Chapter 12
Environmental Flow Impacts on Water Quality of Peninsular River System: Tunga-Bhadra River, India

M. Rajesh, S. Rehana, and C. T. Dhanya

INTRODUCTION

Environmental flows play a major role in terms of quantity and quality for sustainable riverine ecosystems (Brisbane Declaration, 2007). Environmental Flows (EFs) have a variety of impacts in different regions of the world, including fisheries and other aquatic life, assimilative capacity, drinking water security, agriculture, transportation, navigation, industry, flood protection, recreation and tourism, and other cultural aspects (Iyer, 2005). The EFs are a measure of the amount and quality of water flowing in a freshwater river or stream over time. Estimation of EFs should be able to consider hydrologic, hydraulic, habitat and biodiversity, water quality, socioeconomic and cultural aspects with consideration of water regulation policies (Tennant, 1976). Estimation of EFs is generally practiced with consideration of one or multiple factors. Among these, the hydrological aspect with consideration of historical natural flow data is the most common and practiced by several river water management stakeholders (Zeiringer et al., 2018). Environmental flows based on hydrological criteria were conventionally estimated using flow indices based on a selected threshold level, which may be different for various river systems (Sharma and Dutta, 2020).

There have been many developments in calculating EFs based on hydraulics, hydrology, habitat based on the data availability (Chen and Wu, 2019; Jain and Kumar, 2014; Kumar and Kv, 2019; Zhao et al., 2020). Most of the studies considered low flow indices based on specified thresholds of discharge to identify the low flow regimes in the river systems. A low flow can be a measure of the flow in

M. Rajesh · S. Rehana (✉)

Lab for Spatial Informatics, International Institute of Information Technology, Hyderabad, India
e-mail: rehana.s@iiit.ac.in

C. T. Dhanya
Department of Civil Engineering, Indian Institute of Technology Delhi, Hauz Khas, Delhi, India

a stream during dry weather conditions. Low flow can be considered as a seasonal phenomenon of a river system Smakhtin (2001). One of the most widespread informative tools in the characterization of riverine systems low flows based on the discharge is the flow duration curve (FDC) which is very popular in illustrating the low flow response for any river system. The most conservative threshold, which is considered in the low-flow hydrology is Q50. This is also considered as one of the criteria to define streamflow drought analysis to represent the extreme low flow values (Fleig et al., 2006). The stream flows within the range of 70-99% probability of exceedance are mostly used as design low flows (Smakhtin, 2001). In this context, several studies made efforts for the assessment of low flow events based on the data availability and level of accuracy (Jha et al., 2008; Tharme, 2003; Zhou et al., 2017).

Another phenomenon which defines the deficit of water in rivers is hydrological drought which is observed to commence after a meteorological drought (Geng and Shen, 1992). A low-flow period is the annual cycle of streamflow, which can occur once or twice a year depending on the climatic conditions, unlike the hydrological droughts that are generally associated with low flow concepts, where a single hydrological drought can have multiple low flow events (Zelenhasić and Salvai, 1987). The most conventional way to represent hydrological drought based on the indices to capture the occurrence of water availability below average (Van Lanen et al., 2004). Given that, hydrological drought indices also try to capture the water availability anomalies that can be a better measure to identify the extreme low flow events. Low flows indices and hydrological drought indices are always closely related. For example, lowest annual flow of various durations such as 1, 7, 15 and 30 days is one of the ways to interpret the hydrological drought. Low flows can result due to hydrological drought phenomenon which is conventionally related with meteorological drought which originates based on the climatological anomalies (Monish and Rehana, 2019). The hydrological droughts and low flow indices can be valuable to study the occurrence of low flow events and to define low flow durations which are critical for river water quality as most of the indicators gets affected due to reduced water volumes and consequent impact on the riverine aquatic system.

Increasing frequency of low flow events and hydrological droughts in the river water systems necessitates understanding the impacts on river water quality variables. Extreme low flow conditions were always a major concern towards changes in river water quality. For example, longer water residence time periods under low flows can result in higher river water temperatures affecting the self-purification capacity of the river systems. Higher river water temperature can reduce the dissolved oxygen (DO) concentrations and potential for algal blooms (Caruso, 2002). Extreme low flow events and corresponding deterioration of river water quality can have adverse impact on socio-economic conditions and riverine aquatic biodiversity system. The pollutants from various sources such as domestic, industrial, agricultural developments and human activities can introduce significant nutrients into the river systems and intensifies the eutrophication process affecting aquatic life. The organic degradable material from municipal and industrial effluents

into the river systems may decrease in DO concentrations. This is evident during low-flow periods where pollutant transport and dilution capacity gets affected severely with a consequent decrease in the assimilative capacity of the river system.

Given the significance of understanding the river water quality under low flows, the present study emphasized on identification of low flow events and durations based on low flow indices based on threshold basis and hydrological anomaly basis. Overall, the study has considered the concept of FDCs and hydrological drought indices to characterize the low flow events and durations. The study has demonstrated to relate the river water quality impacts during the low flow event commencement. The main emphasis is to understand how different river water quality parameters such as temperature, DO, BOD, pH, nitrates, etc. can affect during a low flow event with respect to a wet reference period. Considering a peninsular river system, the present study tested hypothesis that (1) river water quality variables have significant impact under low flow conditions; and (2) the changes in river water quality concentrations were mainly driven due to reduced water volumes. The present study made efforts to asses the EFs with a focus on hydrological low flows with use of FDCs and hydrological drought index in the assessment of low flow events and impacts on river water quality.

