Assessment of Interannual and Interdecadal Climate Variability Effects on Water Supply in Zayandeh-rood River Basin, Iran

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Abstract: Two of the most prominent known sources of interannual and interdecadal climate variability in the form of El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) are analyzed to assess the influences of these large-scale climate phenomena on water supply in the Zayandeh-rood River Basin. For this purpose, any shifts in the mean and variance of the inflow volume of the Zayandeh-rood Dam in different climate conditions (resulted by different combination of ENSO and PDO phases) has been analyzed and compared with similar statistics in neutral condition to find out if the differences are statistically significant. Correlation analysis indicates that the inflow volume has a direct relation with Pacific Decadal Oscillation Index (PDO Index) and an inverse relation with Southern Oscillation Index (SOI). Also, it was found that any significant shift in the mean January through July inflow volume arises only when El Niño and La Niña events occurs respectively in the positive and negative phase of the PDO. To give some physical justification to the results, precipitation and temperature patterns in the above basin of Zayandeh-rood Dam are analyzed.

1- Introduction

In the Middle East and North Africa (MENA) water has emerged as a key component of global agendas and development policies. Due to limited availability of water and high population growth, the region is increasingly facing water stress. In this respect, better understanding of climate change and climate variability effects on water resources in the MENA region could greatly improve our decisions to face more rationally with this situation in the near future. In this respect, understanding ocean-atmospheric interactions that results in climate modes, and identifying the influences of these phenomena on hydrological and meteorological parameters of different basins in the MENA region is of great importance.

In recent years, mortal events such as flood, drought, forest firing which are mainly due to phenomena such as the increase in the amount of green house gases, global warming and El Niño/La Niña anomalies has become a challenging theme among researchers. Many researchers have investigated the relationships between hydrological and meteorological variables of different basins throughout the world with large-scale climate signals such as El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), North Atlantic Oscillation (NAO), etc. A brief review of the previous studies in this respect is as follows.

Ropelewski and Halpert (1987) showed that La Niña events have different effects on different parts of Africa. While the eastern equatorial part of Africa were experiencing below normal precipitation condition, the southeastern part were facing above normal precipitation condition at the same time [1]. A research by Sun and Furbish (1997) indicated a 40% and 30% shift respectively in annual precipitation and streamflow of the rivers in Florida due to the El Niño and La Niña events [2]. Tootle and Piechota (2004) studied the influences of climate variability on streamflow in the southeastern United States. The results indicated that a strong ENSO signal exists at various lead times to the winter and spring streamflow of the Suwannee River [3]. Barton and Ramirez (2004) analyzed the PDO and ENSO phenomena to assess their impacts on water supply in the Columbia River Basin. They concluded that the basin's runoff is directly related to SOI and inversely related to PDO phases [4]. Vicente-Serrano (2005) determined the impacts of extreme phases of Southern Oscillation (SO, El Niño/La Niña) on droughts in the Iberian Peninsula. He concluded that extreme phase of SO has a significant effect on the occurrence of droughts in this region [5].

Ostovar (2000) analyzed the relationship between El Niño events and annual precipitation in Iran. He concluded that there is a lagged, rather than simultaneous, response of the rainfall in Iran to the ENSO events [6]. Nazemosadat (2001) studied the ENSO influences on 41 stations in Iran. He used the SOI index for the precipitation forecasts [7]. Hazrati and Abrishamchi (2003) analyzed the effects of ENSO and NAO phenomena on the water level of the Uromia lakes in Iran. The results indicated that Simineh-rood stream flows are significantly correlated with the negative NAO index. In addition, they demonstrated that El Niño (La Niña) events increases (decreases) autumn streamflow [8].

In addition to the above results, it has been found that incorporating large-scale climate signals into forecasting models could greatly improve long-lead streamflow forecasting skills. Hamlet and Lettenmaier (1999) devised a simple method to incorporate the ENSO and PDO climate signals into the extended streamflow forecasting approach. The results indicated the increase in the lead time and specificity of the forecasts [9]. Grantz (2003) has utilized large-scale climate information as a spring runoff predictor in a forecasting model to improve the skill and lead-time of the forecasts. The results demonstrated that the incorporation of this information, particularly the 500 mbar geopotential height index, improves the forecasts skills at longer lead times when compared with forecasts only based on snowpack information [10, 11]. Optiz-Stapleton et al. (2007) developed and examined an ensemble streamflow forecasting model incorporated with the Pacific North American (PNA) pattern for the Yakima River Basin. The results showed a significant correlation between the PNA and the spring runoff at the Yakima Basin [12]. Araghinejad (2005) used ENSO and NAO data, as well as the climate predictors of seasonal streamflow in his model. The results indicated a significant improvement in the long-term streamflow forecasts relative to other statistical and conceptual methods [13].

