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Quantifying Indian Ocean Subtropical High-runoff Relationships a Case Study over Campaspe River

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Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

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ABSTRACT

El-Nino Southern Oscillation (ENSO) is one of the factors that widely studied with respect to the variability in rainfall and streamflow. However, there are other factors which also influence the climate variability and patterns of the circulation. This study aims to investigate linkage between Indian Ocean High pressure indices and South Pacific high indices with the Campaspe River streamflow. It was found that the zonal movements of the high-pressure system of South Pacific and Indian Ocean largely affect the flow in the river. A regression model was constructed with Indian Ocean high pressure indices and South Pacific indices that explain 42% of the variability in the flow of the River. A Mann Kendall's tau test was also applied in order to assess the trends in the data. A significant decreasing trend in the streamflow is correlated with the increasing trend in the Indian Ocean high pressure system.

Keywords: Centers of action; streamflow; Indian Ocean high pressure; Mean sea level pressure.

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1. INTRODUCTION

The climate over Australia is highly variable as western to central eastern parts experience desert or semi-arid climate while southeast and southwest corners experience moderate climate with fertile soil due to this varied climate it has been a core issue in many studies. Rodgers et al. [1] investigated that the reduction in annual rainfall, relative to the long-term mean, has been caused a reduction in streamflow over Western Australia (WA) since 1975 which also shows a long-term climate variability over WA. Many studies have been conducted in regard of the climate variability, and its implication and causes, in terms of the rainfall and streamflow. Many climatic factors or indices have been studied and found their association with the long-term variability of the climate. ENSO is one of the indices which has been widely studied and found useful in understanding the relationship with the rainfall and stream flow [2-4]. This index is the comprehensive accumulator of the rainfall and can be used for forecasting streamflow and rainfall [5]. Other climate indicators have also been studied to understand the relationship between rainfall and streamflow, such as Shrestha [6] has documented that the streamflow can be predicted using Sea Surface Temperature (SST) six months prior by selecting best location of the SST. Samuel et al. [7] studied the variability of Southwest of Western Australia rainfall and streamflow with respect to the reduction in rainfall and streamflow. They found that the decreasing trend in rainfall is largely a part of SST variability over the Indian Ocean bounded by the western part ($50°\text{E to }70°\text{E}, 10°\text{S to }10°\text{N}$) and Southern part ($60°\text{ to }70°\text{E}, 25°\text{ to }35°\text{S}$). A much deeper understanding and study were conducted by [8]. They analyzed the relationship of Southwest Western Australia (SWWA) rainfall with the SST anomaly over the Indian Ocean, which is commonly termed as an Indian Ocean dipole or a dipole mode index (IOD or DMI) and mean sea level pressure (MSLP). They observed that African heavy rainfall and drought in Indonesia likely to occur during positive DMI, they found that during positive DMI, change of pressure was caused by the weakening of the convection, resulting in the extension and suppression of Southeast trade winds southward while heavy moisture was transferred to North West, causing heavy precipitation. A baroclinic reduction of rainfall in SWWA was occurred in winter during positive DMI, which caused an anomalous anticyclonic circulation [9].

Another study which relates the prevailing drought in Australia to the anticyclone was carried out by the [10]. They found that the variability in streamflow and rainfall were mainly affected by the high pressure centers and their locations, commonly known to be as 'Centers of Action' (COA). According to this approach, variability in streamflow and rainfall was not only influenced by the magnitude of pressure itself, but also the location of the centers of the highs, i.e. longitude and latitude. They have studied Donnelly and Warren river catchment flow and found that flow in the river was affected by the high longitude and low longitude positions. But they used one threshold value for the whole season. In this study, it was intended to understand and explore that which climate driver(s) of the study governs the flow of the Campaspe River.