DATA AND METHODOLOGY: CASE STUDY

Tunga-Bhadra is a perennial river and one of the major tributaries of Krishna river which is the fifth largest river system of India. Tunga-Bhadra river flows through Karnataka and Andhra Pradesh with an area of 71,417 sq km (Jain et al., 2007). Tunga, Bhadra, Kumudvati, Varada and Hagari (Vedavthy) are the contributing tributaries to the Tunga-Bhadra river. The major tributaries of Tunga and Bhadra originate at Gangamoola hills, western Ghats of Kuduremukh in Chikkamagaluru district, Karnataka, India. Tunga and Bhadra rivers are about 147 km and 178 km, respectively, and join at Koodli to form Tunga-Bhadra river and joins Krishna river at Sangamaleshwaram after flowing for about 382 km through Karnataka and Andhra Pradesh. The mean annual rainfall of Tunga-Bhadra river basin is about 884 mm (Jain et al., 2007). The Bhadra river stretch is highly polluted by major industries such as paper, pulp, rayon, steel and municipal effluents (CPCB, 2020). Major industries along the Tunga-Bhadra river stretch are Mysore Paper Mill, Visveshvarya Industrial Steel Limited and Harihar poly fibre.

The river location considered for the calculation of hydrological based environmental flows is Hosaritti station along the Tunga-Bhadra river (Fig. 1). The hydrological and water quality data was obtained from Advanced Centre for Integrated Water Resources Management (ACIWRM), Bengaluru, Karnataka, India. Daily discharge data at Hosaritti station for a period of 2005 to 2017 was considered in the analysis. Water quality data were obtained for one station, namely, downstream of Haralahalli bridge which is near Hosaritti discharge station for a period of 2005-2017 from ACIWRM, India (Table 1).
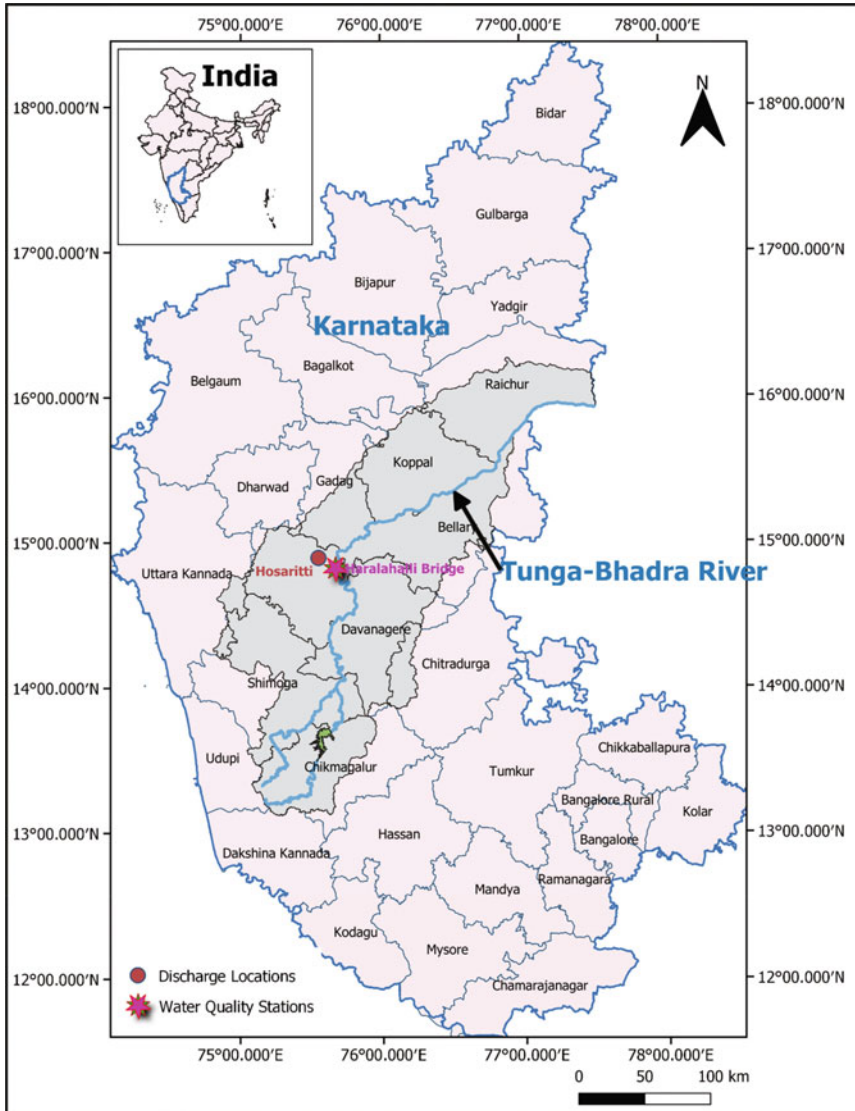
Figure 1. Tunga-Bhadra river basin along with the discharge location and water quality monitoring station, Karnataka, India.

Table 1. Details of selected monitoring stations, Tunga-Bhadra river, Karnataka, India.

Station Type	Station Name	River	Time Period
Discharge Station	Hosaritti	Tunga-Bhadra	2005 -2017
Water Quality Station	Haralahalli Bridge	Tunga-Bhadra	2005 -2017

The present study demonstrates how low flow events can affect the river water quality parameters and used conventional method to define the low flow events based on FDC threshold (Q75) and hydrological anomaly with respect to hydrological drought index, Standardized Runoff Index (SRI). The study identified one common low flow event based on FDC and SRI indices and river water quality was assessed under low flow conditions and compared various hydro-climatology, low flows and river water quality parameters with one low flow duration and reference to wet duration.

Threshold indices for low flows

Environmental flows were estimated using flow indices and flow duration curve (FDC) analysis, and it is a plot between the flow values and the percentage of time that flow is likely to be equal or exceeded.

The step-wise procedure to estimate the low flows using flow duration curves is as follows:

- The monthly stream flows are sorted and ranked from the largest values to the smallest values.
- Each flow is assigned a rank M starting with 1 for the largest value.
- The exceedance probability (*P*), where $P(Q \text{ £ } qi)$ is then calculated as:

$$P = \frac{M}{n+1} \tag{1}$$

where *P* is the probability that a given flow will be equalled to or exceeded, as a percentage of time and *n* the number of flow events.

