

Evaluating hydrological alterations and recommending minimum flow release from the Ujjani dam to improve the Bhima River ecosystem health

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ABSTRACT

Numerous anthropogenic activities like the construction of large dams, storages, and barrages changed the watershed characteristics impacting ecosystem health. In this study, the hydrological alterations (HAs) that have occurred in the Bhima River due to the construction of the Ujjani dam were analyzed. The hydraulic analysis is also performed to determine the hydraulic parameter and recommend the lowest flow release from the dam for improving ecosystem health. Fifty-eight years of data starting from the year 1960 to 2018 were gathered at Yadgir station, which is located downstream of the Ujjani dam. The data were divided into pre- and post-construction river flow discharge. To check for the change in the river flow regime for the post-dam construction period, HA was calculated using Flow Health Software (FHS). The results demonstrate that the dam impoundment reduces high flows primarily by storing flood flow for water supply, irrigation, etc. The velocity and depth provided by the environmental design flow for a flow health (FH) score of 0.62 give a very good habitat to fishes. A minimum release of 24.8 m³/s from the dam is recommended. This study will help policymakers mitigate the impacts of degrading ecosystem health of the Bhima River.

Key words: Bhima River, dams, environmental flow, Flow Health Software, hydrological alterations

HIGHLIGHTS

- The study analyzes hydrological alterations caused by the construction dam, which have disturbed the river flow regime.
- A hydraulic study was performed to determine the hydraulic parameter and to recommend the lowest flow release from the dam for habitat context.
- Pre- and post-construction river flow discharge data were used to analyse the impact of human activities on ecology of river.

1. INTRODUCTION

River flow regime and river flow are closely related to water resources; they are the most concerned elements in the water cycle process and are the core elements to maintain the integrity of the river ecosystem (Kuriqi *et al.* 2019). The hydrological regime refers to the changes in time and space of many hydrological elements, such as precipitation, evaporation, runoff, and water quality in natural water bodies such as rivers, lakes, and reservoirs (Mankar *et al.* 2020; Prabha & Tapas 2020). The hydrological regime is the main driving force of river and floodplain ecosystems. It also has an important relationship with aquatic biodiversity, which affects ecosystems directly or indirectly, affecting habitat and biological composition (Weng *et al.* 2021; Sedighkia *et al.* 2023). The change in the hydrological regime is closely related to the health of the river and the ecological integrity of the river ecosystem. However, with the development of the economy and society, the development of waterways by human beings for flood control, water supply, power generation, agriculture, and shipping has made the hydrological regime difficult (Tapas *et al.* 2022a). Substantial changes occur, which are bound to alter the ecosystem (Hecht *et al.* 2019; Vassoney *et al.* 2021). A good river ecological environment is an essential prerequisite and guarantee for the sustainable and high-quality development of water resources development and utilization (Kuriqi *et al.* 2021; Garrett *et al.* 2023).

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If we did not maintain sufficient water flow in rivers, it can cause a severe effect on both the environment and human communities. When rivers do not receive minimum flow, the ecosystems get disrupted, leading to biodiversity loss. The decline in fish populations is another significant concern. Fish species depend on specific life flow conditions, including spawning, migration, and feeding. Without minimum flows in rivers, these processes are disturbed, resulting in reduced fish populations. This not only disrupts the ecological balance but also affects the livelihoods of communities dependent on fishing for sustenance or economic purposes. Inadequate river flows restrict groundwater recharge, intensifying water scarcity issues. This, in turn, can create conflicts among different water users, impacting socioeconomic development and the overall quality of life.

The global increase in water consumption demand has resulted in changes in the pristine condition of the river, causing changes in the ecological functioning of the river. The streamflow governs the physical and ecological dynamics of rivers. The nutrient cycle, sediment transport, and water flow are examples of ecological processes (Tapas *et al.* 2022b). These processes interact to create distinct ecological traits such as stream morphology, stream temperature, biological community composition, and sedimentation (Berthot *et al.* 2020). Because biotic populations within a specific system depend on the processes and qualities of flow to carry out different phases of their life, it is crucial to safeguard the ecological functions (Peñas & Barquín 2019; Tian *et al.* 2019; Kuriqi *et al.* 2021). Therefore, maintaining a minimum quantity of streamflow, called environmental flow (EF), is essential for sustaining a healthy river ecosystem (Zeiger & Hubbard 2021). Many nations have made it necessary to ensure EFs because they recognize the significance of EF (Berthot *et al.* 2021). Failure to maintain this flow may lead to a decline in the health of water-dependent ecosystems. EFs are not just minimum flows, but it is a combination of high and low flows maintained in the river at different frequencies and seasons. EFs try to strike a balance between the use of water from a river for economic development, societal needs, and delivering ecosystem services (Szalkiewicz *et al.* 2022). Modeling EF in the case of hydrologically altered rivers is the methodology for identifying the volume of river flows required to mimic the pristine flow variabilities over different periods of a year (Ali *et al.* 2019; Tranmer *et al.* 2020). Studies on environment flows have been taken up by different researchers across the world, and it was found that the requirements for EF could be arrived at based on the consideration of hydrology and from the consideration of habitat (ecology and geomorphology) of a few indicator species. The requisite hydrologic regime cannot be maintained by streamflow alone. Additionally, the flow velocity and flow depth must be specified (Gholami *et al.* 2020). The ability to convey sediment and sustain physical habitat are both impacted by the flow velocity and wetted perimeter for the same discharge over short distances. Many of the earlier studies on the Krishna River mainly focussed on analyzing the operational constraints of the water supply system and water quality, but a few of them focus on hydrological alteration (HA) and hydraulic and habitat analysis (Mezger *et al.* 2021; Ranjan & Roshni 2023). EFs examine and explain the effects of changed natural flow patterns and modified flow regimes as a result of hydraulic constructions like dams, abstractions, diversions, or flow additions. In the present study, the HAs (flow changes) that have occurred in the Bhima River due to the construction of the Ujjani dams were analyzed. Additionally, the hydraulic study is performed to determine the hydraulic parameter and to recommend the lowest flow release from the dam for habitat context.

