Meteorological spatiotemporal drought impact assessment on water storage of Kolar reservoir, India

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ABSTRACT

Climate change remains one of the main problems of the century which causes abrupt change in metrological phenomena. Hydrological drought assessment is very critical for ungauged catchments and important for the water storage and management of the reservoir. The research analyses the temporal variation of the drought events in Kolar River basin located in Madhya Pradesh state, India. Also, critical watershed is also identified which suffers most of the drought events. To accomplish this, four drought indices, namely, Standardized Precipitation Index, Reconnaissance Drought Index, and Rainfall Decile, sand Modified China Z-Index, are used for the analysis. Rainfall from three rain gauge stations, namely, Birpur, Brijesh Nagar, and Ichhawar, from the sites were collected from the site ranging from 1988 to 2018 for thirty years. The contemporary research can be treasured source of scientific basis of policy formation and decision of stakeholders involved. Also, the analysis indicates the changing trends in rainfall patterns of the basin which affects the storage and preventive measures to be incorporated in the basin for the future availability of water for agricultural purposes and ever-growing domestic use water demand. It shows based on analysis that middle region of Kolar river basin is more vulnerable to drought in recent years.

Keywords: Drought Indices; Inter-basin transfer; meteorological events; Reconnaissance Drought Index (RDI); Standardized Precipitation Index (SPI)

1. INTRODUCTION

Drought is a natural catastrophe results due to insufficient rainfall intensity and inaccuracy in its prediction during the year. Drought causes extensive occurrence of natural water accessibility and hinders the agricultural production, vegetation growth, socio-economic growth, and overall development of the basin. It results in shortfall in direct surface runoff and sub-surface water storage. Halwatura *et al.* (2017) highlighted that long-term monitoring of soil moisture by drought indices is helpful in determining plant-water stress and can be used to substitute other soil moisture monitoring data. Drought will remain one of the main problems of twenty-first century due to which, by 2030, forty-four percent of population of India will have no access to water and further disbalance in social, ecological, and environmental problems (Ramkar and Yadav, 2018).

With the increase in global temperature and anthropogenic activities, drought events have become more frequent and depicted trend increment. Drought can be analyzed based on duration, severity, occurrence interval or frequency, and spatial extent. Throughout the past researches various drought indices have been used such as Standardized precipitation index (SPI) (So *et al.*, 2014), Reconnaissance Drought Index (RDI) (Mohammed and Scholz, 2018), Rainfall Deciles (RD), and Modified China Z-Index (MCZI) (Ang *et al.*, 2017). In the past, many researchers developed various global circulation models (GCM) for predicting the impact of drought and bias correction in models (Johnson and Sharma, 2015). SPI also shows a strong relation with aridity condition in the region (Asadi Zarch *et al.*, 2017).

In the paper, detailed analysis of droughts based on SPI, RDI, DI, and MCZI indices has been discussed for a semi-arid region of central India which suffers from acute condition of water stress on the water storage reservoir due to increased agricultural demand, industrial needs, and domestic water supply. The aim of the current research is to analyze temporal meteorological drought occurrences and correlation between the reservoir storage. Also, various measures have been suggested based on stakeholder's consultation and intensive research, for increasing reservoir water recharge on regional level for the basin and reducing seepage losses with efficient structures (Amin *et al.*, 2019).

2. STUDY AREA

The study area is Kolar river catchment which arises in the Vindhya Range of Sehore district and flows in a south westerly direction to meet the Narmada near Nasrullaganj in the Raisen district of Madhya Pradesh. Kolar river basin has an upper elevation of 600 meters, elevation of 432 meters at the dam and downwards till Narmada, and 350 meters at the downstream. Kolar catchment is situated in Sehore district of State of M.P. in India between longitude of 77 and 77.25 degrees east and latitude between 22.75 and 23.20 degrees North. Shehore, Ichhawar, and Bhopal (capital of Madhya Pradesh located at a distance of 32 Km) are the main cities located nearby (Basin 2017). Kolar reservoir is the main source for drinking water supply and irrigation water supply (Fig. 1.).