These studies reveal the great importance of investigating the influences of large-scale climate signals on hydrological and meteorological variables of different parts of the world, particularly in the arid and semiarid water stressed MENA region. Therefore, in this research the influences of the changes in the pressure and temperature patterns of the Pacific Ocean, in the form of ENSO and PDO, on the inflow volume of Zayandeh-rood Dam and the precipitation and temperature patterns of the region will be investigated.

The structure of this paper is as follows. A brief overview of the ENSO and PDO phenomena is presented in section 2. Section 3 concisely describes the study basin. The data and methodology used in this study are presented in section 4. Acquired results and conclusion are presented in section 5 and 6, respectively.

2- Overview of Climatic Phenomena

In the following two subsections, a brief description of the large-scale climate signals used in this study is presented.

2-1- El Niño Southern Oscillation (ENSO)

El Niño/Southern Oscillation is a complex ocean-atmospheric interaction that occurs periodically in the tropical Pacific. The oceanic part is called El Niño and the atmospheric part is called Southern Oscillation. ENSO oscillates from a warm phase (El Niño) through a neutral phase (normal conditions) to a cold phase (La Niña) over a period of 2 – 7 years and lasts about 1 – 2 years. During the neutral phase of ENSO, conditions are ‘normal’ in which trade winds blowing westward across the Pacific Ocean pushed by a natural atmospheric pressure difference that is high in the east (Tahiti) and low in the west (Darwin). During El Niño (warm) years, the trade winds weaken and warm waters migrate eastward to the South American coast. The apposite phase i.e. La Niña (cold) phase is the result of the anomalously high westward-blowing winds, which produce strong upwelling and a westward movement of the warm waters along the equator. [7, 8, 11, 14].

Southern Oscillation Index (SOI) is used to measure the magnitude of the phases of ENSO. It is computed as the normalized difference of the sea level pressure at Tahiti (T) and Darwin (D) [4, 7, 8]:

$$SOI = P(T) - P(D) \qquad (1)$$

2-2- Pacific Decadal Oscillation (PDO)

The Pacific Ocean experiences recurring, long-term swings in its temperature structure. These temperature shifts include a climate mode called the Pacific Decadal Oscillation, or PDO. It's an El Niño-like temperature shift, but more gradual and subtle (about 1- 2 degrees C over 15 - 30 years). Although the temperature change due to the PDO is smaller than that experienced during the El Niño/Southern Oscillation, the PDO occurs over a much larger area. Like ENSO, the PDO oscillates between a “warm” (positive) phase and a “cool” (negative) phase [9, 11, 14].

To determine the predominant phase of the PDO, Pacific Decadal Oscillation (PDO) Index is defined using the monthly sea surface temperature variability in a specific region of the North Pacific [9, 11, 14].

3- Basin Description

The Zayandeh-rood River Basin is located in the central plateau of Iran with an approximate area of 41,500 km^2. The water supply in the Zayandeh-rood Basin is allocated for the irrigation, domestic and industrial uses. The main river of the basin, Zayandeh-rood River is about 350 km long which originates from Zagros Mountains in the western part of Iran.

The basin above the Zayandeh-rood Dam has been divided into three smaller sub-basins as follows; 1) Eskandari sub-basin located in the northern part of the basin, established on the Pelasjan River, 2) Ghale Shahrokh subbasin in the southern part of the basin on the Zayandeh-rood River, and 3) Miani sub-basin between the previous two sub-basins. Fig 1 shows the subbasins and the main tributaries of the study basin.