2. STUDY AREA

Bhima River has been taken up for this study. Bhima is one of the major tributaries of the Krishna River, which is one of the major rivers in peninsular India. It flows for about 861 km through the states of Maharashtra, Karnataka, and Telangana. The total drainage area of the Bhima sub-basin is 70,263 km² covering 75% of the area in Maharashtra and the rest in Karnataka. The river originates near Bhimashankar temple in the Bhimashankar hills of Khed Taluka in the Sahyadri range of the Western Ghats, Pune District, Maharashtra, at an elevation of about 1,000 m. This region covers part of the Western Ghats Mountain ranges to Deccan Plateau and has a semi-arid tropical climatic condition. The river joins the Krishna River in Raichur district of Karnataka.

Ujjani dam is the largest dam constructed across the Bhima River. The dam is located at a latitude of 18.0739°N and a longitude of 75.12°E. The reservoir created by the dam has a gross storage capacity of 3,140 Mm³. Stream flow data has been collected at a lower portion of the Bhima River at Yadgir station in Karnataka. The station is located at a latitude of 16.7375°N and a longitude of 77.1253°E. Figure 1 shows the Krishna River basin and the location of the Ujjani dam along with the selected station Yadgir.

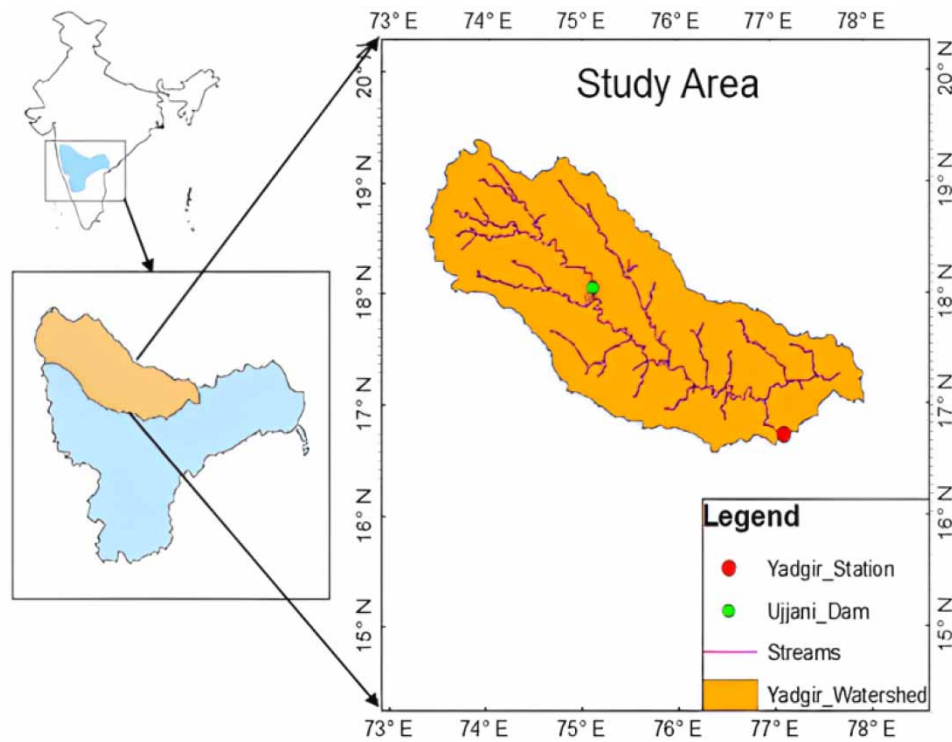


Figure 1 | Location map of the study area.

3. METHODOLOGY

The methodology is divided into three sections: (i) eliminating the effects of climate variability from the hydrological process; (ii) EF and river health assessment; and (iii) habitat hydraulic analysis.

3.1. Eliminating the effects of climate variability from the hydrological process

The main aim of the study is to calculate the environmental flow requirements (EFRs) and to check for HA for the post-impact period. Streamflow data has inherent variability due to the impacts of dam construction and climate variability. The SPI is a multi-scalar probabilistic index that calculates precipitation deficiency during wet and dry spells. This index helps to consider methods for adaptation and mitigation to deal with climate change. SPI describes rainfall variability and indicates the number of standard deviations that a rainfall event deviated from the average given in Equation (1).

Generally, SPI is used to characterize wet and dry conditions. In this study, to eliminate the flow data affected by climate variability, a 12-month SPI is calculated by fitting the gamma distribution to the precipitation series. The wet and dry years were classified based on the classification scale given in Table 1, suggested by Chulsang (2006). Flow data corresponding to normal years whose SPI values range between -0.99 and 0.99 are considered for further evaluation of HA and EFR.

$$SPI = \frac{X_{ij} - X_{im}}{\sigma} \quad (1)$$

where X_{ij} is seasonal precipitation at the i th rain gauge station and j th observation, X_{im} is the long-term mean, and σ is the standard deviation.

