to increase the occurrence of dry summers.

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APPENDICES

APPENDIX A

Correlation coefficients between precipitation and Pacific Decadal Oscillation (*P* ~ PDO), Atlantic Multidecadal Oscillation (*P* ~AMO) and El Niño-Southern Oscillation (*P* ~ ENSO) for 16 watersheds in the Arkansas River and Red River basin.

	(*P*~PDO)		(*P*~AMO)		(*P*~ENSO[2])	
Watershed	***r***	**p-value[1]**	***r***	**p-value**	***r***	**p-value**
Western						
Van Bremer Ar, CO	0.46	**0.002**	0.10	0.46	0.28	0.08
Rayado Cr, NM	0.33	**0.002**	0.10	0.34	0.32	**0.001**
Vermejo R, NM	0.33	**0.001**	0.10	0.29	0.37	**0.001**
Ponil Cr, NM	0.35	**0.005**	0.071	0.54	0.35	**0.002**
Central						
Groesbeck Cr, TX	0.30	**0.03**	0.20	0.16	0.26	0.1
Medicine Lodge R, KS	0.30	**0.01**	0.0100	0.93	0.32	**0.02**
Skeleton Cr, OK	0.22	0.06	0.030	0.44	0.22	0.26
Council Cr, OK	0.36	**0.005**	0.14	0.27	0.26	0.17
Dry Cr, OK	0.24	0.14	0.063	0.69	0.10	0.91
Eastern						
Blue R, OK	0.17	0.14	0.26	**0.02**	0.22	0.19
White R, AK	0.02	0.9	0.30	**0.03**	0.22	0.3
Flint Cr, AK	0.07	0.6	0.14	0.28	0.10	0.78
James Fork R, AK	0.03	0.76	0.17	0.19	0.10	0.84
Sulphur R, TX	0.14	0.28	0.29	**0.02**	0.14	0.69
Baron Fork Cr, OK	0.06	0.58	0.10	0.33	0.22	0.24
Little Cypress B, TX	0.17	0.15	0.20	0.11	0.26	0.08

[1]Statistically significant values ($p \leq 0.05$) are highlighted in black.
[2]Multivariate ENSO index (MEI)

APPENDIX B

Monthly values of the PDO index. Years highlighted in blue are predominantly positive, therefore considered as positive years. Years highlighted in red are predominantly negative, therefore considered as negative

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1929	0.97	0.52	0.5	0.55	1.07	0.5	-0.06	-0.69	0.45	-0.21	1.24	-0.03
1930	0.97	-1.06	-0.43	-0.7	0.06	0.58	-0.45	-0.53	-0.2	-0.38	-0.31	1.2
1931	0.08	1.56	1.13	1.28	1.66	0.39	1.49	0.02	-0.01	-0.17	0.34	1.09
1932	-0.26	-0.58	0.51	1.15	0.64	0.1	-0.12	-0.14	-0.4	-0.29	-0.88	0.02
1933	0.29	0.02	0.15	-0.05	-0.5	-0.68	-1.81	-1.56	-2.28	-1.19	0.55	-1.1
1934	0.17	0.68	1.34	1.63	1.23	0.51	0.44	1.54	1.25	2.1	1.63	1.67
1935	1.01	0.79	-0.11	1.1	0.99	1.39	0.68	0.63	0.98	0.21	0.13	1.78
1936	1.79	1.75	1.36	1.32	1.83	2.37	2.57	1.71	0.04	2.1	2.65	1.28
1937	0	-0.49	0.38	0.2	0.53	1.75	0.11	-0.35	0.63	0.76	-0.18	0.55
1938	0.5	0.02	0.24	0.27	-0.25	-0.2	-0.21	-0.45	-0.01	0.07	0.48	1.4
1939	1.36	0.07	-0.39	0.45	0.98	1.04	-0.21	-0.74	-1.1	-1.31	-0.88	1.51
1940	2.03	1.74	1.89	2.37	2.32	2.43	2.12	1.4	1.1	1.19	0.68	1.96
1941	2.14	2.07	2.41	1.89	2.25	3.01	2.33	3.31	1.99	1.22	0.4	0.91
1942	1.01	0.79	0.29	0.79	0.84	1.19	0.12	0.44	0.68	0.54	-0.1	-1
1943	-0.18	0.02	0.26	1.08	0.43	0.68	-0.36	-0.9	-0.49	-0.04	0.29	0.58
1944	0.18	0.17	0.08	0.72	-0.35	-0.98	-0.4	-0.51	-0.56	-0.4	0.33	0.2
1945	-1.02	0.72	-0.42	-0.4	-0.07	0.56	1.02	0.18	-0.27	0.1	-1.94	-0.74
1946	-0.91	-0.32	-0.41	-0.78	0.5	-0.86	-0.84	-0.36	-0.22	-0.36	-1.48	-0.96
1947	-0.73	-0.29	1.17	0.7	0.37	1.36	0.16	0.3	0.58	0.85	-0.14	1.67
1948	-0.11	-0.74	-0.03	-1.33	-0.23	0.08	-0.92	-1.56	-1.74	-1.32	-0.89	-1.7
1949	-2.01	-3.6	-1	-0.53	-1.07	-0.7	-0.56	-1.3	-0.93	-1.41	-0.83	-0.8
1950	-2.13	-2.91	-1.13	-1.2	-2.23	-1.77	-2.93	-0.7	-2.14	-1.36	-2.46	-0.76
1951	-1.54	-1.06	-1.9	-0.36	-0.25	-1.09	0.7	-1.37	-0.08	-0.32	-0.28	-1.68
1952	-2.01	-0.46	-0.63	-1.05	-1	-1.43	-1.25	-0.6	-0.89	-0.35	-0.76	0.04
1953	-0.57	-0.07	-1.12	0.05	0.43	0.29	0.74	0.05	-0.63	-1.09	-0.03	0.07
1954	-1.32	-1.61	-0.52	-1.33	0.01	0.97	0.43	0.08	-0.94	0.52	0.72	-0.5
1955	0.2	-1.52	-1.26	-1.97	-1.21	-2.44	-2.35	-2.25	-1.95	-2.8	-3.08	-2.75
1956	-2.48	-2.74	-2.56	-2.17	-1.41	-1.7	-1.03	-1.16	-0.71	-2.3	-2.11	-1.28
1957	-1.82	-0.68	0.03	-0.58	0.57	1.76	0.72	0.51	1.59	1.5	-0.32	-0.55
1958	0.25	0.62	0.25	1.06	1.28	1.33	0.89	1.06	0.29	0.01	-0.18	0.86
1959	0.69	-0.43	-0.95	-0.02	0.23	0.44	-0.5	-0.62	-0.85	0.52	1.11	0.06
1960	0.3	0.52	-0.21	0.09	0.91	0.64	-0.27	-0.38	-0.94	0.09	-0.23	0.17
1961	1.18	0.43	0.09	0.34	-0.06	-0.61	-1.22	-1.13	-2.01	-2.28	-1.85	-2.69
1962	-1.29	-1.15	-1.42	-0.8	-1.22	-1.62	-1.46	-0.48	-1.58	-1.55	-0.37	-0.96
1963	-0.33	-0.16	-0.54	-0.41	-0.65	-0.88	-1	-1.03	0.45	-0.52	-2.08	-1.08
1964	0.01	-0.21	-0.87	-1.03	-1.91	-0.32	-0.51	-1.03	-0.68	-0.37	-0.8	-1.52
1965	-1.24	-1.16	0.04	0.62	-0.66	-0.8	-0.47	0.2	0.59	-0.36	-0.59	0.06