4- Data and Methodology

The required data for this study are precipitation and temperature time series of different station in the Zayandeh-rood Basin, as well as the inflow volume time series of the Zayandeh-rood Dam. They were prepared from the Iranian Water Resources Research Center, Regional Water Board of Isfahan, and the Iran Meteorological Organization (IMO) for the period 1970-2007. In addition, the SOI and PDO data were acquired from the Joint Institute for the Study of Atmosphere and Ocean (JISAO) at the University of Washington, Seattle (available at http://jisao.washington.edu).

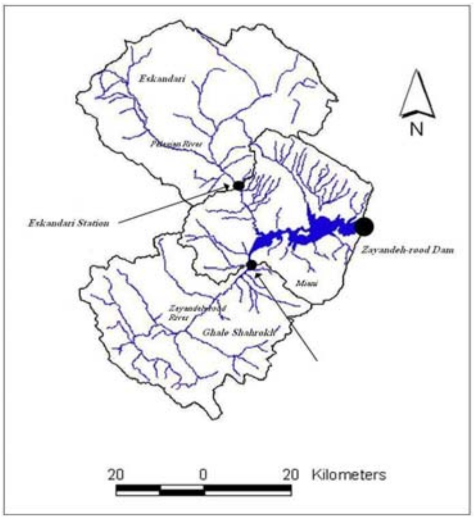

Fig 1. Rivers and Subbasins of the Zayandeh-rood River Basin

Since El Niño and La Niña Phases of ENSO generally develop around September or October [4], it is more convenient to start a water year from October. Thus, four seasons are defined as follows: 1) Fall: October – December, 2) Winter: January – March, 3) Spring: April – June and 4) Summer: July – September. Regarding different aspects of water management including water allocation for different sectors, flood controling, environmental considerations etc., the January through July (Jan-Jul) inflow volume was considered as the general descriptor of the available water in each water year. This period covers the snow accumulation season and snowmelt period of a water year [4, 15].

In order to investigate the influences of the ocean-atmospheric patterns on hydrological and meteorological variables of the study basin more precisely, the mixed effects of the warm and cold phases of the ENSO and PDO are considered. Using the method of Trenberth (1997), the El Niño and La Niña years are defined. According to his method, a water year is called an El Niño (La Niña) year, when the winter NINO3.4 index (December-February) value exceeds more than 0.5 standard deviation above (below) the long term mean value. Otherwise, the water year is considered as a neutral year [4]. Table 1 lists the water years of different phases of ENSO events.

To determine the years of the warm and cold phases of PDO, Mantua (1997) stated that when the averaged October – March PDO index exceeds more than 0.5 standard deviation above (below) the long term mean value, the warm (cold) phase of the PDO would be predominant. In addition, assuming the PDO phases to be continuous epochs, Mantua (1997, 2006) listed the 1900 – 1924, 1947 – 1976, 1999 – 2002 periods as the cold epochs and 1925 – 1946, 1977 – 1998 and 2003 – 2005 periods as the warm epochs. Using the Mantua method, it is found that water years 2006 and 2007 were also in the warm phase of PDO. Now, water years in Table 1 could be further grouped according to the water years of different phases of PDO (Table 2) [4, 16]. Using the Skewness test of normality, it was found that the distributions of the inflow volume in any of the following climate conditions acceptably follow the normal distribution.

The main purpose in this research is to determine the changes in Jan-Jul inflow volume due to the ENSO and PDO phases. Using two statistical tests named t-test and F-test, any shift in the mean and variance of the Jan-Jul inflow volume in each climate condition were tested to investigate whether these shifts are statistically different from the neutral condition [17]. Neutral condition includes years which are neither in the El Niño phase of ENSO, nor in the La Niña phase, irrespective to the predominant phase of the PDO. Finally, to investigate the physical reasons of these shifts, precipitation and temperature patterns in each of the climate conditions for the three subbasins have been analyzed.

Table 1. El Niño, La Niña and Neutral years

El Niño	Neutral	La Niña
1973	1979	1971
1977	1981	1972
1978	1982	1974
1980	1990	1975
1983	1991	1976
1987	1993	1984
1988	1994	1985
1992	1997	1986
1995	2002	1989
1998	2004	1996
2003		1999
2005		2000
2007		2001
		2006

Table 2. Climate Conditions (CC) resulted from the combination of ENSO and PDO phases

Positive PDO		Negative PDO	
El Niño (CC1)	La Niña (CC2)	El Niño (CC3)	La Niña (CC4)
1977	1984	1970	1971
1978	1985	1973	1972
1980	1986		1974
1983	1989		1975
1987	1996		1976
1988	2006		1999
1992			2000
1995			2001
1998			
2003			
2005			
2007			

5- Results and Discussion

Since significant autocorrelations may propagate error during further variability analysis, it is opportune to analyze the autocorrelation function (ACF) of the inflow volume, to remove any significant autocorrelation. As it can be seen on Fig 2, there is no significant autocorrelation coefficient beyond lag-0 at the 5% significant level.