2. DATA AND METHODS

In this study, trends and climate signatures which govern the flow in Campaspe River were analyzed. Campaspe River Catchment (CRC) is a tributary of Murray Darling Basin (MDB) and situated in Southeast Australia (Fig. 1). It starts, its 232 km stream length, to flow from the northern slope of the Great Dividing Range of Wombat State forest through the northern path and descends into MDB. CRC comprises an area of 4179 km^2. This study analyzes only the winter flow and its possible connection with signatures of the climate variability and assesses their trends. Several data sets have been utilized in this study to analyze the association between streamflow and climatic indicators. Monthly data of streamflow, which spans from 1957 to 2008, was obtained from the Department of Water, Australian Government (www.bom.gov.au). Monthly average sea level pressure (SLP) data over the same period for Indian Ocean and South Pacific Ocean were obtained from National Center for Environmental Prediction (NCEP) reanalysis [11]. This dataset was used to compute high pressure indices, i.e. Indian Ocean high pressure (PS IOH), Indian Ocean high longitude (LN IOH) and Indian Ocean high latitude (LT IOH) and for South Pacific Ocean high pressure (SPH PS), South pacific high longitude (SPH LN) and South Pacific high latitude (SPH LT). Monthly timeseries of Southern Oscillation index (SOI), used in this study, obtained from the National climate center of the Australian Bureau of Metrology. The NINO3, NINO3.4 NINO4, NINO12 are SST based indices widely employed throughout the

Fig. 1. Catchment area description of Campaspe River

world are obtained from the National Climate Prediction Center (CPC).

It has been found that there are several centers of high (low) pressure exist on mean global maps of SLP [12] and these were called as 'Center of Action' (COA) by [12]. According to this approach not only the magnitude of the central pressure but also its position plays a significant influence on the variability of various climate patterns of the region. In this study, a simple approach was applied, which produce better result in contrast to the methodology applied by [10]. In this study, magnitude of the intensity of high pressure system, its longitude and latitude positions were defined by I_P, I_Z and I_M respectively over the Subtropical Indian Ocean and Pacific Ocean. The boundaries of these centers of high pressure were selected as 10ºS to 45ºS and 100ºE to 142.5ºE over the Indian Ocean Subtropical High and 10ºS to 45ºS and 150ºE to 220ºE over the South Pacific Subtropical High. Mathematically, it can be defined as,

$$I_P(t) = \overline{P_{(x,y)}}(t) \quad (1)$$

$$I_Z(t) = \overline{Z_x(t)} \quad (2)$$

$$I_M(t) = \overline{M_y(t)} \quad (3)$$

The algorithm starts from a threshold pressure $P_t = 1016\, hpa$ (the threshold pressure (P_t) is defined by examining the mean global maps of SLP over both the Indian Ocean and Pacific Ocean and also this threshold pressure assures us that the index so formed is of high pressure index) and then the algorithm takes a spatial average not only for those grid nodes ($P_{(x,y)}$), over a defined boundary and temporal domain, which hold SLP above or equal to the defined threshold pressure (P_t) but also their corresponding longitude $Z_x(t)$ and latitude $M_y(t)$ positions and saves in three different folders as indices of high pressure system (defined above). The Mann Kendall's tau test was also applied in order to assess the trends in the indices and streamflow. Kendall tau test is a nonparametric test which requires no prior assumption of normality of the data, but serial correlation among the resulting p values should not be exist. The Null (4) and alternative hypothesis (5) are defined as follows,

$$H_o: \tau = 0; there\ would\ be\ no\ trend \quad (4)$$

$$H_o: \tau \neq 0; there\ would\ be\ is\ a\ trend \quad (5)$$

Z test are applied for testing null and alternative hypothesis at a 95% confidence level.