1966	-0.82	-0.03	-1.29	0.06	-0.53	0.16	0.26	-0.35	-0.33	-1.17	-1.15	-0.32
1967	-0.2	-0.18	-1.2	-0.89	-1.24	-1.16	-0.89	-1.24	-0.72	-0.64	-0.05	-0.4
1968	-0.95	-0.4	-0.31	-1.03	-0.53	-0.35	0.53	0.19	0.06	-0.34	-0.44	-1.27
1969	-1.26	-0.95	-0.5	-0.44	-0.2	0.89	0.1	-0.81	-0.66	1.12	0.15	1.38
1970	0.61	0.43	1.33	0.43	-0.49	0.06	-0.68	-1.63	-1.67	-1.39	-0.8	-0.97
1971	-1.9	-1.74	-1.68	-1.59	-1.55	-1.55	-2.2	-0.15	0.21	-0.22	-1.25	-1.87
1972	-1.99	-1.83	-2.09	-1.65	-1.57	-1.87	-0.83	0.25	0.17	0.11	0.57	-0.33
1973	-0.46	-0.61	-0.5	-0.69	-0.76	-0.97	-0.57	-1.14	-0.51	-0.87	-1.81	-0.76
1974	-1.22	-1.65	-0.9	-0.52	-0.28	-0.31	-0.08	0.27	0.44	-0.1	0.43	-0.12
1975	-0.84	-0.71	-0.51	-1.3	-1.02	-1.16	-0.4	-1.07	-1.23	-1.29	-2.08	-1.61
1976	-1.14	-1.85	-0.96	-0.89	-0.68	-0.67	0.61	1.28	0.82	1.11	1.25	1.22
1977	1.65	1.11	0.72	0.3	0.31	0.42	0.19	0.64	-0.55	-0.61	-0.72	-0.69
1978	0.34	1.45	1.34	1.29	0.9	0.15	-1.24	-0.56	-0.44	0.1	-0.07	-0.43
1979	-0.58	-1.33	0.3	0.89	1.09	0.17	0.84	0.52	1	1.06	0.48	-0.42
1980	-0.11	1.32	1.09	1.49	1.2	-0.22	0.23	0.51	0.1	1.35	0.37	-0.1
1981	0.59	1.46	0.99	1.45	1.75	1.69	0.84	0.18	0.42	0.18	0.8	0.67
1982	0.34	0.2	0.19	-0.19	-0.58	-0.78	0.58	0.39	0.84	0.37	-0.25	0.26
1983	0.56	1.14	2.11	1.87	1.8	2.36	3.51	1.85	0.91	0.96	1.02	1.69
1984	1.5	1.21	1.77	1.52	1.3	0.18	-0.18	-0.03	0.67	0.58	0.71	0.82
1985	1.27	0.94	0.57	0.19	0	0.18	1.07	0.81	0.44	0.29	-0.75	0.38
1986	1.12	1.61	2.18	1.55	1.16	0.89	1.38	0.22	0.22	1	1.77	1.77
1987	1.88	1.75	2.1	2.16	1.85	0.73	2.01	2.83	2.44	1.36	1.47	1.27
1988	0.93	1.24	1.42	0.94	1.2	0.74	0.64	0.19	-0.37	-0.1	-0.02	-0.43
1989	-0.95	-1.02	-0.83	-0.32	0.47	0.36	0.83	0.09	0.05	-0.12	-0.5	-0.21
1990	-0.3	-0.65	-0.62	0.27	0.44	0.44	0.27	0.11	0.38	-0.69	-1.69	-2.23
1991	-2.02	-1.19	-0.74	-1.01	-0.51	-1.47	-0.1	0.36	0.65	0.49	0.42	0.09
1992	0.05	0.31	0.67	0.75	1.54	1.26	1.9	1.44	0.83	0.93	0.93	0.53
1993	0.05	0.19	0.76	1.21	2.13	2.34	2.35	2.69	1.56	1.41	1.24	1.07
1994	1.21	0.59	0.8	1.05	1.23	0.46	0.06	-0.79	-1.36	-1.32	-1.96	-1.79
1995	-0.49	0.46	0.75	0.83	1.46	1.27	1.71	0.21	1.16	0.47	-0.28	0.16
1996	0.59	0.75	1.01	1.46	2.18	1.1	0.77	-0.14	0.24	-0.33	0.09	-0.03
1997	0.23	0.28	0.65	1.05	1.83	2.76	2.35	2.79	2.19	1.61	1.12	0.67
1998	0.83	1.56	2.01	1.27	0.7	0.4	-0.04	-0.22	-1.21	-1.39	-0.52	-0.44
1999	-0.32	-0.66	-0.33	-0.41	-0.68	-1.3	-0.66	-0.96	-1.53	-2.23	-2.05	-1.63
2000	-2	-0.83	0.29	0.35	-0.05	-0.44	-0.66	-1.19	-1.24	-1.3	-0.53	0.52
2001	0.6	0.29	0.45	-0.31	-0.3	-0.47	-1.31	-0.77	-1.37	-1.37	-1.26	-0.93
2002	0.27	-0.64	-0.43	-0.32	-0.63	-0.35	-0.31	0.6	0.43	0.42	1.51	2.1
2003	2.09	1.75	1.51	1.18	0.89	0.68	0.96	0.88	0.01	0.83	0.52	0.33
2004	0.43	0.48	0.61	0.57	0.88	0.04	0.44	0.85	0.75	-0.11	-0.63	-0.17
2005	0.44	0.81	1.36	1.03	1.86	1.17	0.66	0.25	-0.46	-1.32	-1.5	0.2
2006	1.03	0.66	0.05	0.4	0.48	1.04	0.35	-0.65	-0.94	-0.05	-0.22	0.14
2007	0.01	0.04	-0.36	0.16	-0.1	0.09	0.78	0.5	-0.36	-1.45	-1.08	-0.58
2008	-1	-0.77	-0.71	-1.52	-1.37	-1.34	-1.67	-1.7	-1.55	-1.76	-1.25	-0.87