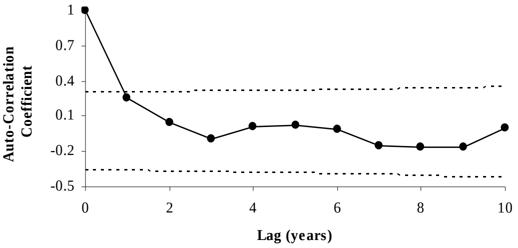

Fig 2. Autocorrelation function (ACF) of Jan-Jul inflow volume at the Zayandeh-rood Dam (95% confidence level)

In order to investigate the influences of ENSO and PDO on the inflow volume of the Zayandeh-rood Dam, cross correlation of the Jan-Jul Inflow volume with the seasonal SOI and PDO indices were analyzed at 95% confidence level (Fig 3 and 4).

As it is shown in Fig 3, the cross correlation with seasonal SOI is mainly significant at short term scale, i.e. there is not a noticeable long term correlation beyond lag-1. The most significant cross correlation is among the Jan-Jul inflow volume and the spring SOI of the previous year (lag-1). This means that the inflow volume has a high correlation with an ENSO event which has been established near 9 month before the snow accumulation season. Since nowadays ENSO events are available with a lead time of 6 month up to one year, the above result could be used beneficially for long-lead hydrological forecasting. Simultaneous (lag-0) correlations also exist among the fall and winter SOI and the Jan-Jul inflow volume. The interesting point is that the Jan-Jul inflow volume of the Zayandeh-rood Dam is inversely related to the SOI index, i.e. by the increment (decrement) of SOI and getting near to the La Niña (El Niño) phase, the inflow volume of the Zayandeh-rood Dam decrease (increase). This is exactly opposite of what is found in the Columbia River Basin [4].This fact demonstrates the diverse influences of large-scale climatic phenomena such as

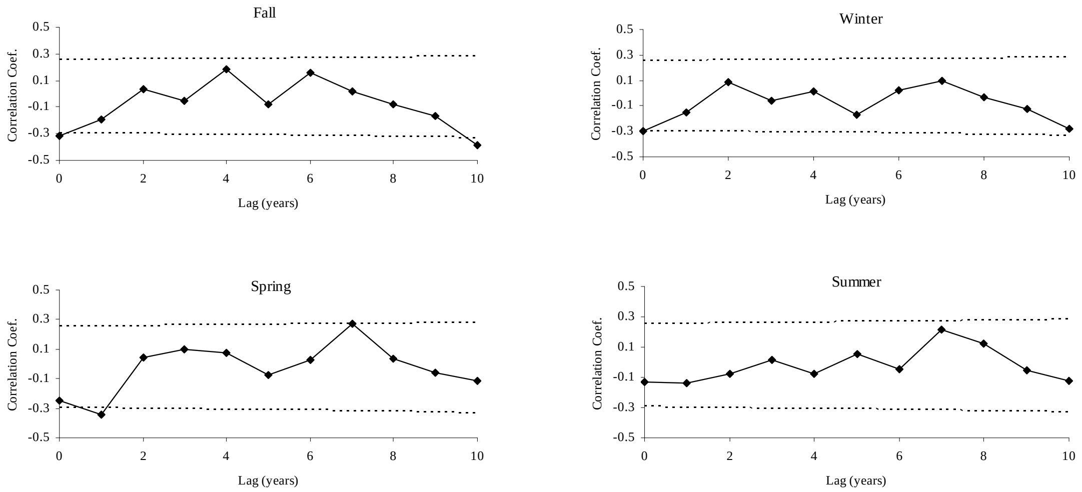

Fig 3. Cross correlation function of the Jan-Jul inflow volume at the Zayandeh-rood Dam and seasonal SOI index