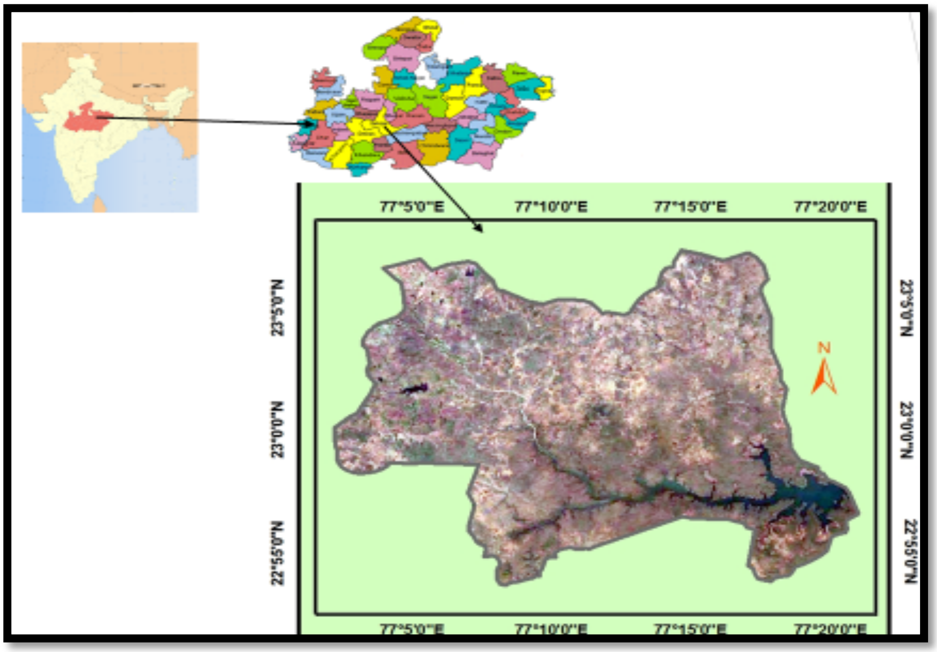

Figure 1. Kolar river watershed map.

Table 1 gives the details of three weather stations located near the basin, namely, Birpur, Brijesh Nagar, and Ichhawar, and their characteristics based on location, elevation, temperature, precipitation, and climate. These three stations have area of 121.05 Km^2, 278.48 Km^2, and 122.68 Km^2 respectively.

Table 1. Characteristics of the three weather stations.

Station	Latitude	Longitude	Elevation	Avg Tmax	Avg Tmin	Precipit-ation	Climate
Birpur	22^0 58’	$77^0$20’	441	31.88	18.76	940	Semi-arid
Brijesh Nagar	22^0 57’	$77^0$08’	505	30.66	16.45	1370	Humid
Ichhawar	23^0 01’	77^0 01’	515	32.24	17.8	1032	Dry - Sub humid

3. DATASETS

The present study of Kolar catchment makes the use of meteorological data available at three sites, namely, Birpur, Brijesh Nagar, and Ichhawar for the daily rainfall data from 1988 to 2018 for the last 31 years (Fig. 2).

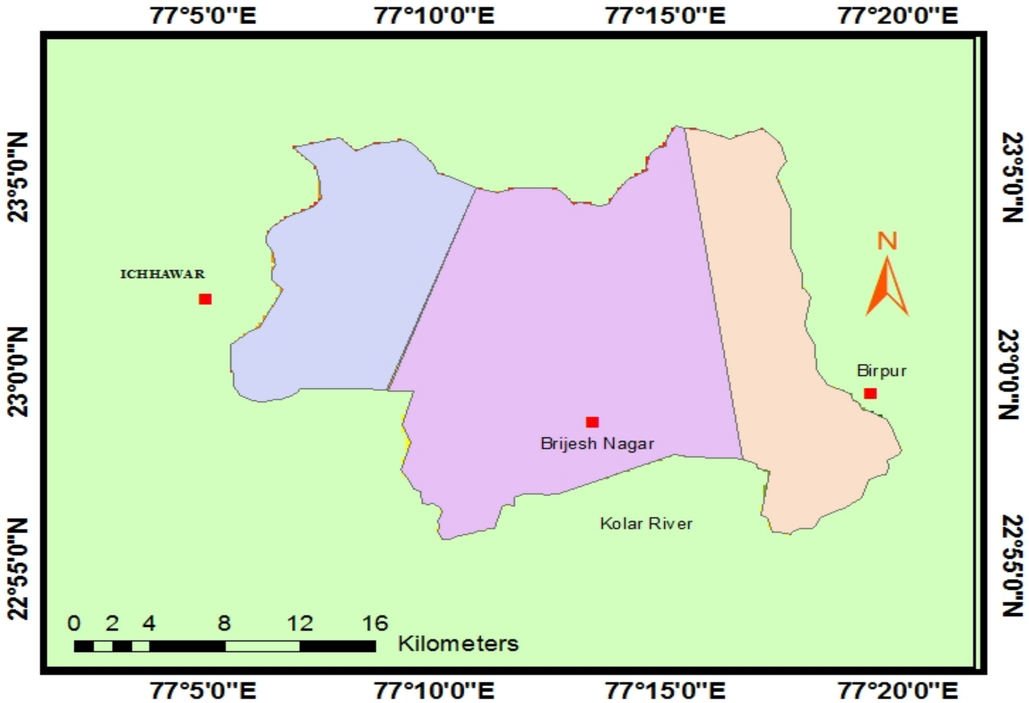

Figure 2. Rain gauge stations at Kolar river watershed.