3.2. EF and river health assessment

In this study, the flow health (FH) hydrological analysis tool, named Flow Health Software (FHS), is used to determine EFR. FHS allows an estimation of EF regimes in terms of minimum monthly flow (MMF) and design flow.

FHS is a tool to assist in the assessment, design, and management of river flow regimes based on the flow duration curve (FDC). FDC is developed for two periods, i.e., the reference period (before dam construction) and the test period (after dam

Table 1 | Standardized Precipitation Index classification

SPI classes	Criterion
Extremely wet	>2
Very wet	1.5 to 1.99
Moderately wet	1.00 to 1.49
Normal	−0.99 to +0.99
Moderately dry	−1.00 to −1.49
Very dry	−1.50 to 1.99
Extremely dry	< −2.00

construction). The FDC of the reference period and test period are compared from top to bottom to determine the FH scores for nine hydrological indicators. Nine hydrological indicators, namely Lowest Monthly (LM), Low Flow (LF), High Flow (HF), Highest Monthly (HM), Persistently Lower (PL), Persistently Higher (PH), Seasonality Flow Shift (SFS), Persistently Very Low (PVL), and Flood Flow Interval (FFI) (Gippel *et al.* 2012). The threshold percentile for each indication varies depending on its significance. FH tool compares monthly flow values in the test period with those in the reference period and assigns a score in such a way that flows that are nearly identical to those in the virgin condition receive a score close to 1, while flows that deviate significantly from the virgin condition receive a score close to zero. The average of nine indices is used to get the overall score varying from 0 to 1. The nine indicators used in FHS are explained below.

3.2.1. Low flow and high flow

LF is the most prevalent flow condition. It determines the amount of aquatic habitat available for most of the part of the year. It affects the diversity of the species and number of organisms living in the river. LF is the sum of the monthly flows in the natural low flow period. The FH score is assigned a value of 1 if the cumulative flow percentile is between 25 and 75 and less than 25%ile of cumulative low flow volume during the reference period. FH score values for the range of flow percentile varying from 0 to 25%ile and greater than 75 to 100 are calculated using Equations (3) and (4), respectively.

Percentile attribute reference distribution is in the range of 25th percentile to 75th percentile.

$$\text{Score} = 1 \quad (2)$$

If the attribute reference distribution percentile range below the 25th percentile.

$$\text{Score value} = 4 \times \left(\frac{\text{Percentile in attribute reference distribution}}{100} \right) \quad (3)$$

If the attribute reference distribution percentile range above the 75th percentile.

$$\text{LF season score value} = 1.75 - \frac{\text{Percentile in attribute reference distribution}}{100} \quad (4)$$

The percentile falls below the 25th percentile range in the attribute reference distribution.

$$\text{Score} = 1 \quad (5)$$

To calculate the HF metric score for a given year, the high flow period's total sum is computed as a part of the HF calculation. This score is based on the percentile of the sum of the flows over the HF period in the reference period, and it is assigned a value according to the relationships outlined in Equations (3) and (4).

3.2.2. Lowest monthly flow and highest monthly flow

LM refers to the lowest monthly flow recorded in a year. If the percentile falls between the 25th and 75th range, an FH score of 1 is assigned. However, for percentiles below the 25th and above the 75th percentile in the attribute reference distribution, the FH score value is calculated using Equations (3) and (4).

HM represents the highest monthly flow in a given year. The HM score for a test year is based on the percentile of the maximum monthly flow in the reference period. A score of 1 is given to any maximum flow value in a test year that exceeds the maximum value in the reference period, and a score of 0 is given to any maximum flow value in a test year that is less than the minimum value in the reference period. The FH score value for percentiles ranging from 0 to 25%ile and greater than 75–100 is calculated using Equations (2) and (3), respectively.

3.2.3. Persistently higher and persistently lower

The PH is a metric that shows how many consecutive months during the natural low flow season have higher flows than expected (i.e., above the 95th percentile). The PH flow index is only valid during low flow periods. The count of the number of consecutive months in a low flow period where the flow is above the upper range (95th percentile) for each month of a reference period is calculated. The score for this indicator is assigned based on Equations (6)–(8).

The count of consecutive months ≤ 1 .

$$\text{Score} = 1 \quad (6)$$

The count of consecutive months > 1 .

$$\text{Score} = 1.2 - 0.2 \times (\text{Maximum cumulative total}) \quad (7)$$

The count of cumulative months is equal to 6.

$$\text{Score} = 0 \quad (8)$$

The PL indicator is valid throughout the year and is based on a threshold percentile set at the 25th percentile. If the flow in the test year exceeds the 25th percentile during the reference period, the index is assigned a value of 0. A value of 1 is assigned if the flow magnitude is below the 25th percentile. If the cumulative aggregate of the test year is 12, the score is 0. If the cumulative total is less than or equal to 1, the test year score is 1. To compute the score for cumulative totals between 1 and 12, Equation (9) is used.

The cumulative sum for PL is calculated between 1 and 12

$$\text{Score} = 1.0909 - 0.0909 \times \text{cumulative sum} \quad (9)$$

3.2.4. Persistently very low

PVL indicates cessation of flow in the river, which results in river degradation and hence also affect migratory river species and river ecological health. The PVL score for a test year assumes that the flow in the reference period is at or below the 10th percentile, which represents the minimum sustainable flow. To maintain adequate water quality and oxygen levels, the monthly flow should not fall below this threshold. If the mean flow value in the test period is higher than the 10th percentile but lower than the reference period and the monthly flow is still insufficient, a value of 0 is assigned; otherwise, a value of 1 is assigned. If the cumulative total is equal to or greater than 6, the test year score is 0. For seasons with a cumulative sum between 1 and 6, the score is determined using Equation (10).