The probability of exceeding a given flow can be estimated as:

$$P_i = P(Q > q_i) = 1 - P(Q \leq q_i) \tag{2}$$

- The flow duration curve is now plotted using flow on a logarithmic scale as the ordinate and the associated exceedance probability *P* as the abscissa.

Standardized Runoff Index (SRI)

The Standardized Runoff Index (SRI) is a widely used index to assess the hydrological drought events due to its simplicity and data availability, which identifies the hydrological anomalies over a river system (Bayissa et al., 2018; Shukla and Wood, 2008). The SRI is calculated by considering monthly streamflow value $Q_{i,j}$, where *i* is the year and *j* is months within the year. Monthly streamflow values and a

Table 2. Characterization of dry and wet conditions based on the Standardized Runoff Index (SRI) and with the cumulative probabilities (Tao et al., 2014; Wang et al., 2015)

Description	Criterion	Cumulative Probability (%)
Extremely wet	SRI ≥ 2.0	2.28
Moderately wet	$1.5 \leq$ SRI < 2.0	6.68
Slightly wet	$1.0 \leq$ SRI < 1.5	15.87
Near normal	$-1.0 \leq$ SRI < 1.0	50.00
Mild drought	$-1.5 \leq$ SRI <-1.0	84.13
Moderate drought	$-2.0 \leq$ SRI <-1.5	93.32
Extreme drought	SRI < -2.0	97.72

historical time series for the streamflow gauge were considered as input variable. More precise results can be obtained with a longer streamflow data available. Shukla and Wood (2008) mentioned that SRI incorporates hydrologic processes that determine seasonal lags in the influence of climate on streamflow.

- For estimating SRI index, the cumulative flow values were estimated individually for each month, then the SRI values for various time scales. The cumulative streamflow $V_{i,k}$, was calculated based on the equation

$$V_{i,k} = \sum\nolimits_{j=1}^{3k} Q_{i,j} \ \ k = 1, 2, 3, 4 \tag{3}$$

Equation (3) gives $V_{i,k}$ values for 3-, 6- and 12-month periods, respectively. The SRI is described with cumulative streamflow volumes $V_{i,k}$ for each reference period k of the ith hydrological year as

$$SDI_{i,k} = \frac{V_{i,k} - \overline{V}_k}{S_k} \ \ k = 1, 2, 3, 4 \tag{4}$$

where and S_k are the mean and the standard deviation of cumulative streamflow for a period k, respectively. The values of SRI greater than zero can be considered as wet conditions and the SRI values greater than zero are classified as dry conditions. The characterization of wet and dry conditions based on SRI values are given in Table 2.

Environmental Flows and Water Quality

Five river water quality parameters such as water temperature, pH, DO, BOD and nitrates based on the data availability were considered to study the effect of low flow events on the river water quality. Monthly values of water quality parameters were taken to study the significance between them during low flow and reference wet periods. Mean, minimum and maximum values of water quality indicators were computed, and the p-values obtained from the two-sample t-test was used to study

the statistical difference in water quality indicators between a dry and wet period. The two-sample *t*-test is a statistical test used in the assessment of the importance of significant differences between groups, which may be related in certain features (Levy, 1967). A paired two-sample *t*-test to presume whether the difference between the sample means is statistically distinct from a hypothesized difference (Cressie and Whitford, 1986).

RESULTS AND DISCUSSION

Low Flow Analysis

The hydrology of river was studied by plotting the mean monthly precipitation and discharges for the Hosaritti station from 1st June 2005 to 31st May 2017. The annual average rainfall for the study location was about 1168 mm and streamflow about 440 m^3/s estimated for the period 2005 to 2017. Figure 2, shows that precipitation and discharge values for Hosaritti station were decreased from 2010 onwards. The Tunga-Bhadra river has experienced a decline in precipitation in recent years along with high fluctuations in the rain patterns based on Karnataka State Natural Disaster Monitoring Centre (KSNDMC). Karnataka state receives an annual rainfall of 1,135 mm in which the south-west monsoon accounts for about 73%. But, since 2011, the state has received an average rainfall of 1,033 mm, which is 10% less than the normal rainfall (The Times of India, 2019). The variations in the rainfall patterns have affected the streamflows severely. The annual streamflow at Hosaritti station has shown a decreasing trend of about 26.1 m^3/s per decade from 2005 to 2017 (Fig. 3). Such decrease of annual streamflows has been found for other river locations along the Tunga-Bhadra river such as Shimoga with about 3.1% and Honnalli with 12.26% based on the study of (Rehana and Mujumdar, 2011.)
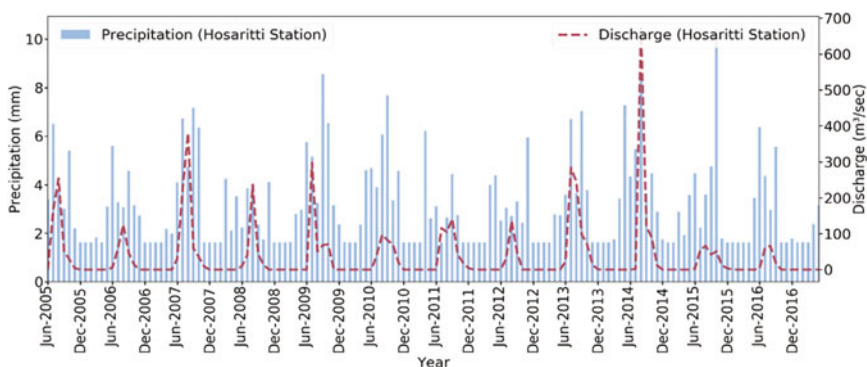