3. RESULTS AND DISCUSSION

In order to analyze the impact of the Indian Ocean and South Pacific Ocean high pressure on the streamflow of the Campaspe River, mean central high pressure for both Indian Ocean and Pacific Ocean and their zonal movement were plotted against observed flow. It is clearly evident from Fig. 2 & 3 that observed flow was highly influenced by the mean central high pressure of both Indian and Pacific Oceans, for example, in 1983-84 when mean central high pressure over Indian Ocean was lowest, above 2000 ML flow was observed (Fig. 2), while low level of flow was observed when Indian Ocean and Pacific Ocean high pressure were at their peaks. Fig. 4 & 5 are plotted in order to analyze the effect of longitudinal movement of the pressure system. These figures clearly explain that the longitudinal movement of Indian Ocean high pressure remains on the belt of $95°E\ to\ 105°E$ and a slightly fluctuation of the high in the belt (east or west) changes the pattern of flow in the Campaspe River (see Fig. 4). Similar observations were also evident from the Fig. 5, when high pressure in Pacific Ocean moves away from the Australia (further eastwards), more flow receives in the catchment and vice versa.

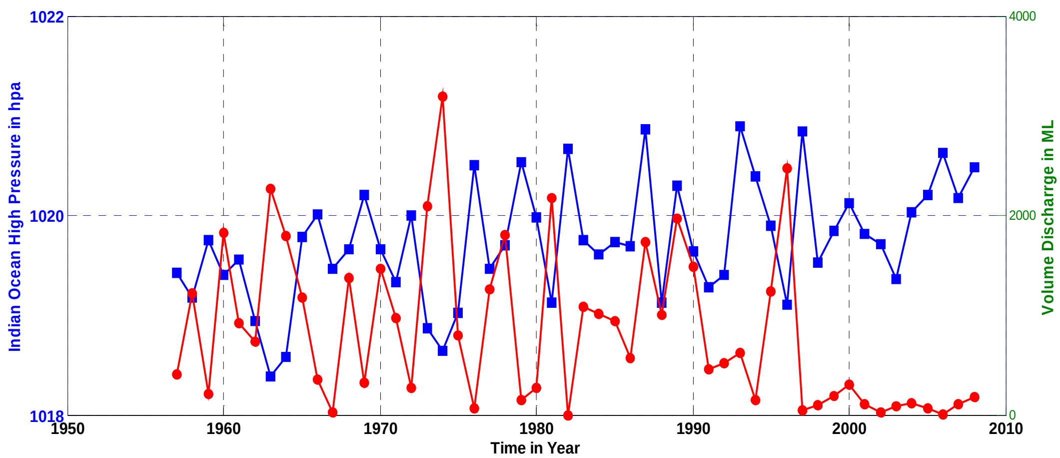

Fig. 2. Illustrate the effect of Indian Ocean high pressure system on the observed flow of the Campaspe River low pressure high flow high pressure low flow

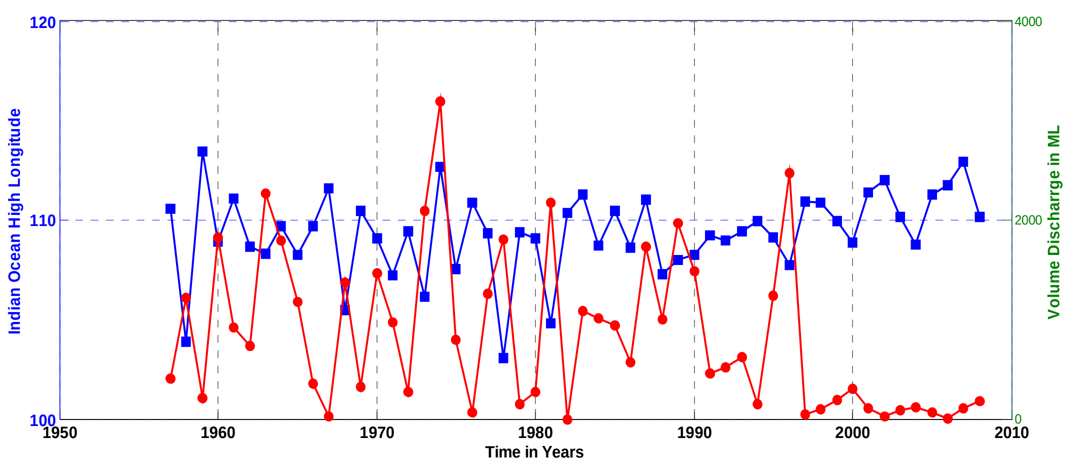

Fig. 3. Effect of longitudinal position of the Indian Ocean high pressure system on the flow of the Campaspe River