The maximum annual cumulative total for PVL falls between 0 and 6.

$$\text{Score} = 1 - \frac{\text{Cumulative Total}}{6} \quad (10)$$

3.2.5. Seasonality flow shift

The seasonal flow shift (SFS) sub-indicator detects when HF and LF month change to other periods of the year. Heavily regulated river dam operations entirely change the seasonality of flows in certain heavily regulated rivers. The shifting of HF and LF seasons to other times of the year is not good for the survival of many species. For each month of the reference year, absolute difference in rank in comparison to the rank of the median monthly flow is calculated to estimate the FH score for SFS.

This rank difference is an integer between 0 and 11. For each reference year, the mean deviation of the ranks (a value between 0 and 6) is determined. The mean of the monthly rank deviations is determined for each test year. In comparison to the reference seasonally, a value of 6 indicates complete flow reversal, while a value of 0 indicates no change. The equations for computing a test year's score are given in Equations (11) and (12). When a low raw value of SFS is desired rather than a high value is bad for the other sub-indicators, the equations are modified to account for the reverse order of the SFS distribution.

If the attribute reference distribution percentile range below the 75th percentile.

$$\text{Score} = 1 \quad (11)$$

If the attribute reference distribution percentile range above the 75th percentile.

$$\text{Score} = 4 - 4 \left(\frac{\text{percentile in parameter reference distribution}}{100} \right) \quad (12)$$

3.2.6. Flood flow interval

The objective of the FFI sub-indicator is to detect reduced flood frequency inflows that floodplain wetlands and exceed the banks. FFI measures the time interval between floods, which increases as the frequency of floods decreases. The negative impact on the environment is due to the duration between individual floods rather than the average frequency. It is not possible to predict the flow size that will cause a flood solely based on hydrology. FFI is calculated using monthly time series, and the annual score is the final score. N represents the time (in months) elapsed since a month with a flow equal to or greater than the default threshold of the 1 in 4-year maximum monthly flow. If the N value is less than or equal to 48, then the score value given to FFI is 1. For N greater than 96, a score of 0 is given to FFI. For N values greater than 48 and less than and equal to 98 score value for FFI is calculated using Equation (13).

For $48 < N \leq 96$,

$$\text{Score} = 2 - \frac{N}{48} \quad (13)$$

The schematic flowchart to calculate HF, HM, LF, LM, PL, PH, and PVL is given in Figures 2 and 3, respectively. Table 2 shows the FH score value as well as the corresponding deviation of post-dam flow data from reference flow data.

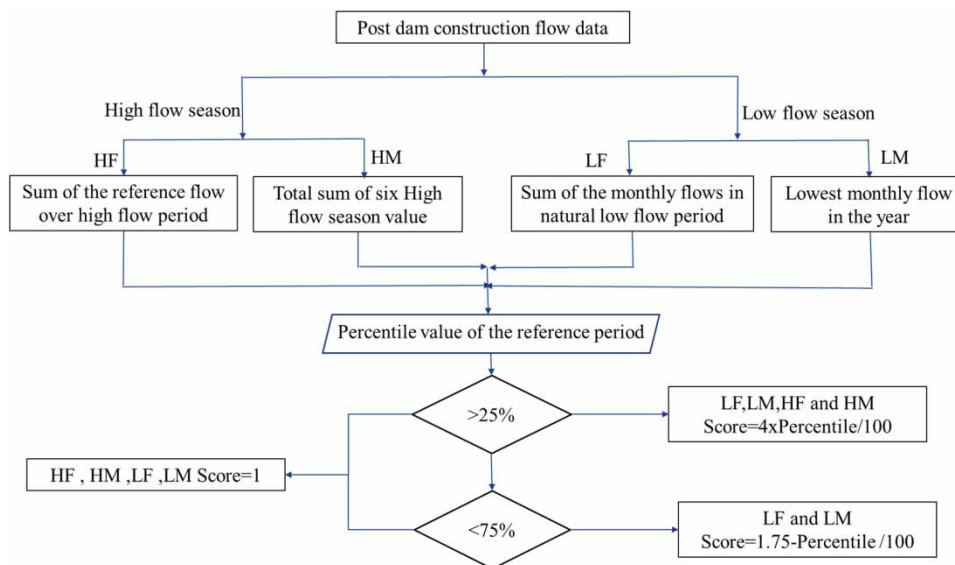


Figure 2 | Flowchart for computation of LF, LM, HF, and HM.

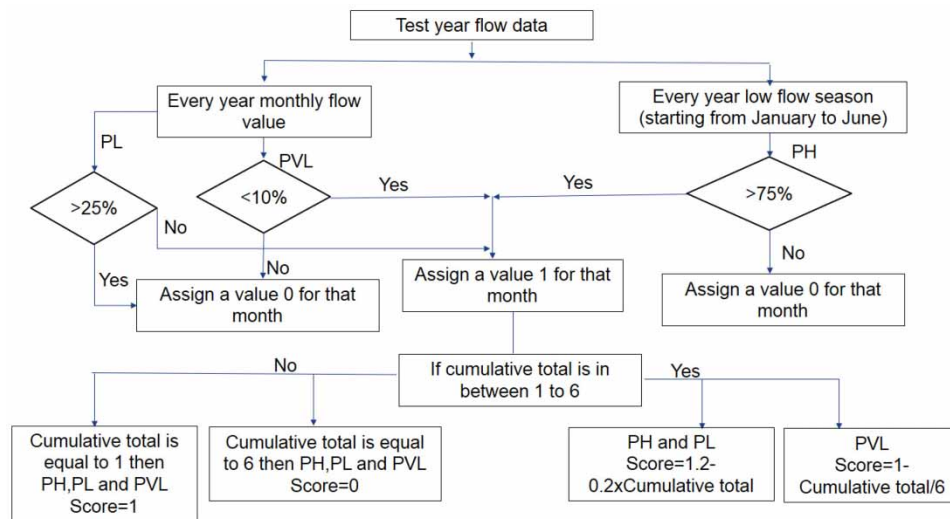


Figure 3 | Flowchart for computing PL, PH, and PVL.