Daily storage level of the Kolar dam, daily storage, area of spread of water, and fortnightly evapotranspiration data were received from Kolar dam authorities. Toposheets for delineating catchment boundaries of the catchment were obtained from survey of India; Bhopal office Birpur is nearby the water level record station at dam. Brijesh Nagar and Ichhawar are in middle and starting point of the river, respectively. The maximum rainfall recorded in Birpur, Brijesh Nagar, and Ichhawar rain-gauge stations are 470.8, 244, and 380.2 mm a day, respectively. Here, in places with high spatiotemporal rainfall variability, such as mountain regions like in Kolar region having variation of slopes from very steep slopes to mild slopes, input data could be a large source of uncertainty in hydrological modeling. Modeling of mountain regions is highly uncertain as it contains data of spatially distributed rainfall and also on the density of rain gauge station. Satellite data are also available for the processing but has to be used after studying the correlation between ground data and satellite data. So, this spatial variation is important for accurate modelling. The highest storage level and dead storage level of Kolar dam are 462.21 m and 432 m, respectively, with a height of 45 m.

4. METHODOLOGY

The present study uses four temporal drought vulnerability indices for drought intensity assessment in three sub-watersheds. The spatial drought analysis for the selected years was steered based on previous analysis. A comprehensive analysis for watershed prioritization is conducted based on the drought indices. Various drought related mitigation measures were also suggested based on stakeholder’s meeting and literature reviews. Fig. 3 shows the flowchart of methodology adopted.

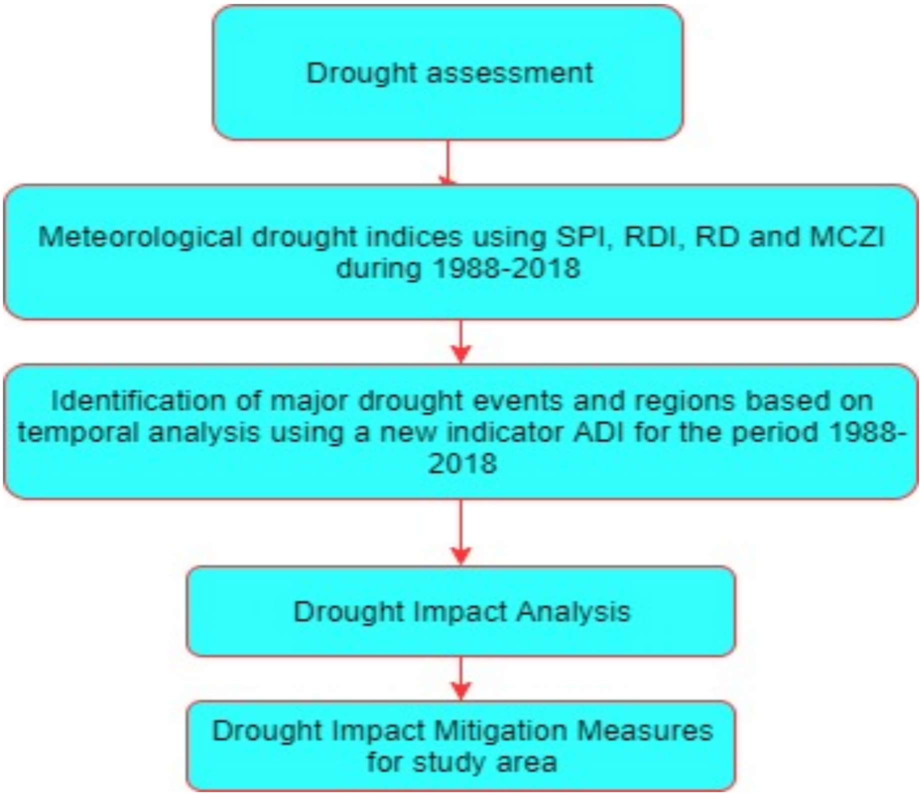

Figure 3. Methodology adopted in the analysis.

4.1. Standardized Precipitation Index (SPI)

SPI is one of the most versatile and popular droughts indices which is used for meteorological droughts characterization and classification. Gama distribution probability density function is used to calculate the SPI. It is represented by g(x) and by the given below formula:

$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{\frac{-x}{\beta}}\ (x > 0)$ (1), where $\Gamma(\alpha)$ is the gamma function; *x* (mm) is the amount of precipitation (x>0); α is the shape parameter (α>0); and β is the scale parameter (β>0). SPI and RDI value classification is given in Table 2.