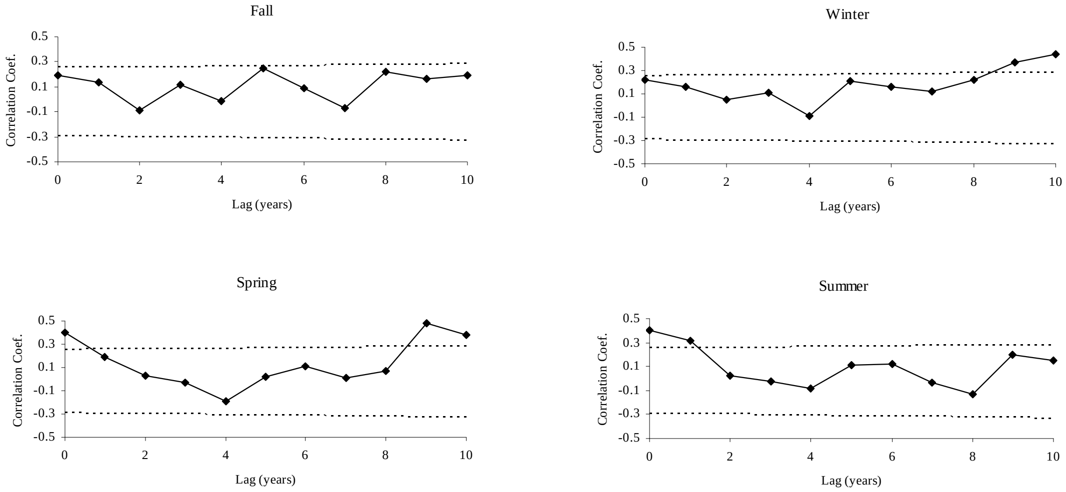

Fig 4. Cross correlation function of the Jan-Jul inflow volume at the Zayandeh-rood Dam and seasonal PDO index

ENSO on different parts of the world, and even on different parts of a continent such as Africa [1].

Similarly, the cross correlation of the seasonal PDO index and the Jan-Jul inflow volume has been investigated (Fig 4). Significant correlation with the spring and summer PDO of the same year and the summer PDO of the previous year could be seen. In addition, the positive correlation of Jan-Jul inflow volume and the PDO index indicates the direct relation among these two.

Fitting a normal distribution to each climate condition could graphically illustrate the shifts in the mean and variance of the climate conditions with respect to the similar statistics of the neutral condition. Meanwhile, it should be noted that the El Niño/-PDO (CC3) climate condition was omitted due to the lack of data in this group. There is only a one year data of inflow volume for this group which belongs to the year 1973.

Fig 5 shows the probability density function (PDF) for the El Niño/+PDO (CC1), El Niño/-PDO (CC2), La Niña/-PDO (CC4) and the neutral condition. While the mean Jan-Jul inflow volume at the Zayandeh-rood Dam during the neutral years is 1170 Million Cubic Meter (MCM), it is 1373 MCM (117% of the neutral years) during the El Niño/+PDO years, 1216 MCM (104% of the neutral years) during the La Niña/+PDO years, and 946 MCM (81% of the neutral years) during the La Niña/-PDO years. Therefore, it could be inferred that major shifts in the mean exists when the ENSO and PDO are in phase. Using the t-test, any shifts in the mean Jan-Jul inflow volume of CC1, CC2 and CC4 were compared with the similar statistic in the neutral condition at 95% and 90% confidence level. The results indicate that the mean Jan-Jul inflow volume of El Niño/+PDO and La Niña/-PDO years are statistically different with the neutral condition at 90% confidence level.