Figure 2. Monthly average precipitation and discharge of Tunga-Bhadra river at Hosaritti station, India (2005–2017).
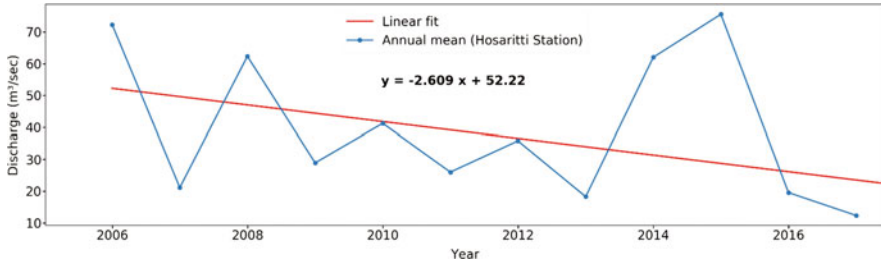
Figure 3. Annual discharge at Hosaritti station along with linear trend line from 2005 to 2017
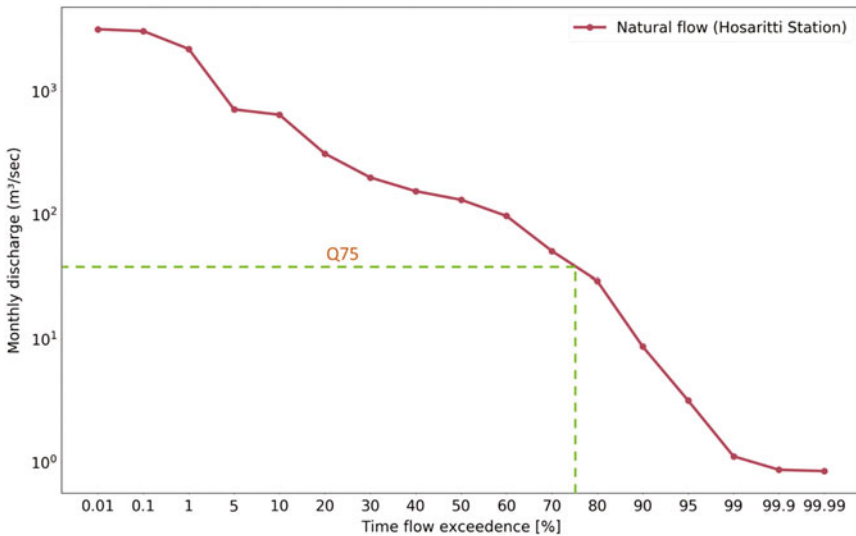

Figure 4. Mean monthly flow duration curve (flow on a logarithmic scale) of Tunga-Bhadra river at Hosaritti station, India (2005–2017).

To study the low flow events and river water quality impacts for the river location under consideration, the Q75 value was used as a threshold-based index (Fig. 4). The low flow events identified based on Q75 are presented in Fig. 5 and Table 2. The Q75 value for Hosaritti station was estimated as 40 m³/s based on the FDC (Fig. 4). Based on Q75 value, every year has experienced almost one low flow event. Each year's low flow duration based on the threshold of Q75 has been denoted with rectangular boxes labelled from *a* to *l* along the river location of Hosaritti (Fig. 5). For example, the low flow event with a duration of about 240 days starting from November 2005 to June 2006 has been denoted with a rectangular box *a*. Following this about 12 low flow events were identified based on Q75 value as threshold from 2005 to 2017 with an average duration of 252 days at Hosaritti station along Tunga-Bhadra river.
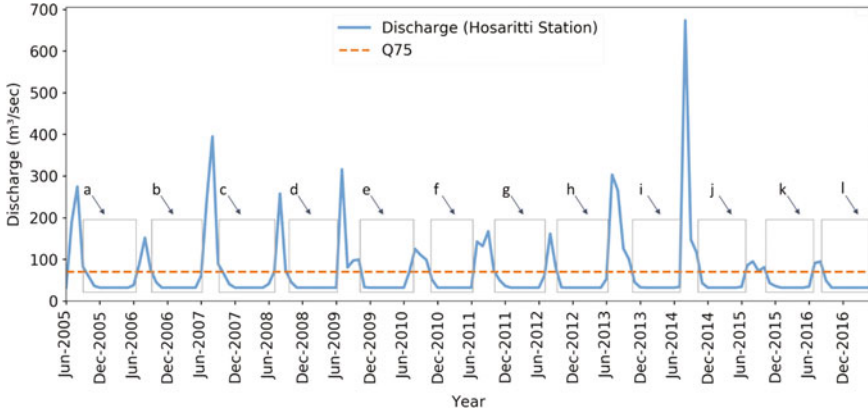
Figure 5. Low flow events and durations along Tunga-Bhadra river at Hosaritti station, India (June 2005-May 2017).
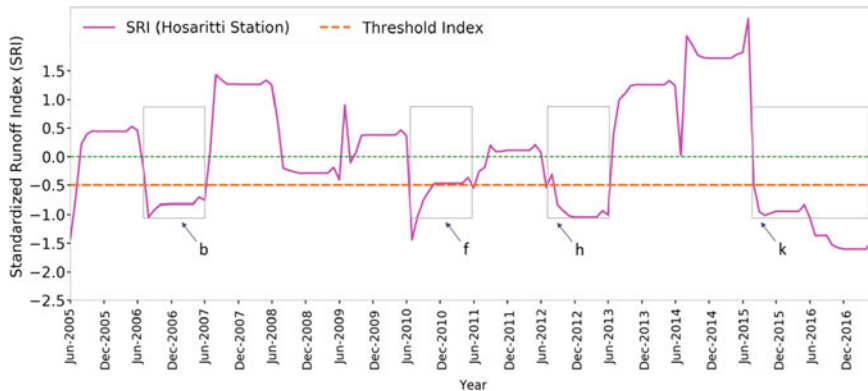

Figure 6. The SRI index on a 12-month scale at Hosaritti station, Tunga-Bhadra river, India, estimated (2005-2017).