Table 2. SPI and RDI value classification

SPI value	Class
2.0 ≥	Extremely wet
1.5 to 1.99	Very wet
1 to 1.49	Moderately wet
0.99 to -0.99	Near normal
-1 to -1.49	Moderately dry
-1.50 to -1.99	Severely dry
Below -2.0	Extremely dry

4.2. Reconnaissance Drought Index (RDI)

RDI provides the actual image of the dry condition; it is used worldwide compared to other indices. A positive value of RDI shows dry condition, and a negative value shows wet condition. This index behaves in a way similar to SPI. Thus, the interpretation of the values of RDI is similar to that of SPI (Table 2). RDI can be calculated as normalized and standardized values. It is expressed as $\alpha_0^{(i)} = \frac{\sum_{j=1}^{k} P_{ij}}{\sum_{j=1}^{k} PET_{ij}}$(2), where Pij is the precipitation for the *j*th month and *i*th hydrological year, PET_{ij} is the potential-evapotranspiration, and *k* is the total number of years of available data.

4.3. Rainfall Deciles (RD)

In RD, the precipitation totals indicators with precedence of three months consecutively are ranked based on the impact of drought against climatologic records. If the sum falls within the lowest deciles of the historical distribution of 3-month totals (Table 3), then the region is considered to be under drought conditions. They are grouped into five categories as below.

Table 3. Rainfall deciles classification.

RD value	Criteria
1-2	Much below normal
3-4	Below normal
5-6	Near normal
7-8	Above normal
9-10	Much above normal

4.4. Modified China Z-Index (MCZI)

The National Climate Center of China developed the CZI in 1995 as an alternative to The National Climate Center of China developed the MCZI in 1995 as an alternative to the SPI when mean precipitation follows the Pearson type III distribution (Wu *et al.*, 2001). MCZI is calculated as follows:

$$MCZI_{ij} = \frac{6}{C_{si}} X \left(\frac{C_{si}}{2} X \varphi_{ij} + 1\right)^{1/3} - \frac{6}{C_{si}} + \frac{C_{si}}{6}, \qquad (3)$$

where i is the time scale of interest and j is the current month; $MCZIij$ means the MCZI's amount of the current month (j) for period i; Csi is the coefficient of skewness; and φ_{ij} is the standardized variation. The classification of MCZI is same as that of SPI.

5. ANALYSIS, RESULTS, AND DISCUSSION

This section elaborates the drought impact and quantification in terms of four drought indices SPI, RDI, RD, and MCZI. Spatial variation of area under the effect of three rainfall stations is calculated based on Thiessen polygon method in Arc-GIS. Fig. 2 shows the variation of the area.

5.1. Standardized Precipitation Index (SPI)

Figure 4 shows the spatiotemporal variation of three observed rain gauge stations. As shown clearly, SPI values have shown moderately dry to extreme drought conditions prevailing in the region. After 2000, frequency of moderate dry condition has increased significantly and observed in 2000, 2001, 2008, 2009, 2010, 2014, 2015, 2017, and 2018. In earlier years, Birpur station was more susceptible to drought condition, Ichhawar in the middle, and in recent years Brijesh Nagar station is the main concern as it has also higher catchment area. In 2008, the region was hit with the worst lifetime drought with only thirty-two percent of the dam storage was achieved. SPI also shows a strong relation with aridity condition in the region (Asadi Zarch *et al.*, 2017). In recent years, Brijesh Nagar catchment, in spite of being humid area, is contributing more to drought condition.

5.2. Reconnaissance Drought Index (RDI)

Figure 5 shows the RDI values of the three stations based on simplified equation of rainfall and evapotranspiration which again depends on temperature. It is more reliable than SPI as it gives more parameters for the analysis as it uses PET, in addition to precipitation, as a key variable for assessing the severity of drought (Asadi Zarch*et al.*, 2015). The years which are affected by drought are 2000, 2008, 2009, 2013, 2016, and 2018. The variation of drought condition is from moderately drought to severely drought condition. The trend observed in the Birpur station is high in the beginning of decade of 2000 with the value of 2.13 and is in near moderate drought condition in last years.