Table 2 | Flow health score and deviation from reference condition

Flow health score	Deviation
0.0–0.2	Very large
0.2–0.4	Large
0.4–0.6	Moderate
0.6–0.8	Small
0.8–1	Very small

3.3. Estimation of EF in the FH system

The environment flow regime can be designed in two ways by using FHS – the MMF and the design flow method. In the MMF technique, EF is calculated based on a set of target scores for the nine indicators or an overall FH score. MMF gives a low-risk condition for EFR calculation. It is difficult to get the flow regime extracted from the MMF method in real-life conditions because it suggests a high flow volume. In the design flow approach, the E-flow regime is determined by user interest, and it is obtained by assuming a particular percentage of the mean reference flow for each month. The design flow method enables one to choose any flow regime by entering the flow for each month and displaying the FH score for chosen flow regime. The new flow data was given as input to FHS to carry out EF analysis and calculate HA. FHS gives the value for HA in terms of the overall FH score. The flowchart of the adopted methodology is presented in Figure 4. For each month, the minimum EF was estimated, considering small alterations for a score value of 0.82. The design flow method was adopted to check for hydraulic parameters like velocity and depth. Design flow was adjusted for low-risk conditions, which is 40% of mean annual flow (MAF) for a score value of 0.62 which signifies a good habitat condition (Tennant 1976). This designed flow was imported in HEC-RAS and was run as the 1D model in a steady-state case to compute water surface profiles.

3.4. HA and non-attainment analysis

HA refers to a modification of flow characteristics relative to reference or natural conditions. To study the effect of the Ujjani dam construction, the modified monthly flow data was divided into a reference period (1966–1980) and a test period (1981–2018), and HA was calculated. FHS calculates the overall score for nine predefined indicators of flow deviation called the FH score, indicating HA of the river. The required minimum EF is determined using the MMF technique for an overall FH score of 0.82. This flow represents a very low-risk EF regime.

Table 3 | Non-attainment and its related alteration condition

Flow non-attainment value	Alteration
0–33%	High
34–66%	Medium
>66%	Low

3.5. Habitat hydraulic analysis

The purpose of a hydraulic model is to establish upper and lower bounds on water depth and velocity for determined EFR flow conditions. This is done in order to maximize the region below the water surface where aquatic life can produce food by ensuring that the stream's flow is at an appropriate velocity and depth. Therefore, it's crucial to pay attention to how quickly the hydraulic parameters change as the discharge occurs. The relationships of the hydraulic analysis are used to determine the physical properties of the Bhima River utilizing the complete range of calculated monthly EFR. 'Instream habitat' in a river setting is influenced by the depth of water, velocity of flow, and surface area. Fishes are more likely to survive in a river with favorable instream circumstances (depth and flow rate) than one with a subpar instream habitat structure. Therefore, utilizing the findings of the hydraulic analysis, an attempt was made in this study to explain the rate at which the computed EFR supplies the minimum and maximum water depth and velocity in the Krishna River. FHS was coupled with HEC-RAS software for calculating hydraulic parameters such as velocity and depth. A variety of fish species such as catfish, carp, *Anguilla*, *Notopterus*, *Silonia*, *Mystus*, and seenghala, generally found in the Krishna River, are considered for analysis. For these species, the minimum and maximum water depth and velocity that should be maintained in the river ranged from 0.35 to 0.8 m and from 0.4 to 0.8 m/s, respectively (Uday Kumar & Jayakumar 2018). Tennant method (1976) is the most widely used method all over the world to design environment flow to sustain the biological integrity of river ecosystems. This method assumes a certain percentage of MAF to sustain the life of the ecosystem. According to Tennant, 10% MAF might be considered the lowest limit for aquatic ecosystem and biological environment survival, 30% MAF is expected to provide a suitable habitat state, and 40% MAF is supposed to indicate a good habitat condition. The instream flow regime for fish, wildlife, recreation, and related natural resources is shown in Table 4 according to Tennant's descriptions. To carry out hydraulic analysis, the EF was arrived at using FHS corresponding to 40% of the MAF for a FH score of 0.62. Hydraulic parameters, namely, velocity and depth, were calculated at discrete cross-sections (0.5 km, 17 km, and 35 km D/s) of the Ujjani dam.