The monthly values of SRI were calculated for 12-month time scale for a period ranging from 1st June 2005 to 31st May 2017, and the SRI time series was plotted for Hosaritti station as (Fig. 6). The intensity of drought was explained with reference to the low flow events estimated based on Q75 values (Fig. 5; Table 2). The study considered the extreme low flow events based on both threshold-based criteria of Q75 and hydrological anomalies-based criterion drought index of SRI. For this, the study considered -–0.5 as SRI threshold to pick the hydrological low flow events which are also consistent with Q75 criterion. By considering the SRI threshold as –0.5 Hosaritti station had experienced drought between August 2006 to June 2007 (Fig. 6: box (b)), June 2010 to May 2011 (Fig. 6: box (f)), June 2012 to June 2013 (Fig. 6: box (h)) and August 2015 to May 2017 (Fig. 6: box (k)). It can be noted

Table 3. Low flow events and drought events occurred over Hosaritti location over Tunga-Bhadra river basin

Location	Low flow events (Fig. 5)	Occurrence (days)	Hydrological Drought events (Fig. 6)
Hosaritti	(box, a): Nov 2005 to June 2006	240	
	(box, b): Nov 2006 to June 2007	240	**(box, b): August 2006 to June 2007**
	(box, c): Oct 2007 to June 2008	270	
	(box, d): Oct 2008 to June 2009	270	
	(box, e): Nov 2009 to June 2010	240	**(box, f): June 2010 to May 2011**
	(box, f): Nov 2010 to June 2011	240	**(box, h): June 2012 to June 2013**
	(box, g): Nov 2011 to June 2012	240	
	(box, h): Oct 2012 to June 2013	270	**(box, k): Aug 2015 to July 2016**
	(box, i): Nov 2013 to July 2014	270	**(box, k): July 2016 to May 2017**
	(box, j): Nov 2014 to July 2015	270	
	(box, k): Nov 2015 to July 2016	270	
	(box, l): Nov 2016 to May 2017	210	

that the identified hydrological drought events are also consistent with the low flow events and durations identified based on Q75 values are shown in Fig. 5 and Table 2.

The study focused on one of such common low flow periods which was identified based on Q75 and SRI to analyze the river water quality impacts under low flows. For example, from Figs. 5 and 6, and Table 3, a recent and yet common low flow period from December 2015 to May 2016 (Fig. 5: box, (k)) was considered to study the river water quality impacts at Hosaritti station along Tunga-Bhadra river. A comparison conducted for various water quality parameters such as air and river water temperatures, pH, DO, BOD, and nitrates. The river water quality parameters during one of the extreme low flow period was investigated and compared with the reference period which is the preceding period (June 2013 to November 2013). The study compared low flow period with the wet reference period before the occurrence of a low flow period. The river water quality indicators under low flow period of December 2015 to May 2016 was compared with a wet reference period of June 2013 to November 2013.

Before understanding river water quality impacts under low flows, the basic climatology of the study area was compared for low flow period and referenced

Table 4. Annual total precipitation and maximum air temperature at discharge stations for low flow period, reference period, and averaged over the entire period 2005 - 2017

Discharge location	Parameter	Low flows Dec 2015-May 2016	Reference June 2013-Nov 2013	Average 2005-2017
Hosaritti	Annual total precipitation (mm)	354	805	1168
	Air temperature (^{o}C)	35.75	28.44	31.64

wet period. The climatology of a low flow period and reference period were compared by comparing the precipitation and temperatures for Hosaritti station. Annual total precipitation and maximum air temperatures were compared for low flow period with reference period (Table 4). Comparison of annual total precipitation, mean and maximum air temperatures for low flow period and for reference period demonstrates drier and warmer conditions during the low flow period. Annual total precipitation was substantially lower (354 mm) during the low flow period, while the maximum air temperature was incredibly higher (35.75 °C) when compared to the reference period (Table 4). The long-term average annual rainfall was noted as 1168 mm over the basin, whereas, average annual rainfall during low flow and reference periods were noted as 354 mm and 805 mm, respectively. Table 4, shows that the annual precipitation was low during low flow event duration, i.e., December 2015 to May 2016 compared to the preference period (June 2013 to November 2013) for Hosaritti station along Tunga-Bhadra river. While the annual rainfall is decreased, the maximum air temperatures were observed to be increased during low flow period for Hosaritti station. The low flows in current study are observed to be a combined effect of both lower precipitation and higher air temperatures.

The study compared the hydrological aspects for a low flow period with the reference period by comparing the discharge values. For this, the study compared the low flow hydro-climatology of Hosaritti station for low flow period and reference period. The lower precipitation values, higher temperatures and therefore consequent decrease in stream flows were observed under low flows compared to hydrological period over Tunga-Bhadra river basin.

River Water Quality Analysis

Impact of low flows on river water quality was studied by observing variation in the water quality parameters under low flow and wet reference periods. The variations within each water quality parameter were studied using the statistical test, such as a two-sample *t*-test (Table 5). The *t*-test was conducted on each water quality parameter for the low flow period and reference period (Table 5).

Table 5. Mean and significant values of surface water quality variables at Haralahalli bridge in low flow period (Dec 2015 to May 2016) and reference period (June 2013 to Nov 2013). Values indicate significant relationships with a low flow period ($P < 0.05$).