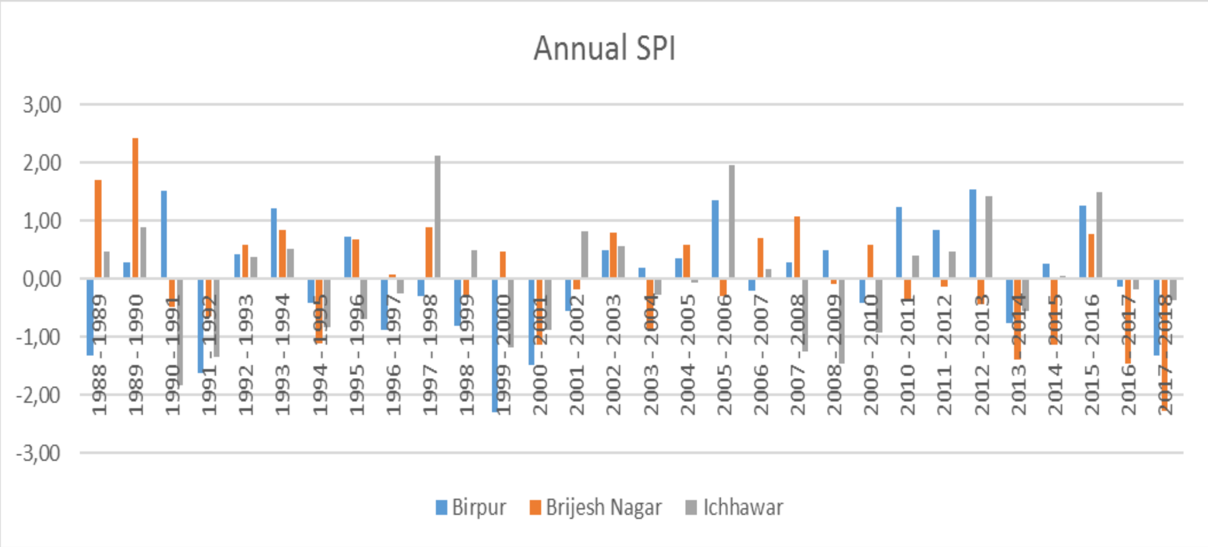

Figure 4. Annual SPI for the observed stations.

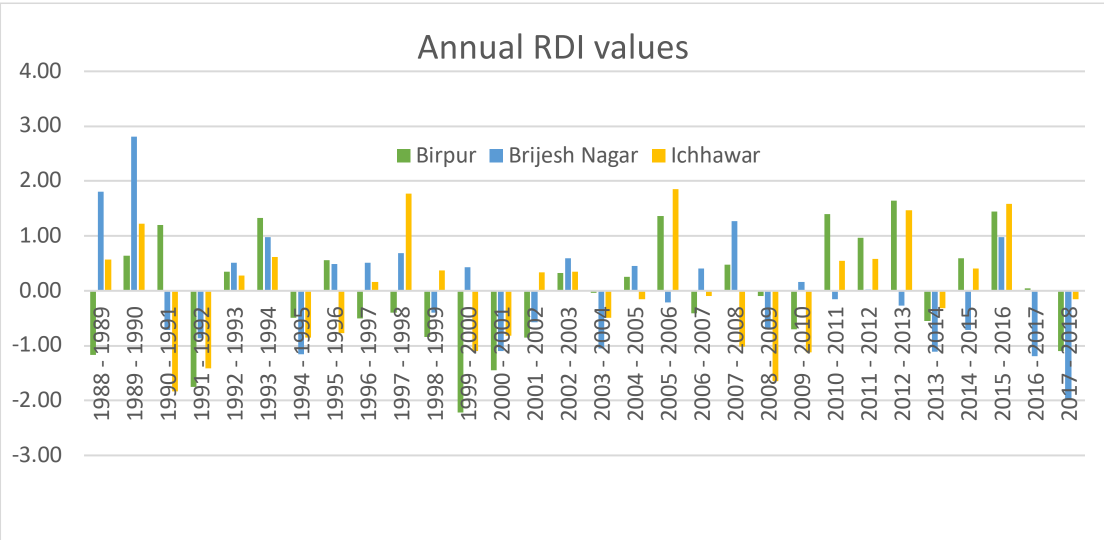

Figure 5. Annual RDI for the observed stations.

This trend is observed due to massive plantation in the Birpur region. In Brijesh Nagar catchment, the trend was observed to be ranging from moderately dry to extremely drought condition. In Ichhawar, mixed trends were observed, with drought condition being moderate drought to severe drought. Even though Ichhawar is far situated from Kolar dam, it has a great impact on the reservoir storage of the dam as it is perceived that, during the severely drought year for Ichhawar 2000, 2009, and 2010, the dam was filled by 50, 32, and 54 percent.

5.3. Rainfall Deciles

Figure 6 shows the temporal variation of RD in three rain gauge stations of Kolar basin. The years, based on RD, which were affected by drought are same as those determined based on RDI. During the year of 2008, it was much below normal, as 1 for the Ichhawar station shows that Ichhawar station has prominent role in deciding the impact of drought as this year has the lowest record of reservoir storage, although Brijesh Nagar has the highest recorded rainfall. During later years, the drought conditions of Brijesh Nagar become more prominent.