4. RESULTS AND DISCUSSION

The hydrological analysis and steady flow analysis were done by eliminating climate impact and separating the data into pre- and post-impact data, and the results are explained. EFR was estimated by using FHS for two conditions, namely, the MMF and design flow. The minimum environment flow method is used to suggest flow that should be released from the dam to

Table 4 | Environment flow for various conditions in different seasons (Tennant 1976)

Condition	Wet seasons	Dry seasons
Flushing/maximum flow (from 48 to 96 h)	200% mean annual flow (MAF)	200%
The optimum range of flow	60–100% MAF	60–100% MAF
Outstanding habitat	60% MAF	40% MAF
Excellent habitat	50% MAF	30% MAF
Good habitat	40% MAF	20% MAF
Fair or degrading habitat	30% MAF	10% MAF
Poor or minimum habitat	10% MAF	10% MAF
Severe degradation	0–10% MAF	0–10% MAF

maintain the health of the river in good condition. EF values estimated from the design flow method were used for calculating velocity and depth.

To detect the HA and calculate EFR, the effect of climate variability was eliminated by using SPI. The estimated value of SPI was plotted as shown in Figure 5. The result is presented in two parts: hydrological analysis and hydraulic analysis.

4.1. Hydrological analysis

Based on the SPI value, considering only the normal years (i.e., SPI lies -0.99 to $+0.99$), the years 1973, 1974, 1985, 1986, 1989, 2000, 2004, 2008, 2011, 2012, and 2018 were eliminated from streamflow data at Yadgir station. After studying the degree of deviation beyond a range of natural variability for each parameter in FHS, the FH score values were estimated for each parameter based on the range where they fell within the 25th and 75th percentile range of reference distribution. Then the average of the parameters was taken for each year to check for overall alteration for the post-impact period. The calculated value of FH score indicators is provided in the later sub-section dealing with the HA. For the estimated EFR, hydrological and hydraulic analyses are carried out.

4.2. Hydrological alteration

In this study, the impact of dam construction on the flow regime of a river was investigated. To conduct the analysis, it is assumed that the river was in its natural or pristine condition before the dam construction took place. This period was considered to be from the year 1960 to 1980. After the construction of the dam, it is observed that the changes in the river's flow regime are examined by FH scores. The results showed a significant decrease in the FH scores, indicating that the dam construction had a significant impact on the river's flow regime. The FH scores for the year 1981, the first year after the dam operation started, were found as 0.93. This high score suggested that the river was still in its natural condition at that time. However, after that, it is observed that the actual change in the flow regime began from the year 1982.

The mosaic chart for the score parameters is shown in Figure 6. Very large alterations have occurred in terms of indicator LM and large alterations occurred in LF and SFS. The higher alteration in low flow will affect native fish spawning and will encourage the growth of invasive species. From the mosaic chart, the higher alteration was found in SFS for a large part of the post-construction years, which showed a shifting of the high and low flow seasons to other parts of the year, which is not a favorable condition for the survival of many species. Moderate alterations occurred on HF, PL flows, HM flow, and PVL flow. PL values were lower than 0.5 for some post-impact years, implying that flows in those years were noticeably lower than the expected range for two or more consecutive months. The small alteration occurred in FFI, and a very small alteration occurred in PH. After the year 2009, PVL scored zero, which was indicative of the cessation of flow in the river. Hence, the flow regime change was more predominant after the year 2008. However, indices like PH were not significantly impacted. Due to the drastic fall in flow from 2001 to 2018, the FH score varied from 0.36 to 0.17. The analysis revealed that the construction of the dam caused a significant alteration in the riverine function, primarily due to a decrease in the flow quantity from the dam.

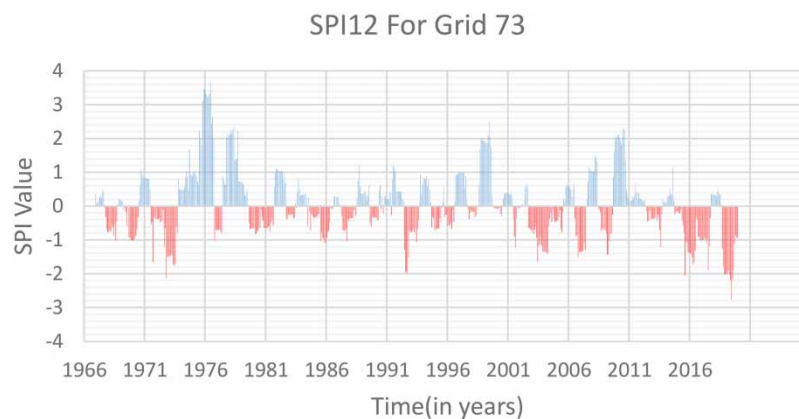


Figure 5 | SPI graph for grid number 73.

