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Assessment of Temporal Flow Variations Due to Dam Operation– A Case Study of Bargi Dam, Jabalpur District, India

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Abstract

The case study dam project, Bargi Dam, situated in Madhya Pradesh, India, is among the initial major dams, that have already been constructed as part of a proposed series of thirty dams along the Narmada River. This dam was operational since the year 1988. The temporal fluctuations in the flow were assessed by applying the Range of Variability Approach (RVA) using the Indicators of Hydrologic Alteration (IHA) software. When assessing the impact of the dam on the flow regime, duration of 13 years for both the ante- and post-impact periods have been considered. The Range of Variability method has utilized a set of 33 parameters to measure the hydrologic alteration occurred due to the dam operation. The optimal values for these parameters can be achieved by adjusting the dam's discharges and assessing the resulting impacts on the downstream environment. Through this method, temporary environmental flow requirements (EFRs) may be arrived at for a given project site.

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Keywords

Temporal Flow Variations;
Range of Variability Approach;
Environmental Flow Requirements;
Indicators of Hydraulic Alteration.

Abbreviations

RADPFI : Rural Area Development Plan Formulation and Implementation guidelines
C.G.W.B : Central Ground Water Board
LBC : Left Bank Canal
RBC : Right Bank Canal

Introduction

A nation's progress depends greatly on management of its water resources, which must be done with great care. In India, scenario regarding water resources is represented in Table 1. Total yearly input of water is estimated as 4000 km^3 occurring through precipitation (rainfall and snowfall) and out of that 53% either get lost through the evaporation process or turn into soil moisture. Remaining part, about 47%, which become the flow in the rivers. Out of the total precipitation received, only about 28% is becoming utilisable as surface water resource (61%)

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and ground water resource (39%). By looking at the projected water demand in the year 2050 (Table 1), which is 1450 km^3, the estimated deficit works out as 327 km^3. This deficit may reduce to 127 km^3, if 200 km^3 of additional utilisable water resources is created through trans-basin transfers.

Table 1: Estimation of Water Deficit in the case of India (year 2050)[24]

Sl.No.		Quantity (km^3)	Percentage
1	**Precipitation (Rainfall + snowfall) per Year**	4000	100
	Evaporation + Soil Water	2131	53.3
	Average Potential flow in rivers per Year	1869	46.7
2	**Quantity of Utilisable Water Resources**	1123	28.1*
	Surface Water	690	61.44**
	Ground Water	433	38.55**
3	Storage Created w.r.t Utilisable Water	253.31	36.72^^
	Storage Under Construction w.r.t Utilisable Water	50.737	7.35^^
4	**Estimated Water Demand as of the Year 2050**	1450	129***
	Estimated Water Deficit as of the Year 2050	327	29***

*Based on the annual precipitation as 100%, ** by considering 1123 km3 as 100%,
***based on utilisable water resources as 100%, ^^by considering surface water as 100%

India's extensive network of rivers shows a significant seasonal variation in its flows because of the country's seasonal rainfall patterns and protracted dry spells. The Indian mainland is drained by about 120 small (drainage area upto 2,000 km^2), 45 medium (drainage area 2,000 to 20,000 km^2), and 15 big (drainage area >20,000 km^2) rivers, in addition to the many ephemeral streams in the western arid region.[1] The nation is frequently divided into 19 major river basins/drainage regions, which are depicted in Figure 1 for large-scale assessments of water resources. Basins most of the major Rivers including Narmada have been strongly affected due to flow fragmentation and regulation brought out by dams. Numerous rivers in India do not flow into the sea for most of the year and are subject to water stress due to several factors, including their geographic position, changes in land use and cover in the basins, a number of regulating systems, climate change, agricultural practices, etc. [2] Therefore, it can be expected that in case of such rivers, the needs of the river ecosystems are also not being met.