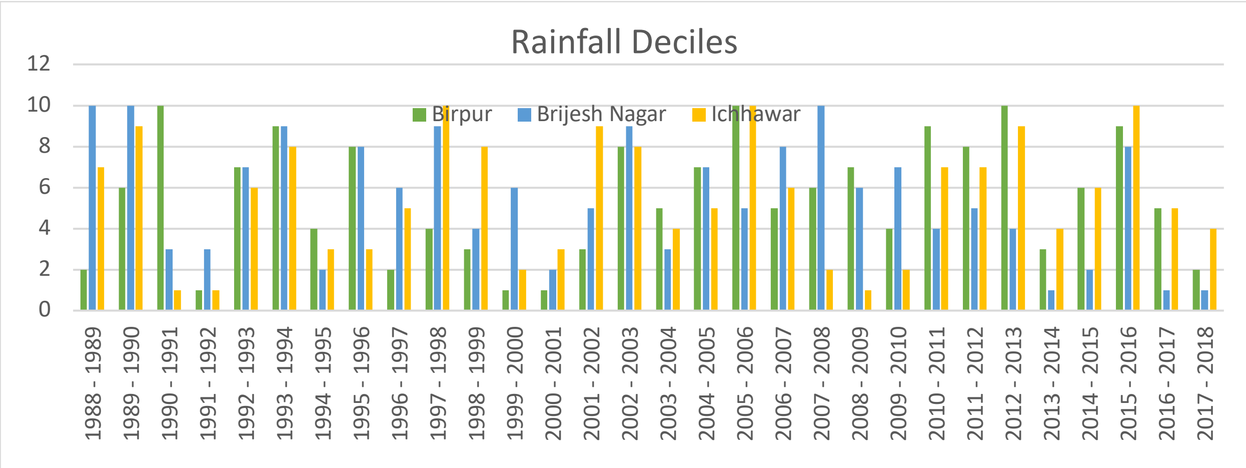

Figure 6. Annual rainfall deciles for the observed stations.

5.4. Modified China Z-Index (MCZI)

Mean precipitation is used to calculate this index for the meteorological stations. Figure 7 shows the variation of index of thirty years. Years affected with drought having severe drought condition are 2001, 2008, 2010 and year affected by extreme drought is 2017. The values of MCZI are varying intermittently. It shows a good correlation with SPI. Brijesh Nagar is severely affected by drought in 2001 and 2014 due to which storage was reduced by 55 and 38 percents, respectively. Brijesh Nagar shows severely dry trend in recent years in 2017 and 2018.

6. RECOMMENDED COUNTERACTIVE ACTIONS FOR DROUGHT IMPACT MITIGATION

As per the results obtained in the present investigation of drought impact in Kolar basin, there is urgent need for preventive measures to be taken to minimize impact of low water availability for various purposes. Based on stakeholders meeting and study of the area, the following measures are suggested.

6.1. Organic Farming

Organic farming based on natural fertilizers should be promoted. Due to prolonged use of artificial fertilizers, it has been observed that water requirement for the crops increases and soil quality also degrades. So, it will help in better production and improved quality (Arsic*et al*., 2013).