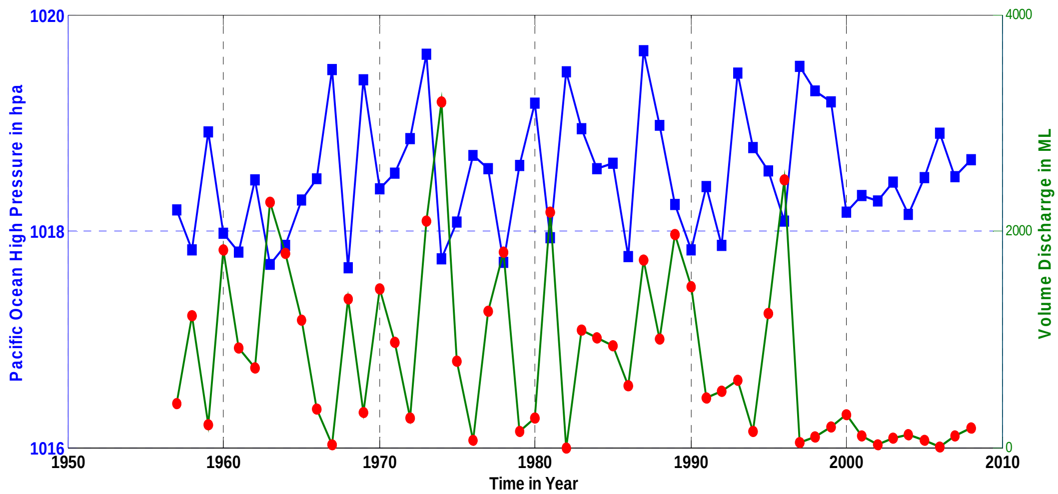

Fig. 4. Illustrate the effect of South Pacific Ocean high pressure system on the observed flow of the Campaspe River low pressure high flow high pressure low flow

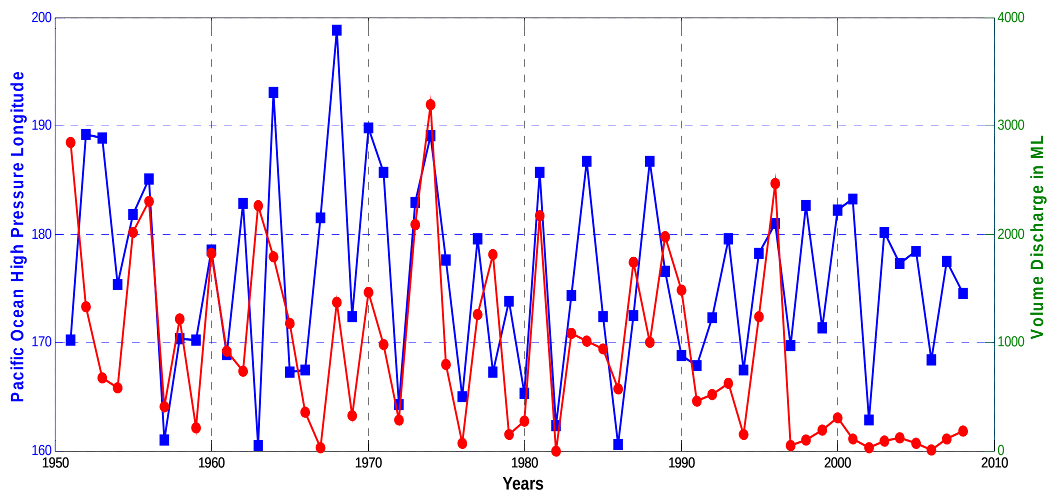

Fig. 5. **Effect of longitudinal position of the South Pacific Ocean high pressure system on the flow of the Campaspe River**