This result is also evident in Fig 5. As it can be seen, the normal distribution fitted to the El Niño/+PDO climate condition has a tangible shift to the right of the neutral condition which states the increment of the inflow volume during this condition. On the other hand, the leftward shift of the La Niña/-PDO distribution indicates the decrease of the

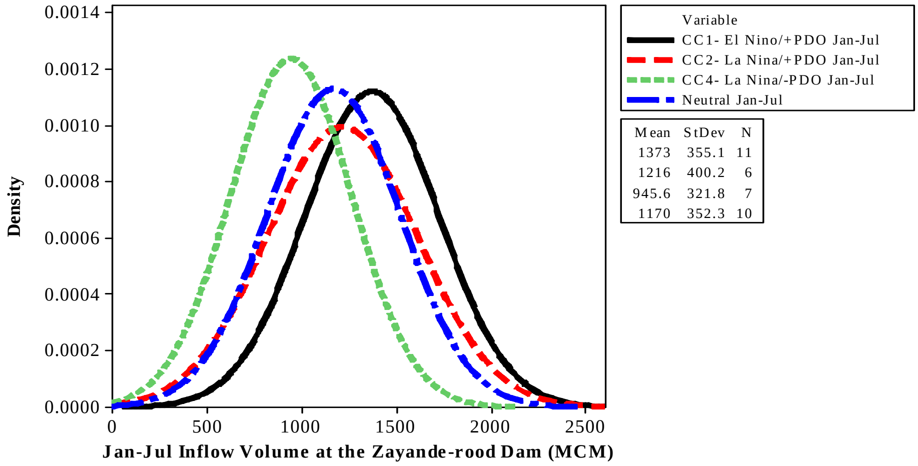

Fig 5. Probability density function (PDF) of the mean Jan-Jul inflow volume of the CC1, CC2, CC4 and neutral condition at the Zayandeh-rood Dam

inflow volume during the La Niña/-PDO years. The interesting point is that although there exists a significant statistical difference among the means of CC1 and CC4 as compared with the neutral condition, F-test indicates that the variances of the CCs are not statistically different at the 95% confidence level. This means that although the CCs distributions are centered on different means, the spread of the data around the mean of each climate condition is similar to the neutral condition.

In order to physically investigate the reasons of these changes, the precipitation and temperature patterns of the three subbasins, Eskandari, Ghale Shahrokh and Miani, during El Niño/+PDO and La Niña/-PDO years have been analyzed (Fig 6 through Fig 9). The data range including ± 0.5 standard deviation from the long term seasonal mean is considered as the normal precipitation and temperature.

During the El Niño/+PDO climate condition, a significant shift toward normal and near above normal precipitation is detectable particularly in the fall season. In addition, the temperature patterns show a significant shift toward normal and below normal temperature in the spring season, specifically for the Zayandeh-rood Dam station, which lead to a cooler weather. Consequently, the near above normal precipitation and below normal temperature patterns during this period, would cause expansion of the snow accumulation season, increment of the precipitation, and finally the increment of the inflow volume of the Zayandeh-rood Dam reservoir.

During the La Niña/-PDO years, there exists a salient shift toward below normal precipitation in the fall and winter seasons of all the three subbasins. In addition, the above normal temperature patterns in the spring season lead to a warmer weather and an earlier snow melting period with respect to the neutral condition. These two factors together would cause a reduction in the snow covered area, earlier snow melting period, increasing the likelihood of having more rain rather than snow, etc., which consequently reduce the amount of the inflow volume of the Zayandeh-rood Dam.