2009	-1.4	-1.55	-1.59	-1.65	-0.88	-0.31	-0.53	0.09	0.52	0.27	-0.4	0.08
2010	0.83	0.82	0.44	0.78	0.62	-0.22	-1.05	-1.27	-1.61	-1.06	-0.82	-1.21
2011	-0.92	-0.83	-0.69	-0.42	-0.37	-0.69	-1.86	-1.74	-1.79	-1.34	-2.33	-1.79
2012	-1.38	-0.85	-1.05	-0.27	-1.26	-0.87	-1.52	-1.93	-2.21	-0.79	-0.59	-0.48
2013	-0.13	-0.43	-0.63	-0.16	0.08	-0.78	-1.25	-1.04	-0.48	-0.87	-0.11	-0.41
2014	0.3	0.38	0.97	1.13	1.8	0.82	0.7	0.67	1.08	1.49	1.72	2.51

APPENDIX C

Oneway Analysis of $Cv_{,P}$ by region

Oneway Anova

Summary of Fit

Rsquare	0.316543
Adj Rsquare	0.211395
Root Mean Square Error	0.023432
Mean of Response	0.238125
Observations (or Sum Wgts)	16

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Region	2	0.00330589	0.001653	3.0105	0.0843
Error	13	0.00713786	0.000549		
C. Total	15	0.01044375			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Western	4	0.242500	0.01172	0.21719	0.26781
Central	5	0.256000	0.01048	0.23336	0.27864
Eastern	7	0.222857	0.00886	0.20372	0.24199

APPENDIX D

One-way ANOVA analysis of $Cv_{,Q}$ by regions of the ARRB.