Water quality station	Water quality variable		Low flow period	Reference period	P-Value
Tungabhadra at Haralahalli bridge	Water Temperature	Mean	28.33	25.33	**0.02**
		Minimum	26	22	
		Maximum	31	27	
	pH	Mean	7.80	8.23	
		Minimum	7.6	7.7	**0.03**
		Maximum	8.1	8.7	
	DO	Mean	7.73	7.25	
		Minimum	7.2	6.6	**0.10**
		Maximum	8.4	7.8	
	BOD	Mean	2.97	2.33	
		Minimum	2.3	2.0	0.20
		Maximum	5.0	3.0	
	Nitrate	Mean	0.49	0.14	
		Minimum	0.27	0.10	**0.00**
		Maximum	0.59	0.20	

The river water temperatures were observed to differ significantly at the Haralahalli bridge station ($P < 0.05$) during low flow period. For example, average air (water) temperature for low flow period was noted as 35.75 (28.33) and 28.44 (25.33) °C for the low flow and hydrological periods, respectively. The increased water temperatures under low flows can be correlated with the increase in air temperature (Fig. 6) (Rehana, 2019). An increase in river water temperature can result in decrease in DO levels (Fig. 7), which may lead to anaerobic conditions affecting the aquatic life and self-purification capacity of the river system (Rehana et al., 2019). River water temperature is an important quality parameter affecting the physical, chemical and biological characteristic of a river system and aquatic life of riverine environment (Webb et al., 2003). Linear regression models relating to air and water temperatures become popular in the prediction of river water temperature (Neumann David W. et al., 2003; Rehana and Mujumdar, 2011). Air and water temperatures were observed (Fig. 8a) to follow a linear trend at Hosaritti station. River water temperatures were observed to increase with the increase in maximum air temperatures during the study period (Fig. 7). Research findings of the current study are in agreement with the results of Rehana and Mujumdar (2011) for the same case study at stations Shimoga (Tunga river) and Honnalli (Tunga-Bhadra river) in terms of linear dependency of air and water temperatures (Rehana and Dhanya, 2018).

But unlike direct relation between air and water temperatures, the discharge is observed to follow a quadratic relationship with the river water temperature (Fig. 8 (b)). The river water temperature decrease to a point and then increase at Hosaritti station. Such an inverse relationship between river water temperature and discharge
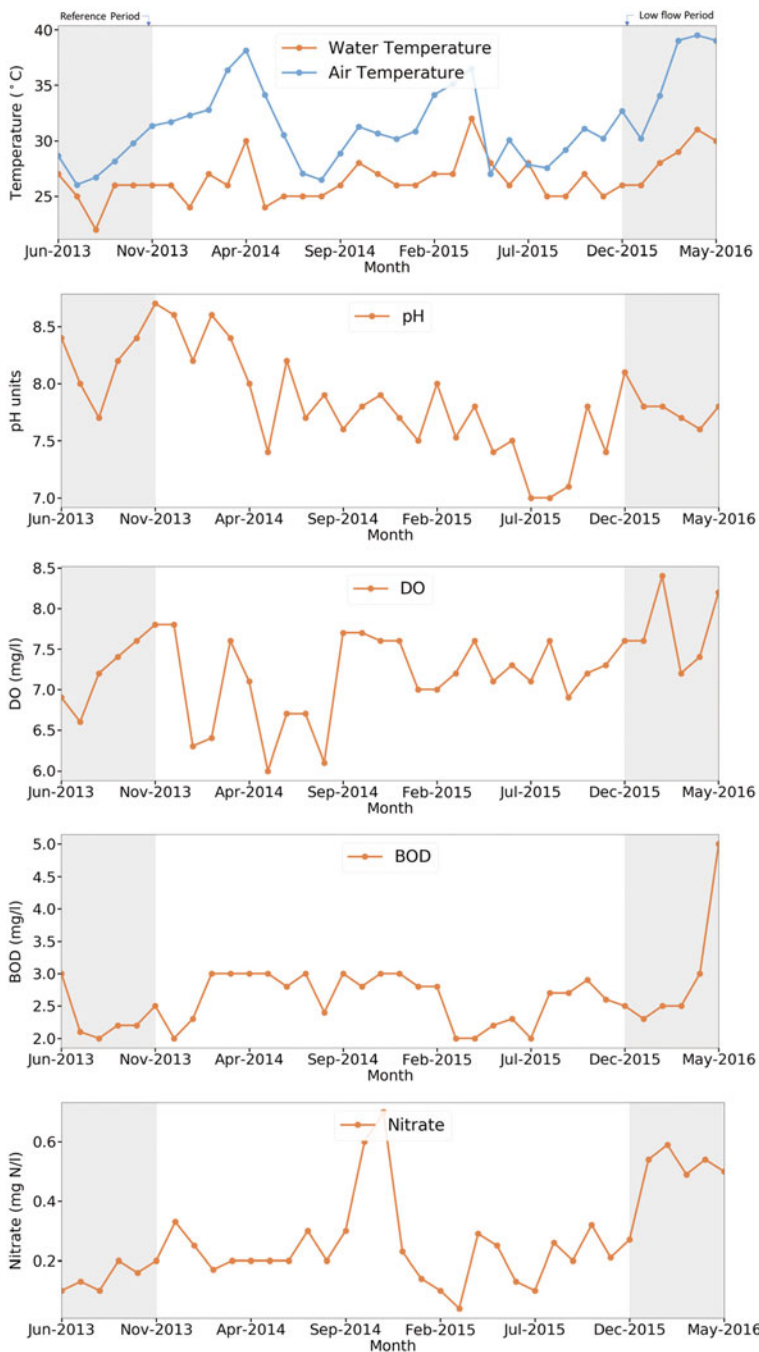
Figure 7.   Water temperature, max air temperature, pH, DO, BOD and Nitrate (2013-2016)
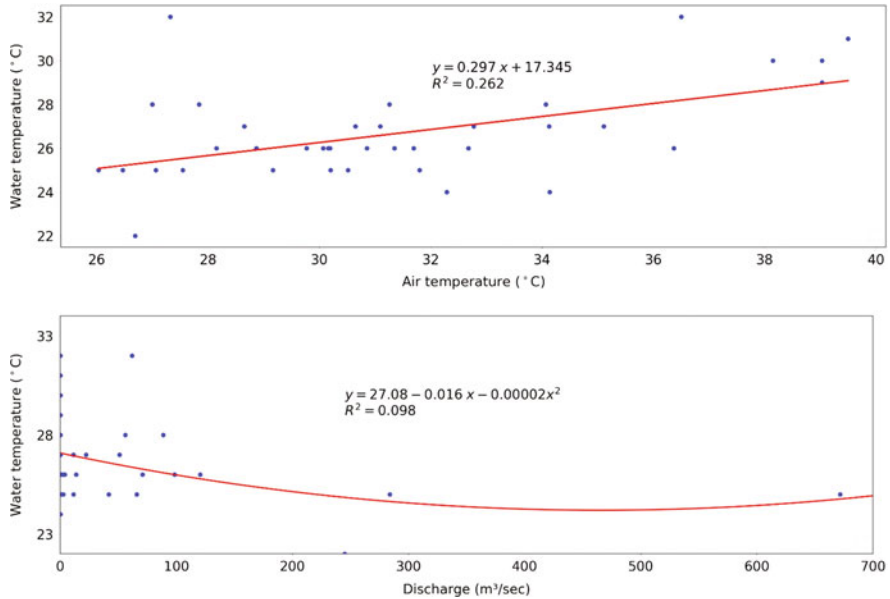
Figure 8. Relation between monthly (a) river water temperature and max air temperature and (b) water temperature and discharge at Hosaritti (2013-2016).