For further investigation of variability and trend in streamflow of Campaspe River, a correlation matrix was computed between streamflow and all climate indicators (Table 1). All correlations were computed on the 95% intervals and p-values for each correlation was also presented. Indian Ocean High pressure indices, Pacific Ocean high pressure indices and ENSO indicators have shown significant correlation coefficients. ENSO has been widely used as a climate predictor for many regions of the world, similarly, in this study also ENSO indices (NINO 3, NINO 4 and NINO3.4) showed significant correlations except NINO 12 while Indian Ocean high pressure and longitude have shown a strong correlations with coefficients -0.55 and -0.45 respectively. South Pacific high pressure and its longitude have also strong impact on the streamflow of Campaspe River with correlation coefficients -0.477 and -0.355 respectively. Southern Oscillation index, the pressure difference between Darwin and Tahiti, also showed significant correlation (see Table 1). Now important point is that which variable or variables should be used, in particular, which describe the maximum variability of the streamflow in the Campaspe River. There might be some variables, which are not independent, means that they are multicollinear. This problem was resolved by using variance inflation factor (VIF), which quantifies the variance increased by each predictor because of a dependent nature of variables. The Variables are said to be collinear if VIF for any predictor is greater than 5 and or less than 1 then variables are said to be strongly dependent (the limitations of VIF also varied in different disciplines) while collinearity can be ignored if VIF value lies 1 to 5. It was found that ENSO based all indicators, SOI and SAM were dependent (collinear) not only on each other but also on Indian Ocean and Pacific Ocean pressure indices while PS IOH, LN IOH, SPH PS and SPH LN are independent.

Table 1. Correlation matrix of MJJA flow with all climatic indices at 95% level of significance

	MJJA flow	P-value
PS IOH	**-0.55**	0.00
LN IOH	**-0.45**	0.001
LT IOH	0.06	0.64
SPH PS	**-0.41**	0.002
SPH LN	**0.35**	0.01
SPH LT	0.05	0.68
AO	0.008	0.95
SOI	**0.42**	0.002
IOD	-0.25	0.06
NINO 3	**-0.32**	0.01
NINO 3.4	**-0.31**	0.02
NINO 4	**-0.38**	0.005
NINO 12	-0.21	0.12
MEI	**-0.34**	0.01
NAO	0.03	0.81
SAM	**-0.31**	0.02

In order to quantify the variability of Campaspe River, a regression model was constructed using South pacific and Indian Ocean indices, which accounts maximum variability of the river than the other variables of the study. It is found that, $Streamflow = 658934 - 457 * PS\ IOH - 95.3 * LN\ IOH - 181 * SPH\ PS + 16.5 * SPH\ LN$ explains 42.6% of the variability of the Campaspe River streamflow. Fig. 6 depicts the observed flow of the Campaspe River versus fitted flow and it is quite clear that our regression model follows the pattern of the observed flow. Simple residual analysis was also performed in order to assess the linearity of the data. Normal probability plot of residual was presented to conform whether any nonlinear behavior exist. It was clearly illustrated from the Fig. 7 that there were no definite patterns exist in order to guarantee the nonlinear behavior except few values in the beginning and in the end. This implies that the linear regression model is coherent. Nash-Sutcliff coefficient $E = 1 - \frac{\sum_{i=1}^{n}(O_i - O_{mod,i})2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}$ is also used in order to assess the predictive power of the model, where O_i, $O_{mod,i}$ represents observed value and modelled value. It is found to be 0.42. The Nash-Sutcliff coefficient values varies from $-\infty\ to\ 0$. Negative values indicate that mean of the observed data is good predictor than the model, while value equals to 1 signify that the model prediction perfectly match to the observed data. The root mean square value for the model is also computed and it is found to be 580 ML.