Summary of Fit

Rsquare	0.482266
Adj Rsquare	0.402614
Root Mean Square Error	0.200071
Mean of Response	0.719375
Observations (or Sum Wgts)	16

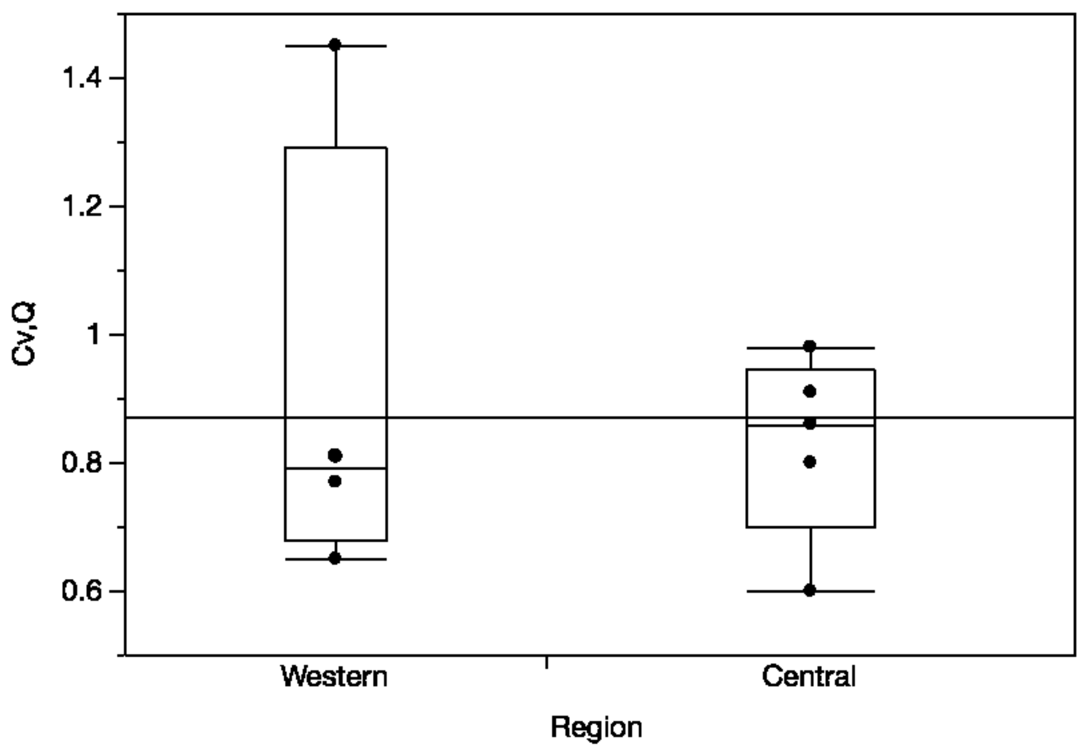
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Region	2	0.4847223	0.242361	6.0547	0.0139*
Error	13	0.5203714	0.040029		
C. Total	15	1.0050938			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Western	4	0.920000	0.10004	0.70389	1.1361
Central	5	0.830000	0.08947	0.63670	1.0233
Eastern	7	0.525714	0.07562	0.36235	0.6891

Oneway Analysis of $Cv_{,Q}$ By region



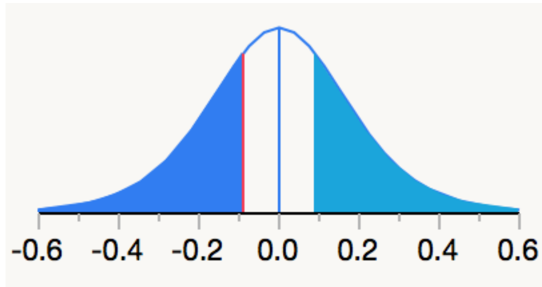
Oneway Anova
Summary of Fit

Rsquare	0.036735
Adj Rsquare	-0.10087
Root Mean Square Error	0.25967
Mean of Response	0.87
Observations (or Sum Wgts)	9

t Test
Central-Western
Assuming equal variances

Difference	-0.09000	t Ratio	-0.51667
Std Err Dif	0.17419	DF	7

Upper CL Dif	0.32190	Prob > |t|	0.6213
Lower CL Dif	-0.50190	Prob > t	0.6893
Confidence	0.95	Prob < t	0.3107