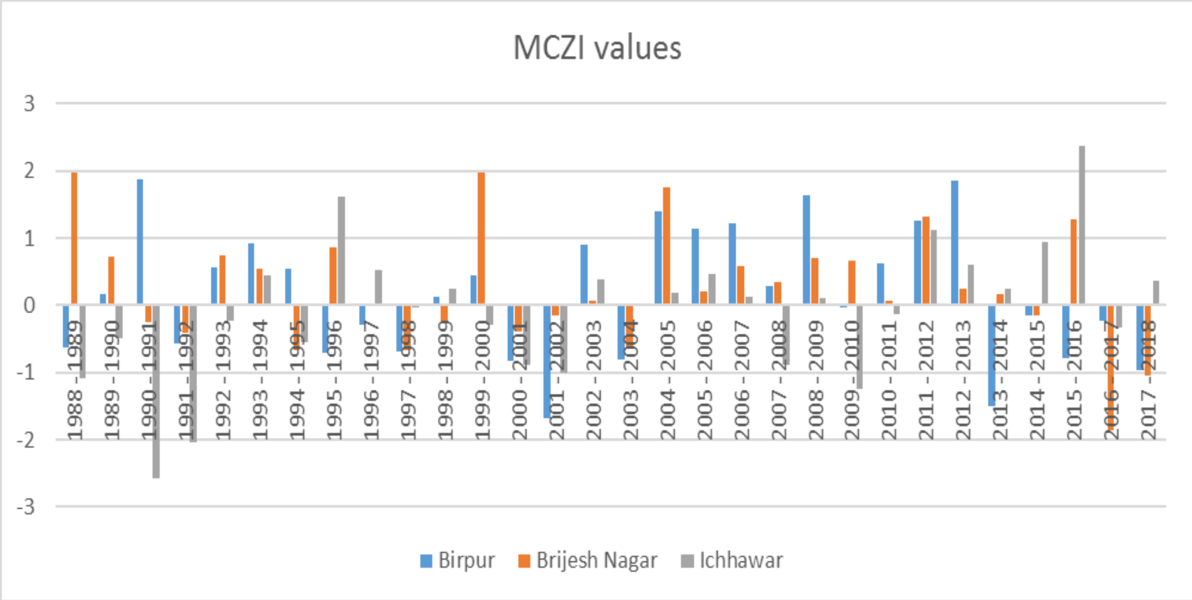

Figure 7. Annual MCZI for the observed stations.

6.2. Crop Divergence

Main crops are pulses, sugarcane, wheat, paddy, onion, garlic, and tomatoes. Due to variation in temperature, climatic conditions, and precipitation annually and seasonally, a rotation of cropping patterns of diverse nutrients requirement is suggested. Farmers are advised to grow food crops and commercial crops simultaneously. Beans and peas are recommended to grow as they are advanced form of legumes which restores soil productiveness.

6.3. Water Conservation Practices

Various practices to conserve water in local areas like rainwater harvesting, recharge well, plantation along the agricultural farm boundary, rational use of ground water, modern irrigation systems, efficient water supply system to minimize losses, and so on should be promoted.

6.4. Water Resource Integration

Integrated water resource management practices should be implemented in the area affected by drought. Available water resources should be critically assessed so that excess water can be delivered to drought prone area. Also, proper planning has to be done for judicious use of water for the socio-economic use.

6.5. Inter-basin Transfer

Inter-basin transfer is also advantageous to this catchment, and primary investigations suggest that area with surplus water can be transferred to Kolar basin (Shumilova *et al*., 2018; Zhang et al., 2015; and Quan et al., 2016). Inter basin transfer of water resources is one of the most innovative methods to solve the disparity between supply and demand of water resources available at regional level. Sip and Kolar rivers are the right bank tributary of holy river Narmada. Figure 8 shows the details of the proposed work. Sip river joins Narmada river at Satdev barrage. The Sip river originates at RL 540M near village Nayakhera in Tehsil lchhawar, and after flowing for 75km it meets Narmada river at RL 270M near Satdev village in Sehore district. Kolar river originates at RL 507M near Bordikalan village, and after flowing for 24.25km, Kolar dam is being built on this river. The rainfall-runoff estimation carried out on the sip river suggests a runoff generation of thirty-five (35) million cubic meters of water to the dam. It will not only help in addressing water shortage but will also help in socio-economic problem.

7. CONCLUSION

In this study, spatiotemporal meteorological drought indices of Kolar river basin were analyzed using SPI, SDI, RD, and MCZI using rainfall and temperature data of the last thirty years from 1988 to 2018. It has been observed that major drought events were in 2000, 2008, 2014, 2017, and 2018. Drought events in the recent years are showing increasing trends. It is also strongly correlated with storage capacity of the Kolar dam. It shows, based on analysis, that middle region of Kolar river basin is more vulnerable to drought in recent years. So, future indicates a water scarce Kolar basin. Based on literatures, primary surveys, and stakeholder's consultation, various remedial measures were also suggested such as organic farming, crop rotation, water conservation practices, water resource integration, and inter-basin water transfer from water surplus regions to water scarce region. Due to variation in temperature, climatic conditions, and precipitation annually and seasonally, a rotation of cropping patterns of diverse nutrients requirement is suggested. The inference derived from this observation can be very instrumental in planning strategies for the drought mitigation and water resource management and help to reduce gap between water availability and demand.