Table 2. Correlation matrix of MJJA flow with all climatic indices at 95% level of significance after detrending the time series

	MJJA flow	P-value
PS IOH	**-0.47**	0.00
LN IOH	**-0.40**	0.003
LT IOH	0.16	0.25
SPH PS	**-0.38**	0.005
SPH LN	**0.38**	0.005
SPH LT	0.10	0.45
AO	0.1	0.48
SOI	**0.38**	0.005
IOD	**-0.29**	0.03
NINO 3	**-0.28**	0.04
NINO 3.4	**-0.29**	0.03
NINO 4	**-0.31**	0.02
NINO 12	-0.25	0.07
MEI	**-0.28**	0.04
NAO	0.01	0.93
SAM	-0.25	0.06

The Mann Kendall's tau test was applied to analyze the trend in the data of both streamflow and all other indices of the study. Kendall's tau test summary is listed in Table 3 and also significant values are highlighted in bold face. It was found that the significant declining trend was observed in the data of streamflow and strong increasing trend is also observed in Indian Ocean high central pressure and NINO 4 index (Table 3). All other anomalies and indices have shown no significant increasing or decreasing trend. This implies that the declining trend in the streamflow data is caused by the increasing trend in the PS IOH. It remains an arguable question in this study that why ENSO indicators are not explaining much of its variability as compared to our pressure indices of Indian Ocean and South pacific Ocean? ENSO phenomena consist on mainly three phases, El-Nino, La-Nina and neutral. El-Nino and La-Nina correspond to the extreme events and these events around the globe showed an extreme impact on the climate i.e. drought and flooding. Since ENSO is a coupled process of Ocean and atmosphere due to this reason it may change the circulation patterns. During El-Nino Events a reduced rainfall particularly, in winter occurs in eastern and northern part of the Australia due to weakening and reversal of the weak trade winds. Although, many studies have linked the drought of Muray-Darling river basin with the ENSO phenomena, however, some analysis have shown that not every drought was linked with the El- Nino event, for example in 1997-1998 drought was confined to the south eastern part of Australia during a very strong El-Nino phase. Nicholls [13] studied the trends in the ENSO phenomena over Australian region, revealed as ENSO characteristic has changed its pattern since 25 years. In the other study, finding also suggested that the weak relationship was evident during 1985-86 [14]).

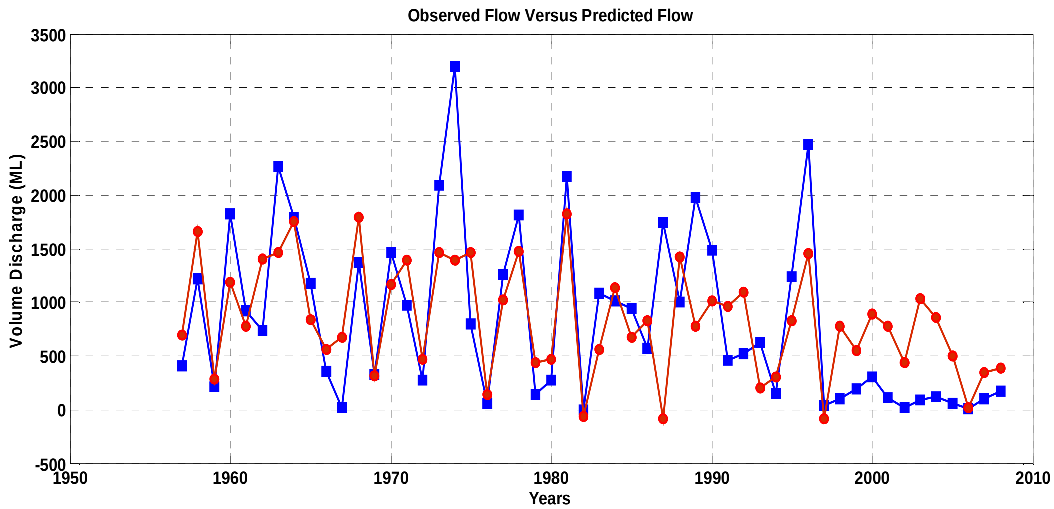

Fig. 6. Observed flow versus a predicted flow using PS IOH, LN IOH, SPH PS and SPSH LN as predictor in regression model