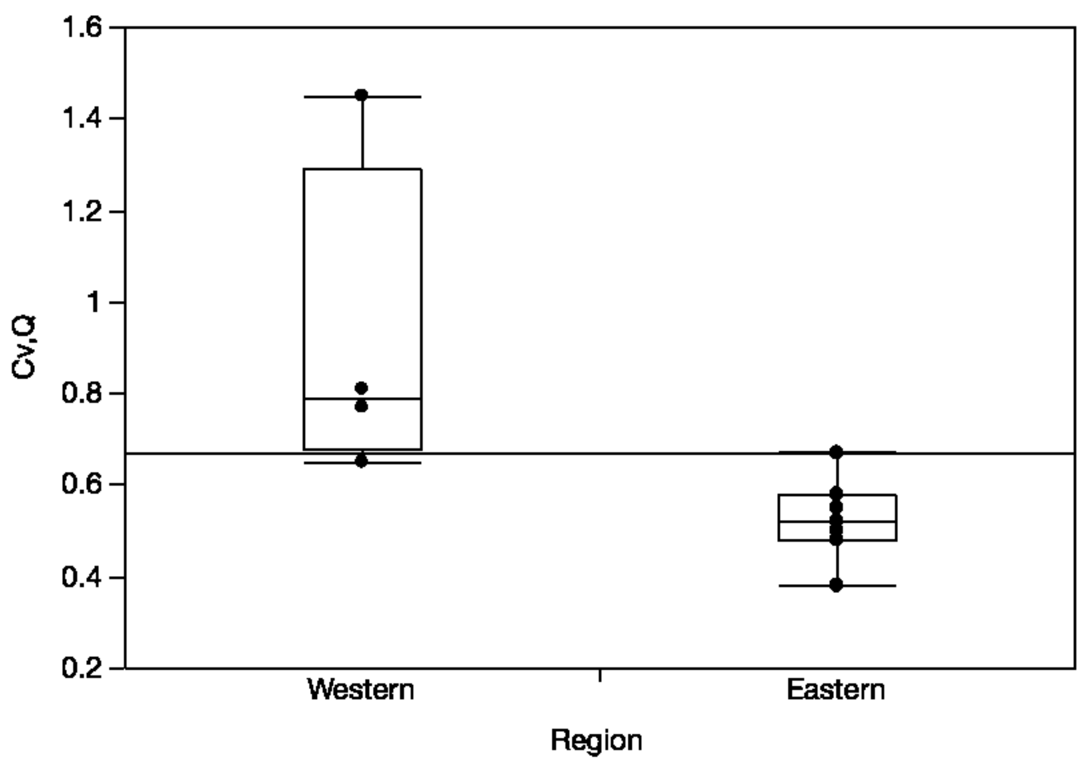
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Region	1	0.01800000	0.018000	0.2669	0.6213
Error	7	0.47200000	0.067429		
C. Total	8	0.49000000			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Western	4	0.920000	0.12984	0.61299	1.2270
Central	5	0.830000	0.11613	0.55540	1.1046

Oneway Analysis of $Cv_{,Q}$ by region

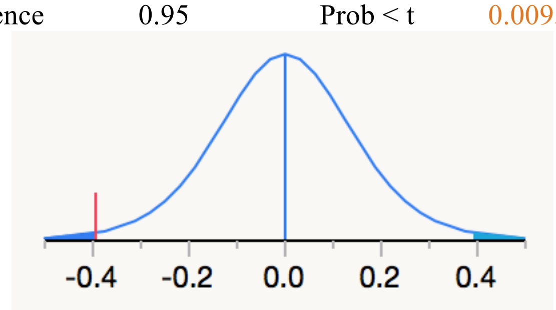


Oneway Anova
Summary of Fit

Rsquare	0.475344
Adj Rsquare	0.417049
Root Mean Square Error	0.220296
Mean of Response	0.669091
Observations (or Sum Wgts)	11

t Test
Eastern-Western
Assuming equal variances

Difference	-0.39429	t Ratio	-2.85554
Std Err Dif	0.13808	DF	9
Upper CL Dif	-0.08193	Prob > |t|	0.0189*
Lower CL Dif	-0.70664	Prob > t	0.9905
Confidence	0.95	Prob < t	0.0095*