was also noted for other river systems globally (Rehana, 2019; Webb et al., 2003). With such relation between river water temperature and stream flows, it can be concluded that the decrease in discharge during low flow events can increase the river water temperature resulting in poor water quality in terms of decrease in DO levels (van Vliet and Zwolsman, 2008). The river water temperature for Haralahalli station during the low flow period was noted at 28.33 °C, whereas for the reference period it was 25.33 °C (Table 5). At the same time, the discharge for Haralahalli station for the low flow period (December 2015 to May 2016) was noted as 7 m³/sec, whereas for the reference period (June 2013 to November 2013) it was 122 m³/sec. It can be noted that river water temperature is also defined by various factors such as excess heat from industries and municipal effluents which may lead to such inconsistency in the temperatures and river flows (Thomann and Mueller, 1987).

As per IS:2296-1982, the tolerance limit of pH is 6.5 to 8.5. A statistically significant change has been observed in pH values at Haralahalli bridge station during low flow and reference wet period. Mean pH values at Haralahalli bridge water quality station was observed to be in tolerance limits. Relatively higher pH values were observed at lower discharges (Fig. 9) at the Haralahalli bridge station. The Dissolved Oxygen (DO) is an important river water quality parameter and generally considered as the pollution level indicator in water quality monitoring. As per IS:2296-1982, the minimum tolerance limit of DO in river systems is 4 mg/l. The DO values at Haralahalli Bridge station was observed to be above the tolerance limit (Fig. 7). For example, the DO level for Haralahalli bridge station in
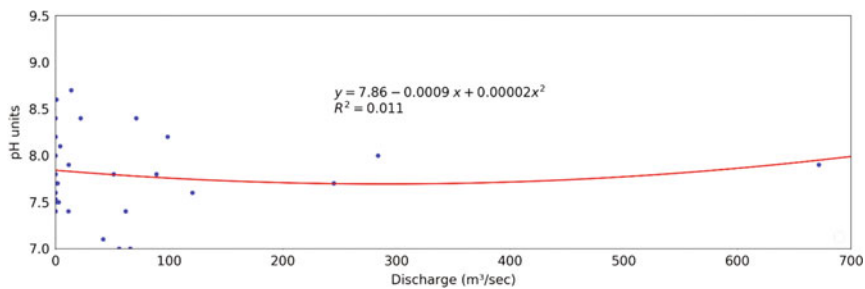
Figure 9. The relation between monthly discharge and pH at Haralahalli bridge (2013-2016).
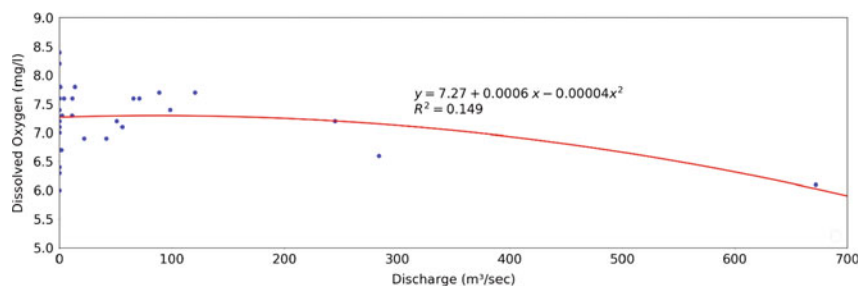

Figure 10. Relation between monthly discharge and dissolved oxygen at Haralahalli bridge (2013-2016).

the low flow period was noted as 7.73 mg/l, whereas, the DO levels for the reference period was noted as 7.25 mg/l. The higher DO values at Haralahalli bridge station during the lower discharges (Fig. 10) can be because of an increase in primary production in the river water (Zwolsman and van Bokhoven, 2007).

The next important river water quality indicator analyzed for the low flow period is BOD. As per IS:2296-1982, the maximum tolerance limit of BOD is 2 mg/l for tolerance limits for inland surface waters, class - A, with the use as a drinking water source without conventional treatment but after disinfection. The BOD values at Haralahalli station was observed to be more than the tolerance limit (Fig. 7). High BOD values indicate that the river is heavily polluted. The higher BOD value of about 2.97 mg/l was noted under low flow period, while for wet period the BOD value was noted as 2.33 mg/l (Table 5). Note that the high BOD values at the lower discharge values at the Haralahalli bridge station (Fig. 11). Higher BOD values during low flows may have severe impact on the riverine aquatic system (Sharma and Dutta, 2020).