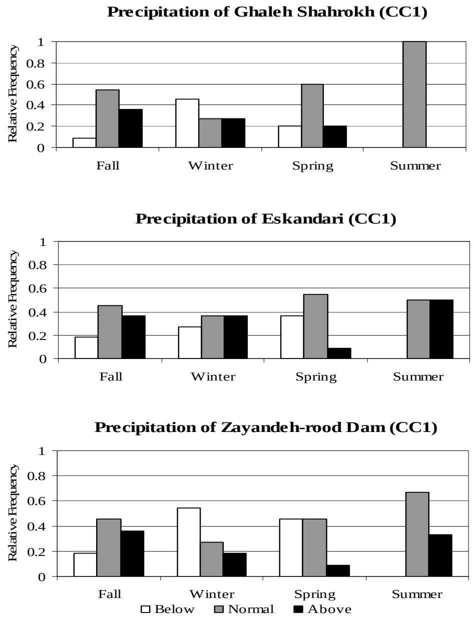

Fig 6. Relative frequency of precipitation anomalies during El Niño/+PDO

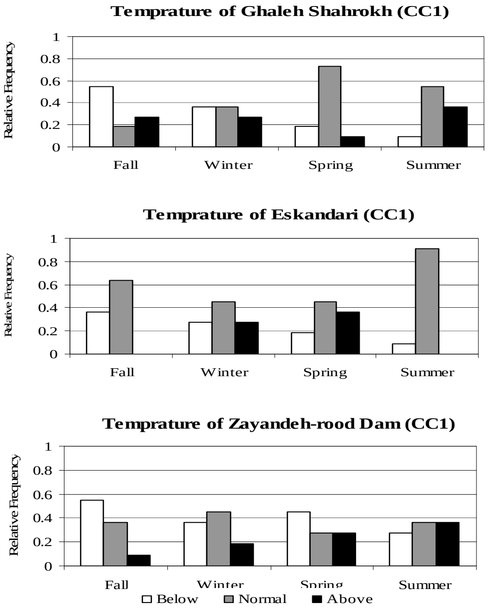

Fig 7. Relative frequency of Temperature anomalies during El Niño/+PDO

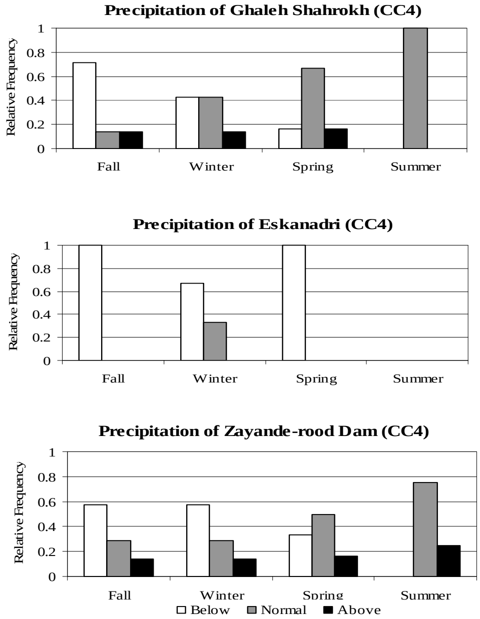

Fig 8. Relative frequency of precipitation anomalies during La Niña/-PDO

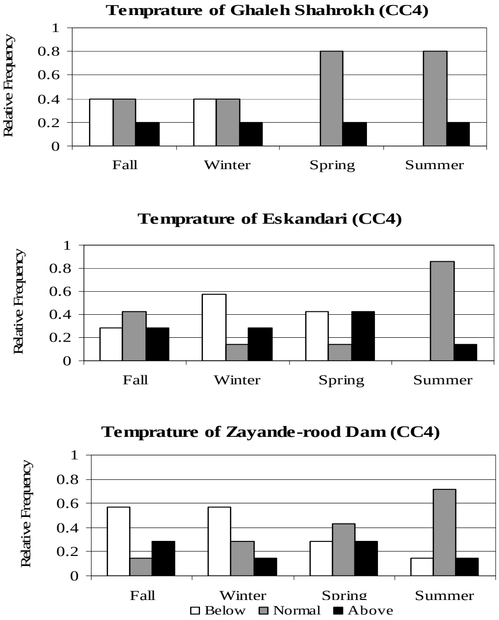

Fig 9. Relative frequency of Temperature anomalies during La Niña/-PDO

6- Conclusions

In this research, in addition to giving a description of the ENSO and PDO phenomena, the statistical relations of these large-scale climate signals with the water supply of the Zayandeh-rood River Basin was investigated. The results indicated that the El Niño phase of the ENSO has an incremental influence on the inflow volume of the Zayandeh-rood Dam. On the other hand, the La Niña phase has a reverse impact, i.e. reducing the inflow volume. Effects of the warm and cold phases of the PDO are similar to the El Niño and La Niña effects, respectively. The correlation analysis also revealed that the inflow volume of the Zayandeh-rood reservoir is inversely related to SOI and directly related to the PDO index.

Further more, it has been found that the most salient shifts in the inflow volume of the Zayandeh-rood Dam occur in the El Niño/+PDO and La Niña/-PDO climate conditions. In such conditions, the meteorological patterns in the basin experience an increment (decrement) in the precipitation and a decrement (increment) in the temperature patterns during the El Niño/-PDO (La Niña/+PDO) years.

In addition, the statistical tests indicated that, although the inflow volume distributions in different climate conditions are centered on different means, the variance or spread of the data around the means are not statistically different.

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