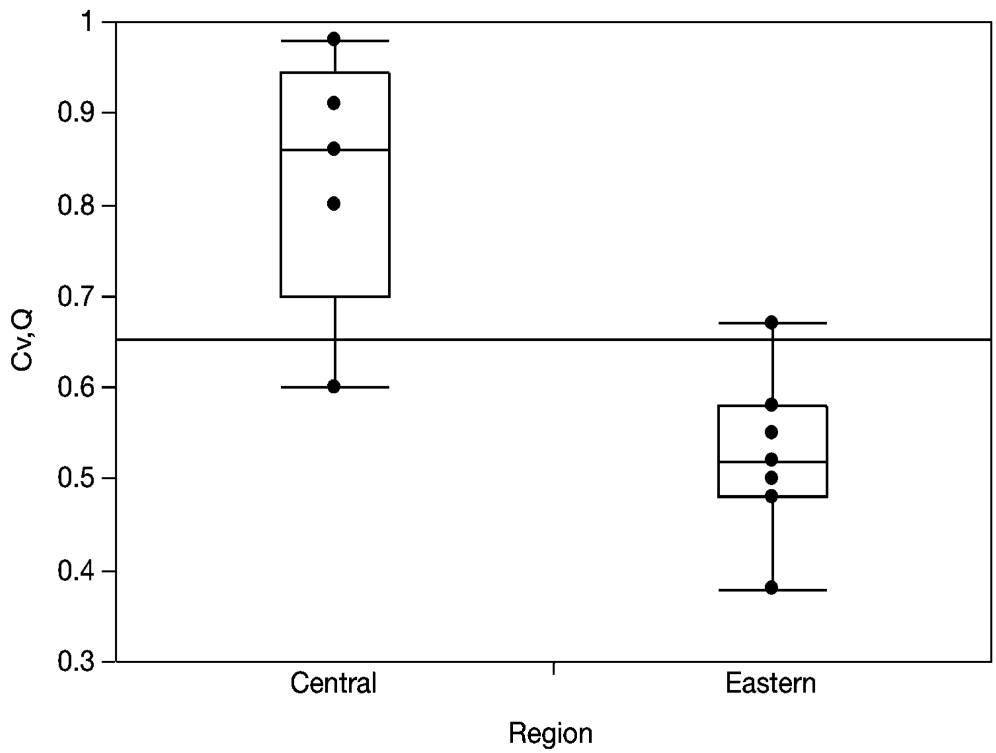
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Region	1	0.39571948	0.395719	8.1541	0.0189*
Error	9	0.43677143	0.048530		
C. Total	10	0.83249091			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Western	4	0.920000	0.11015	0.67083	1.1692
Eastern	7	0.525714	0.08326	0.33736	0.7141

Oneway Analysis of $Cv_{,Q}$ By region

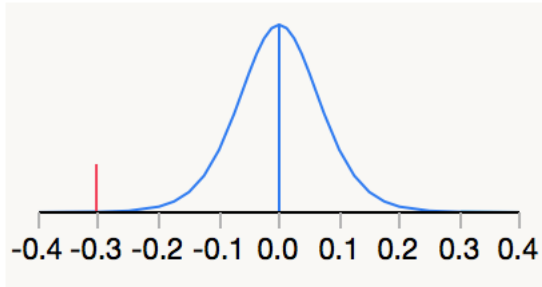


Oneway Anova
Summary of Fit

Rsquare	0.671733
Adj Rsquare	0.638907
Root Mean Square Error	0.114879
Mean of Response	0.6525
Observations (or Sum Wgts)	12

t Test
Eastern-Central
Assuming equal variances

Difference	-0.30429	t Ratio	-4.52361
Std Err Dif	0.06727	DF	10
Upper CL Dif	-0.15441	Prob > |t|	0.0011*
Lower CL Dif	-0.45416	Prob > t	0.9994
Confidence	0.95	Prob < t	0.0006*



Analysis of Variance

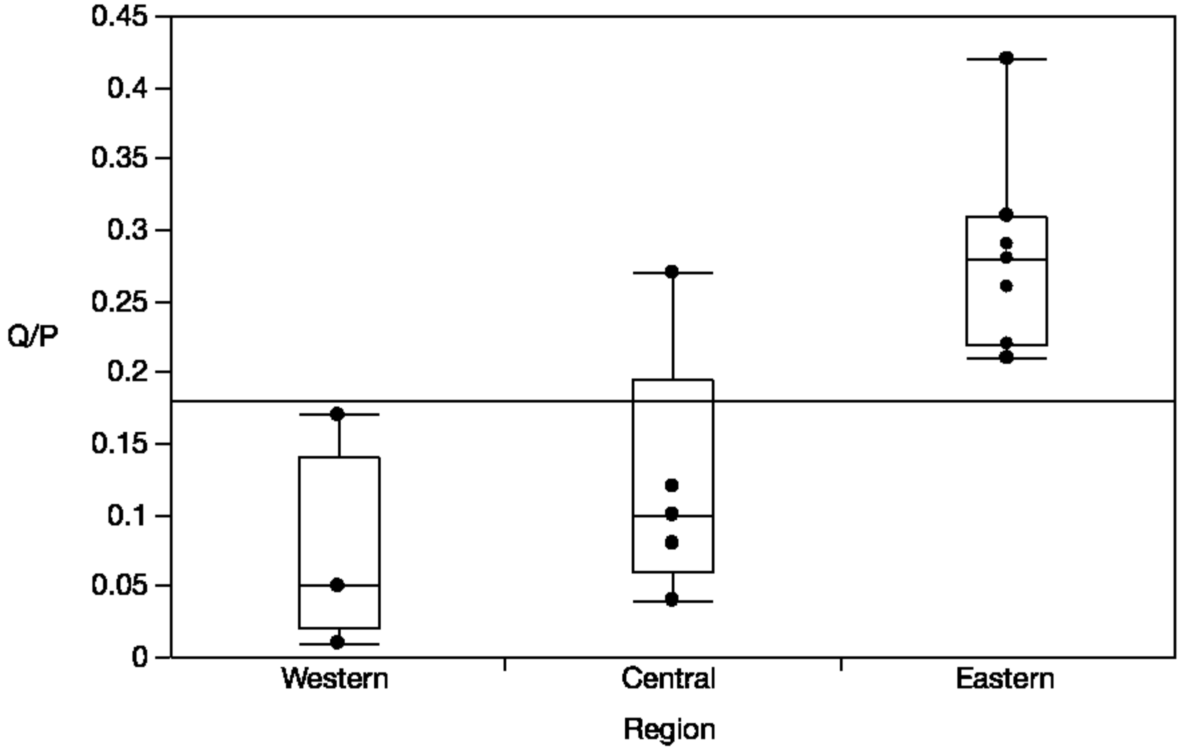
Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Region	1	0.27005357	0.270054	20.4630	0.0011*
Error	10	0.13197143	0.013197		
C. Total	11	0.40202500			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Central	5	0.830000	0.05138	0.71553	0.94447
Eastern	7	0.525714	0.04342	0.42897	0.62246