As per IS:2296-1982, the maximum tolerance limit of nitrate is 20 mg/l for tolerance limits for inland surface waters, class - A, with the use as drinking water source without conventional treatment but after disinfection. Though the nitrate differs significantly ($P < 0.05$) at Haralahalli bridge, the values were observed to be below the desirable limit (Fig. 7; Table 5). For example, the average nitrate
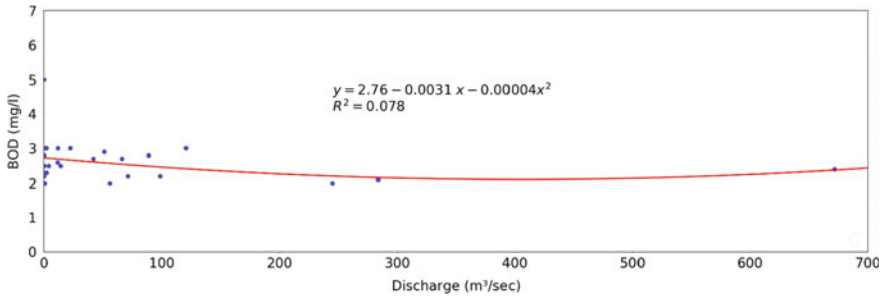
$$y = 2.76 - 0.0031\,x - 0.00004x^2$$
$$R^2 = 0.078$$

Figure 11. Relation between monthly discharge and BOD at Haralahalli bridge (2013-2016).

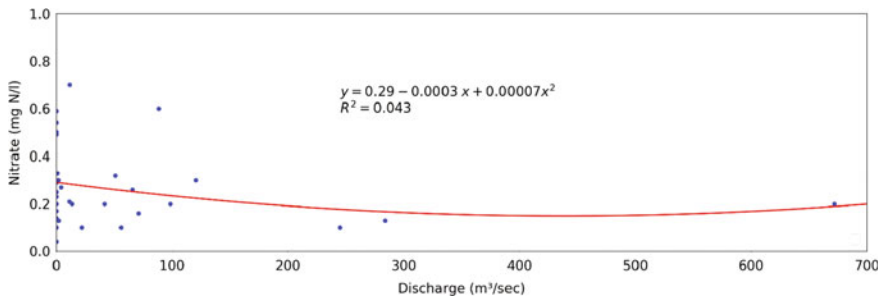$$y = 0.29 - 0.0003\,x + 0.00007x^2$$
$$R^2 = 0.043$$

Figure 12. Relation between monthly discharge and nitrate at Haralahalli bridge (2013-2016).

concentration during the low flow and wet referenced durations was 0.49 mg/l and 0.14 mg/l, respectively, with higher maximum values during low flow periods. Although the nitrates concentrations are within the desirable limits, higher concentrations were expected during low flow periods compared to the reference periods (Fig. 12). Increase in the nitrate concentrations under low flow conditions can be due to the reducing dilution capacity of the water body (Prathumratana et al., 2008; van Vliet and Zwolsman, 2008; Zwolsman and van Bokhoven, 2007). Furthermore, the decrease in nitrate concentration can be expected due to the reduced agricultural runoff and drainage (Muchmore and Dziegielewski, 1983).

CONCLUSIONS AND FUTURE DIRECTIONS

Environmental flows are important in the context of river water quality management. Sufficient hydrological based environmental flows should be maintained along the river stretches to maintain the river water quality parameters within desirable limits. Flows are very much essential for maintaining the river regime in terms of its self-purification capacity, sustainable aquatic life and vegetation, well-being of livelihoods etc. River water systems have to be protected in terms of both quantity and quality. In India, the low flow management is challenging due to several aspects

including water regulation policies and other socio-economic and cultural factors. In India, rivers have great religious significance during holy dips along the banks of rivers, necessitates maintaining minimum quantity and quality of flow (Jain and Kumar, 2014). Given the emerging importance of flows in the riverine systems, it is essential to develop an appropriate environmental flow estimation strategy for Indian context given the seasonal hydroclimatological variability. Further, a detailed understanding about the river water quality impacts under low flow events in the present study is of very much relevance for the water resources management under low flow events.

The present study made efforts to understand the river water quality responses under low flow event compared to referenced wet periods along a peninsular river system, Tunga-Bhadra river, India. The emphasis of the study was to assess the impacts of low flow events on the river water quality parameters such as water temperature, BOD, DO, pH, nitrates etc. of Tunga-Bhadra river, India. The research findings of the present study demonstrate that low flows significantly impacted river water quality of Tunga-Bhadra river system. The lower precipitation values, higher temperatures and therefore consequent decrease in stream flows were observed during a low flow compared to hydrologically wet period over the Tunga-Bhadra river. Results showed significant effect of low flow durations with respect to the river water temperature when compared to the reference wet period. The pH is observed to be nominal, while DO and BOD are offsetting desirable limit at Haralahalli bridge station, indicating deterioration of water quality due to industrial effluents. The nitrate concentration is observed to be in desirable limits. As per standards given by the CPCB (CPCB, 2020) for the designated best use of water, the river water quality at Haralahalli station is not meeting any of the criteria due to high amounts of BOD present. Higher concentrations of BOD and nitrates were observed during low flow events compared to reference hydrological period. Whereas, lower concentrations of pH and DO were noted under low flow conditions compared to reference wet period. The most affected river water quality variable during low flow events is river water temperature along Tunga-Bhadra river. Higher river water temperatures were noted for low flow duration period compared to reference wet period, which can directly impact DO levels. The river water quality concentration responses of major water quality parameters are mainly determined by its behaviour with the fluctuations in the discharge.

This study demonstrates how threshold based low flow index of Q75 using FDC and hydrological drought index of SRI could be scaled-up and used for assessing and identification of low flow events. The study considers extreme low flow events based on both threshold-based criteria of Q75 and hydrological anomalies-based criterion drought index of SRI.

One of the major limitations is the non-availability of discharge data for the possible implementation and understanding of the river low flow analysis and its response towards river water quality. Specifically, estimating low flows for ungauged catchments is a challenging factor for water resources management and policy making. Due to limitation of the data availability, the present study demonstrates the environmental flow impacts on river water quality at low flow events and

duration with one river location, which can be extended to other stations based on data availability. Since, environmental flow is a multifaceted phenomenon, therefore, coupling of other flow indices may generate enhanced results for analysts and policy makers. To conclude, this study gives an overview of hydrological low flow events and its potential impacts on water quality parameters.

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