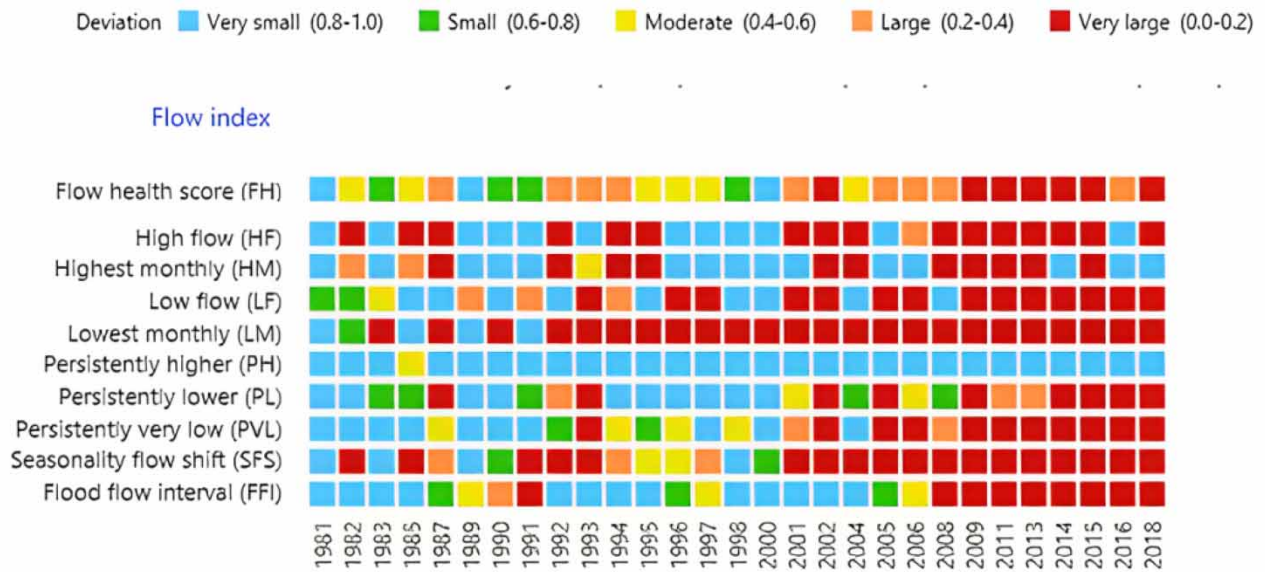


Figure 6 | Mosaic chart for flow health score.

4.3. EFR and non-attainment analysis

In this study, the minimum EF method was utilized to determine the minimum flow release from the dam required to maintain good river health. If the dam authority maintains the calculated minimum flow values in a river, an FH score of 0.82 can be achieved, which is considered a small alteration. The estimated flow value and corresponding non-attainment percentage for each month are presented in Table 5. The non-attainment percentage indicates the percentage of time during which the flow value did not meet the minimum EFR. Upon analyzing the non-attainment percentages, it was found that the non-attainment of flow value for almost all months was greater than 67%. This finding suggests that for most of the months, the actual flow rate was less than the minimum EF required for good river health. Overall, this analysis indicates that the river ecosystem was poor due to insufficient flow from the dam. It highlights the importance of implementing measures to maintain a minimum EF to promote good river health and ecosystem functioning.

Table 5 | Minimum environmental flow and corresponding non-attainment percentage

Month	Minimum monthly flow (m ³ /s)	Non-attainment (%)
January	17.09	79.31
February	5.94	75.86
March	1.84	68.96
April	1.09	82.75
May	3.60	79.31
June	38.4	65.51
July	367.47	72.4
August	357.69	48.27
September	808.72	72.41
October	133.72	65.51
November	62.74	79.31
December	15.15	68.96

4.4. Hydraulic analysis

In order to sustain the ecology along the river, it is required to determine whether the depth of flow and velocity of flow are sufficient after computing the EFR. With the help of the estimated EF values, the hydraulic model calculates the maximum and minimum water depth and velocity limits in the basin.

4.4.1. Minimum flow criteria

From a fisheries point of view, the average velocities should be in the range of 0.6–1.2 m/s, and depth should be in the range of 0.5–0.7 m. Table 6 shows the values of velocity and depth for different considered sections for the estimated values of minimum EF (low risk to river health).

The results of the HEC-RAS modeling for FH Score = 1 showed that the velocity in the system ranged from 0.12 to 2.69 m/s. Water depth varied from 0.02 to 2.46 m. From the steady flow analysis, it was found that the depths and velocity calculated from minimum environment flow (for FH Score of 1) criteria were not providing a conducive environment for fish habitat, especially during the low flow LF season (February, March, April, and May). Based on the hydraulic parameters, it can be observed that the velocity was maintained in the required range, but depth needs to be increased by adjusting the flow regime in FHS. The regime was further designed in FHS utilizing the design flow approach, the outcomes of which are discussed in the following sections. According to the hydraulic analysis, the range was maintained for the velocity, but the depth must be raised by modifying the design flow regime, particularly for LF periods.

4.4.2. Design flow criteria

Based on trial and error, the flow for each month was adjusted, and a new flow regime was designed for 40% of MAF. Tables 7 and 8 show the designed flow and corresponding hydraulic parameters value at different considered sections.

For the first set regime in the design method, the FH score value was 0.67, which indicated a small alteration. The hydraulic parameter velocity through the system ranged from 0.5 to 2.88 m/s. Water depth varied from 0.3 to 2.36 m. Based on the designed flow from Table 7, it can be observed that the velocity was maintained in the range, but depths of flow need to be increased by adjusting the design flow regime, especially for low flow periods or seasons. The regime has been redesigned with special targets for the month of February, March, April, and May.

Considering the hydraulic parameter, the regime was designed again using FHS, which gave the value of the FH score as 0.62. Table 8 gives the values of hydraulic parameters for different months. It is found that the parameter velocity ranged from 0.5 to 2.6, and the depth ranged from 0.35 to 2.27 m. With special consideration of LF month, both the parameters provide a

Table 6 | Velocity and depth for minimum environmental flow (FH score = 1)

Month	Minimum environmental flow (m ³ /s)	Hydraulic parameter					
		0.5 km D/s of Ujjani dam		17 km D/s of Ujjani dam		35 km D/s of Ujjani dam	
		Velocity (m/s)	Depth (m)	Velocity (m/s)	Depth (m)	Velocity (m/s)	Depth (m)
January	18.924	0.57	0.29	0.52	0.43	0.46	0.49
February	6.576	0.28*	0.1*	0.33*	0.24*	0.4	0.27*
March	2.042	0.2*	0.03*	0.17*	0.1*	0.4	0.14*
April	1.203	0.12*	0.02*	0.12*	0.05*	0.4	0.1*
May	3.946	0.15*	0.04*	0.25*	0.17*	0.34*	0.2*
June	42.515	0.98	0.49	0.72	0.67	0.62	0.75
July	430.324	2.84	1.66	1.91	2.35	1.89	2.31
August	418.873	2.81	0.64	1.89	2.1	1.86	2.28
September	889.290	3.87	2.46	2.64	2.31	2.69	3.34
October	156.591	1.83	0.98	1.23	1.35	1.14	1.42
November	73.474	1.31	0.66	0.9	0.9	0.79	0.99
December	17.423	0.54	0.27	0.51	0.41	0.45	0.47

Values marked with * are not providing a conducive environment for fish habitat.