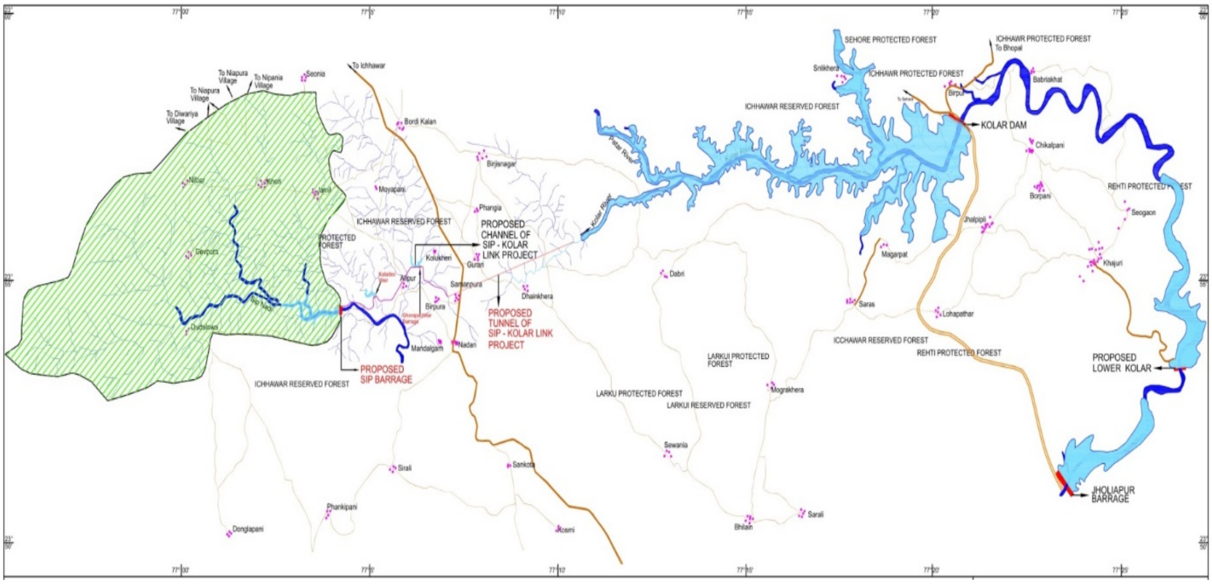

Figure 8. Inter linking of basins of Sip river and Kolar river.

REFERENCES

Amin, H., Khan, M. & Ajmal, M. M. K. (2019), Dynamics of gabion weirs and its comparison to reinforced concrete weirs, Kuwait Journal of Science, 46(2), 94–103.

Asadi Zarch, M.A., Sivakumar, B., Malekinezhad, H. and Sharma, A. (2017) Future aridity under conditions of global climate change. Journal of Hydrology 554, 451-469.

Asadi Zarch, M.A., Sivakumar, B. & Sharma, A. (2015) Droughts in a warming climate: A global assessment of Standardized precipitation index (SPI) and Reconnaissance drought index (RDI). Journal of Hydrology 526, 183-195.

Arsic, S., Mijajlovic, N., &Kljajic, N.(2013)Organic production and its role in environmental protection. Scientific Papers. Series "Management, Economic Engineering in Agriculture and rural development", 13 (3), 17-24.

Wang, F. Q., Zheng, Z. Kang, P. & Wang, L., (2017), Applicability evaluation on the indexes of typical drought in Henan province, china, Applied Ecology and Environmental Research, 15(3), 253–262.

Halwatura, D., McIntyre, N., Lechner, A. N. & Arnold, S., (2017), Regional Studies Capability of meteorological drought indices for detecting soil moisture droughts, Journal of Hydrology: Regional Studies. Elsevier, 12, 396–412.

Johnson, F. & Sharma, A. (2015) What are the impacts of bias correction on future drought projections? Journal of Hydrology 525, 472-485.

Mohammed, R. & Scholz, M.(2018) Climate change and anthropogenic intervention impact on the hydrologic anomalies in a semi-arid area: Lower Zab River Basin, Iraq, Environmental Earth Sciences. 77(10), 1–19.

Quan, Y., Wang, C., Yan, Y., Wu, G., &Zhang, H. (2016), Impact of Inter-Basin Water Transfer Projects on Regional Ecological Security from a Telecoupling Perspective, Sustainability, 8(162)

Ramkar, P. & Yadav, S. M.(2018), Assessment of a Semi-Arid Part of Middle Tapi River Basin, India, International Journal of Disaster Risk Reduction, 28, 414-426

Shumilova, O., Tockner, K., Thieme, M., Koska, A. & Zarfl, C. (2018), Global Water Transfer Megaprojects : A Potential Solution for the Water-Food-Energy Nexus ?, Frontiers in Environmntal science 6(150), 1–11

Solakova, T., Michele, C. D. & Vezzoli, **R.**, (2014), Comparison between Parametric and Nonparametric Approaches for the Calculation of Two Drought Indices: SPI and SSI', 19(9), 1–11.

Wu, H., Hayes, M. J., Weiss, A. & Hu, Q.(2001), An evaluation of the Standardized Precipitation Index, the China-Z-Index and the Statistical Z-Score, International Journal of Climatology, 745–758.

Zhang, L., Li, S., Loaiciga, H. A., Zhuang, Y.& Du., Y. (2015), Opportunities and challenges of inter-basin water transfers : a literature review with bibliometric analysis, Scientometrics, 150(1), 279-294