APPENDIX E

Oneway Analysis of *Q/P* by region



Oneway Anova
Summary of Fit

Rsquare	0.654392
Adj Rsquare	0.601221
Root Mean Square Error	0.075779
Mean of Response	0.18
Observations (or Sum Wgts)	16

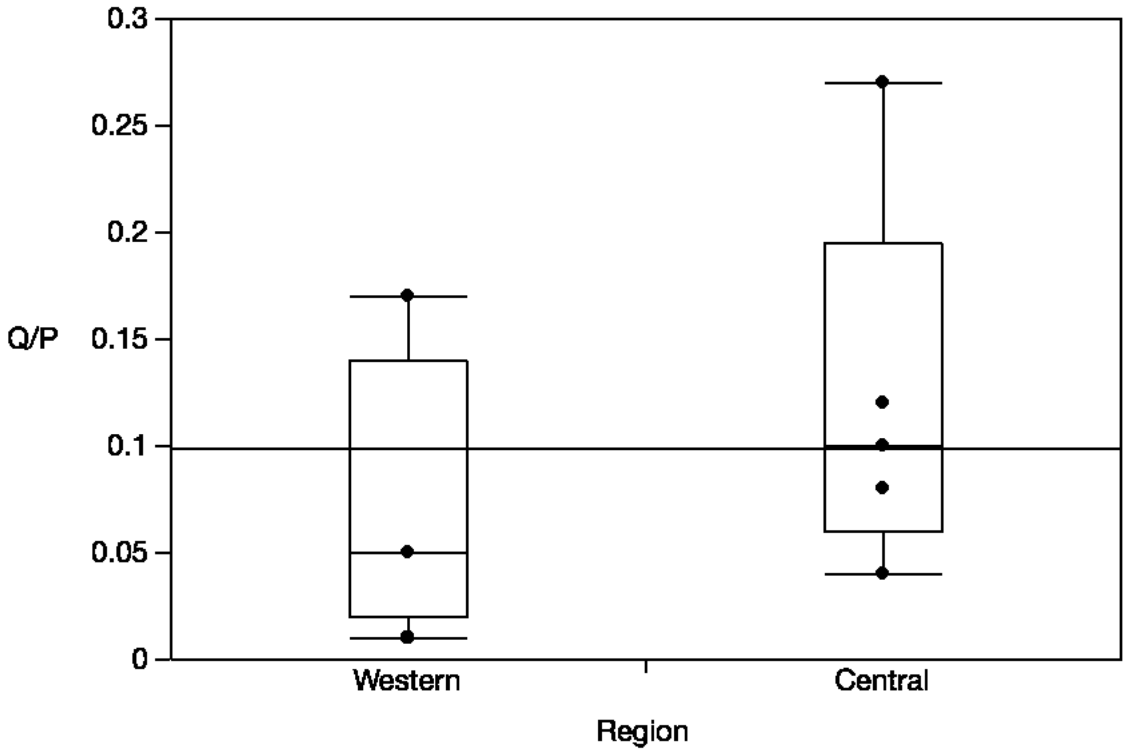
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Region	2	0.14134857	0.070674	12.3074	0.0010*
Error	13	0.07465143	0.005742		
C. Total	15	0.21600000			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Western	4	0.070000	0.03789	-0.0119	0.15186
Central	5	0.122000	0.03389	0.0488	0.19521
Eastern	7	0.284286	0.02864	0.2224	0.34616

Oneway Analysis of *Q/P* by region

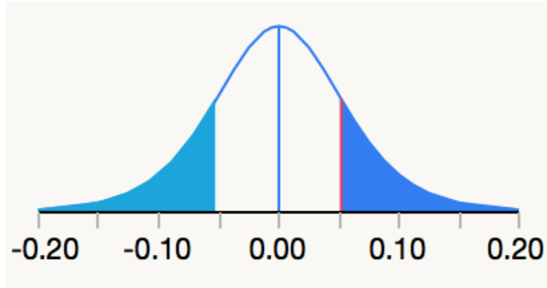


Oneway Anova
Summary of Fit

Rsquare	0.117158
Adj Rsquare	-0.00896
Root Mean Square Error	0.080427
Mean of Response	0.098889
Observations (or Sum Wgts)	9

t Test
Central-Western
Assuming equal variances

Difference	0.05200	t Ratio	0.963813
Std Err Dif	0.05395	DF	7
Upper CL Dif	0.17958	Prob > |t|	0.3672
Lower CL Dif	-0.07558	Prob > t	0.1836
Confidence	0.95	Prob < t	0.8164