Table 7 | Recommended flow regime (40%, FH score = 0.67) and corresponding depth and velocity

Month	Design flow (m ³ /s)	Hydraulic parameter					
		0.5 km D/s of Ujjani dam		17 km D/s of Ujjani dam		35 km D/s of Ujjani dam	
		Velocity (m/s)	Depth (m)	Velocity (m/s)	Depth (m)	Velocity (m/s)	Depth (m)
January	25.1	0.69	0.4	0.58	0.51	0.51	0.57
February	22.6	0.64	0.34	0.56	0.5	0.5	0.54
March	20.2	0.58	0.31	0.54	0.45	0.5	0.51
April	19.9	0.58	0.3	0.53	0.44	0.5	0.5
May	20.5	0.59	0.31	0.54	0.45	0.47	0.51
June	39	0.93	0.46	0.69	0.64	0.6	0.72
July	201	2.04	1.12	1.37	1.01	1.3	1.6
August	108	1.55	0.81	1.05	1.11	1	1.19
September	446	2.88	1.69	1.94	1.4	1.92	2.36
October	107	1.55	0.81	1.05	1.1	0.95	1.19
November	27.8	0.75	0.38	0.61	1.53	0.53	0.6
December	23.2	0.65	0.34	0.57	0.48	0.5	0.55

Table 8 | Recommended flow regime (40%, FH score = 0.62) and corresponding hydraulic parameters

Month	Design flow (m ³ /s)	Hydraulic parameter					
		0.5 km D/s of Ujjani dam		17 km D/s of Ujjani dam		35 km D/s of Ujjani dam	
		Velocity (m/s)	Depth (m)	Velocity (m/s)	Depth (m)	Velocity (m/s)	Depth (m)
January	31	0.81	0.4	0.63	0.57	0.55	0.64
February	28.6	0.76	0.38	0.61	0.54	0.53	0.61
March	27.3	0.74	0.37	0.6	0.51	0.52	0.6
April	24.8	0.69	0.35	0.58	0.46	0.5	0.57
May	25	0.69	0.35	0.56	0.5	0.51	0.57
June	37	0.9	0.45	0.6	0.62	0.6	0.7
July	190	1.99	1.08	1.34	1.5	1.26	0.56
August	108	1.55	0.81	1.05	1.11	0.95	1.19
September	440	2.6	0.68	1.78	2.27	1.91	1.69
October	107	1.55	0.81	1.05	1.1	0.95	1.19
November	27.8	0.75	0.38	0.61	0.53	0.53	0.6
December	24.2	0.67	0.35	0.57	0.5	0.5	0.56

conductive environment for each month and each section, especially in the habitat context. The results of steady flow for this flow value showed that the values of average velocities and depth are under the considered range for the fishes.

From the adjusted design discharge, the inflection flow value is 24.8 m³/s, giving a satisfactory value of depth and velocity for all the months. Keeping this in view, the minimum suitable flow releases from the dam should be above 24.8 m³/s in the lean flow period. Due to the drastically reduced number of suitable habitats, the reduction in discharge below this inflection point is regarded as hazardous for the species under consideration.

5. CONCLUSION

The hydrologic analysis showed that from the pre-impact period to the post-impact period, changes in the hydrology of the Bhima River had taken place. The following conclusions are made from this study:

- Significant hydrologic changes were brought about along the Bhima River as a result of the construction, shown by the significant drop in FH score value from 1981 to 2018 from 0.93 to 0.17.
- According to the seasonal analysis, as seen by the SFS parameter showed that for more than 18 years, of FH score is almost equal to 0 for the post-construction years. It indicates improper dam operation caused the high seasonal flow shifting.
- The minimum flow requirement of the selected fish species found in the river was estimated to be 24.8 m³/s during the dry season (i.e., March, April, and May) of downstream of the Ujjani dam.
- The indicators High Flow, Low Flow, and SFS illustrate the basic flow components of a natural flow regime. A higher alteration in the low flow indicator showed that the river was mostly dry during the dry season for post-dam construction years.

5.1. Suggestion for future study

- For the EFR study, more stream gauging stations should be set up so that minimum EFR to maintain pre-development ecology can be ensured.
- The upstream flow conditions for this study in HEC-RAS analysis have been assumed as unchanged, but they vary from section to section. Accordingly, further research can be taken with varying flow conditions for each section considering LULC and river topographical change along the river boundary.
- For this study, a selective fish species has been considered. Future research may take other native plants and species to maintain biodiversity.
- EF criteria can be studied for different climate scenarios using various climate change models.
- For different considered scenarios, the flow can be predicted, and the hydrological change in the river regime can be examined to determine which possibilities will result in acceptable FH scores. As a result, a framework for cooperative management of this transboundary river and the exchange of hydrological data between states will be developed.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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