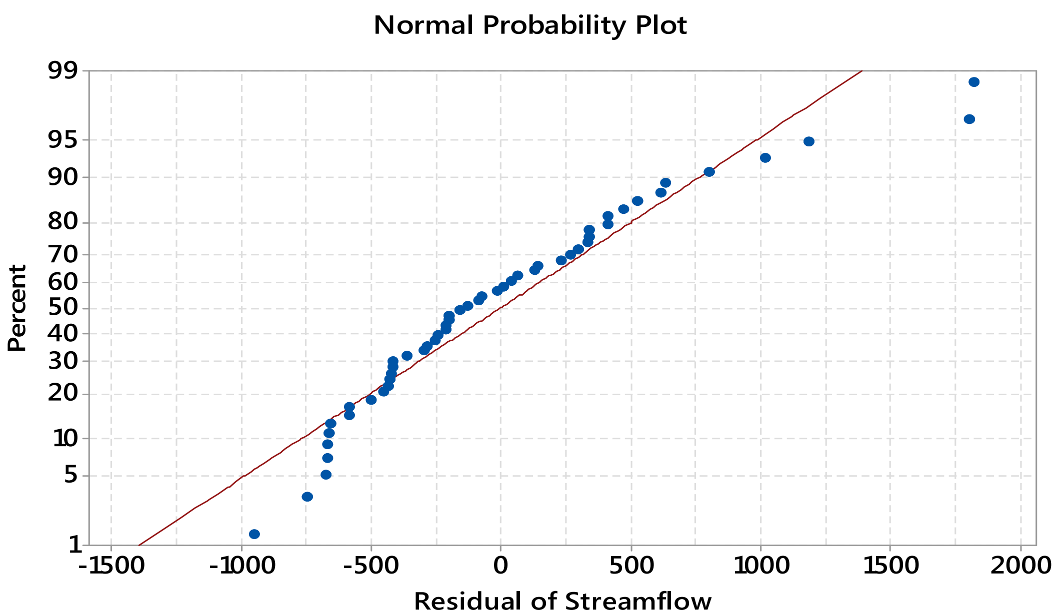

Fig. 7. Normal probability plot of the residual of the streamflow. Clearly, depicts the linear pattern in the streamflow

Table 3. Kendall tau test summary

	N	Kendall tau	Z score	P value
MJJA Streamflow	52	**-0.29**	**-3.12**	**0.001**
PS IOH	52	**0.29**	**3.06**	**0.002**
LN IOH	52	0.17	1.78	0.07
LT IOH	52	0.15	1.65	0.09
SPH PS	52	0.14	1.54	0.12
SPH LN	52	0.02	0.29	0.76
SPH LT	52	0.06	0.69	0.48
AO	52	0.15	1.65	0.09
SOI	52	-0.12	-1.25	0.20
IOD	52	-0.02	-0.26	0.78
NINO 3	52	0.13	1.39	0.16
NINO 3.4	52	0.07	0.76	0.44
NINO 4	52	**0.20**	**2.13**	**0.03**
NINO 12	52	-0.06	-0.63	0.52
MEI	52	0.14	1.54	0.12
NAO	52	-0.05	-0.56	0.56
SAM/AAO	52	0.13	1.36	0.17

4. CONCLUSION

Numerous studies have shown that ENSO has the significant effect over streamflow around the world. However, several other variables can also be employed in studying the relationship with rainfall and streamflow. In this study, a modified COA approach was applied, similar to [10]. It was found that the streamflow in Campaspe River is mostly driven or affected by the zonal movement of the Indian Ocean and Pacific Ocean high pressure centers. When mean central high pressure of the Indian Ocean moved towards (near) the Australia a low flow was observed while high flow was evident when high pressure center left away the Australian region. To quantify the variability in the flow of the river a regression model was constructed that explained 42% of the variability of the River flow. The Mann Kendall's tau test was applied in order to find trends in the data of both streamflow and indices of climate predictors. A Significant decreasing trend in streamflow was observed with correspond to significant increasing trend in the PS IOH. This explains the declining trend in the streamflow data. The increasing trend in the mean central pressure over the selected region over the oceans was may be due to the couple of the global warming and anthropogenic activities.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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