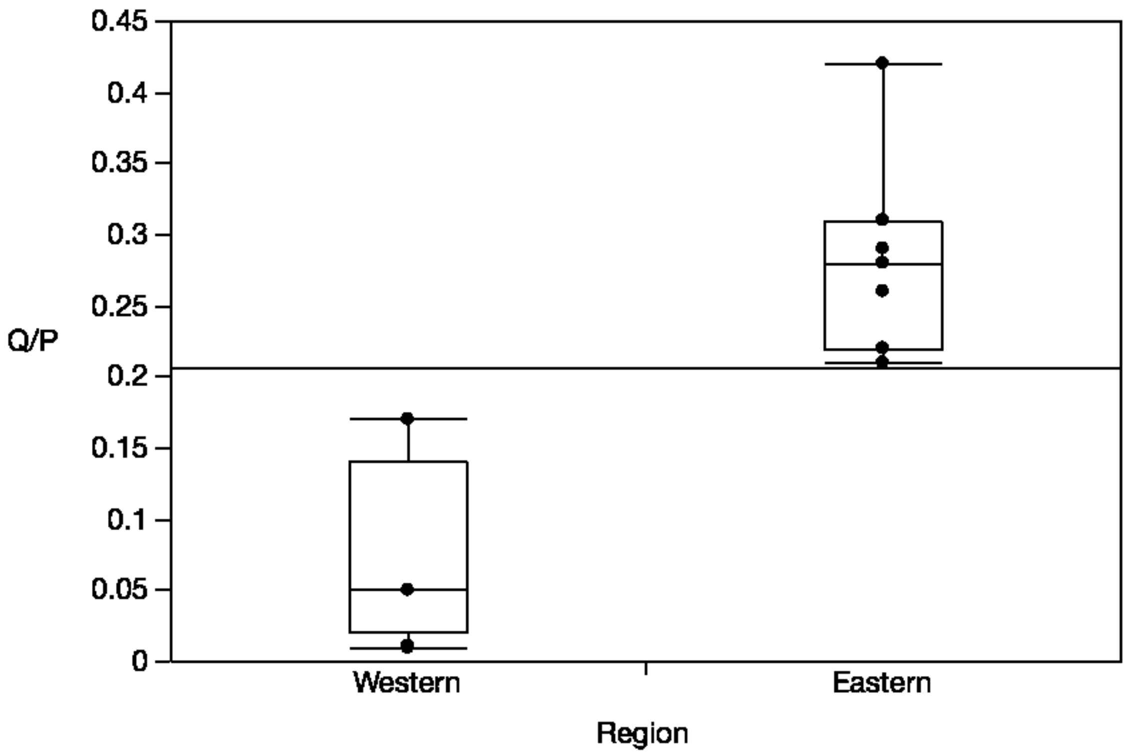
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Region	1	0.00600889	0.006009	0.9289	0.3672
Error	7	0.04528000	0.006469		
C. Total	8	0.05128889			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Western	4	0.070000	0.04021	-0.0251	0.16509
Central	5	0.122000	0.03597	0.0369	0.20705

Oneway Analysis of *Q/P* by region

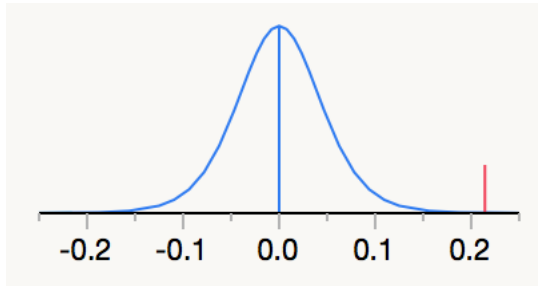


Oneway Anova
Summary of Fit

Rsquare	0.727543
Adj Rsquare	0.69727
Root Mean Square Error	0.069739
Mean of Response	0.206364
Observations (or Sum Wgts)	11

t Test
Eastern-Western
Assuming equal variances

Difference	0.214286	t Ratio	4.902321
Std Err Dif	0.043711	DF	9
Upper CL Dif	0.313167	Prob > |t|	0.0008*
Lower CL Dif	0.115404	Prob > t	0.0004*
Confidence	0.95	Prob < t	0.9996



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Region	1	0.11688312	0.116883	24.0328	0.0008*
Error	9	0.04377143	0.004863		
C. Total	10	0.16065455			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Western	4	0.070000	0.03487	-0.0089	0.14888
Eastern	7	0.284286	0.02636	0.2247	0.34391

VITA

Renato Matheus Rahal

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Master of Science

Thesis: PRECIPITATION AND STREAMFLOW RESPONSES TO CLIMATE VARIABILITY IN THE ARKANSAS RIVER AND RED RIVER BASINS

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