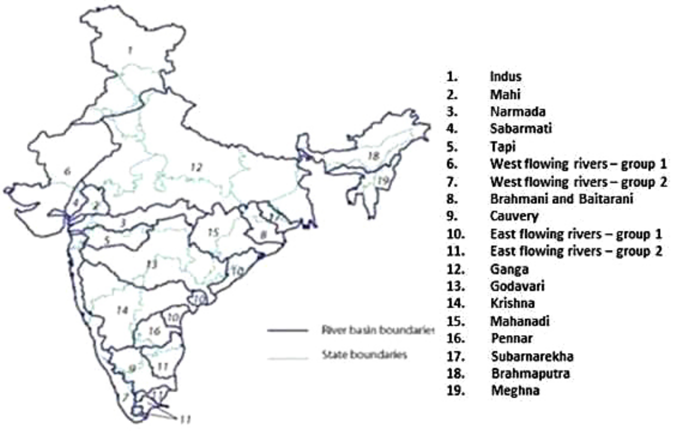

Fig. 1: Major River Basins in India

Dams have been providing multiple benefits to the humans such as irrigation water supply, drinking water supply, power generation, control of floods, industrial water supply, fisheries, navigation and drought mitigation.[3,4] Out of the total irrigated land area of the world, about 30-40% is catered by the large dams.[3] Even though the reservoirs generated through the dams provide multiple benefits, its major drawback is the need to resettle the population having affected by the resultant inundation.[4] Water quality parameters such as temperature, turbidity etc. get affected because of the dam's storage, which will exert negative impacts on its downstream section. It may take coverage of large distances for these parameters to get back to suitable range for the aquatic flora and fauna[3,5] Hydropower plants inject cold water from deep in the reservoir into the warmer waters of the receiving environment, causing temperature and dissolved oxygen oscillations in the downstream section of the dam, especially in summer months.[6] Flow in a river downstream of a dam is composed of the dam releases, base flow contribution and flows contributed by the tributaries (if any) situated between the dam site and the gauging site.

In this paper, Range of Variability Approach (RVA) has been applied in case of a multi-purpose dam project namely 'Bargi', located in Jabalpur District, Madhya Pradesh state for assessing the alteration of flow regime after its construction across the Narmada River. Through this method, temporary environmental flow requirements (EFRs) may be arrived at for a given project site. In the hydraulic data analysis, there is a parameter defined as the hydraulic periodicity, which is a time series pattern with regular intervals. More specifically, a time series is cyclical if its repetition intervals are not constant and cannot be exactly characterized. Conversely, seasonal time series reoccur at constant and well-defined intervals. Due to their inconsistency and tendency to repeat over long periods of time, cyclical patterns are harder to discover and require longer period data to identify.[7] The study8 demonstrated that the hydraulic periodicity may be used to improve the prediction efficiency of Range of Variability Approach (RVA). In the study[8] it has also been shown that for getting better accuracy in determining the degree of hydraulic alteration between the ante-impact and the post-impact periods, the length of data set to be considered in both periods should be either equal to the periodicity length or be its multiple.

Based on the data procured from 17 fish sampling stations along the Narmada River,9 has observed that there is a decline in the genetic divergences on the lower stretches of the Narmada River, which could be due to the obstruction to fish migrations and the fragmentation of their habitats due to the construction of large dams such as Bargi, Indira Sagar and Sardar Sarovar. The level of genetic divergence increases with the hierarchy of the taxonomic level (genus, family, order), which indicates that at the lower taxonomic levels, there have been loss of diversity. In case of the Narmada River, fish species such as Baam is in vulnerable category and other species namely Godar and Phonda are in near threatened category as per the International Union for Conservation of Nature (IUCN).[9,10]

Environmental Flows – Definition

The oraganisations involved in this field have provided several definitions for Environmental Flow. Environmental flow has been defined more precisely as the "quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems, which in turn support human cultures, economies, sustainable livelihoods, and well-being" as per the Brisbane Convention on Environmental Flows.[11] The environmental flow assessment methods have been broadly classified into the following classes: hydrological, hydraulic rating, habitat modelling, and holistic. The quantity and suitability of instream physical habitats are used in habitat simulation methods, hydrologic data is used in hydrologic methods, hydraulic data is used in hydraulic rating methods, multi-disciplinary expertise and inputs are used in holistic methods. There has been a lot of research on these topics around the World, but more were forthcoming from countries such as USA, Australia, and South Africa.

The assessment process followed for arriving at the flow regime which meet the needs of the aquatic ecosystems at an acceptable level is defined as the Environmental Flow Assessment (EFA).[12] The aspects of the flow regime such as magnitude, frequency, timing, duration and the rate of change are termed as the Environmental Flow Requirements (EFR).[13]

Environmental Flow Assessment Methodologies in Indian Context

The theory of environmental flows in Indian rivers has been hindered by a lack of information, understanding of hydrology-ecology connections, and legislative support. For the existing river valley / hydropower projects, apart from the notification for regulation of environmental flow within Ganga River,[14] no similar regulations exist at present for any other river basins within India. As per the notification on environmental flows for Ganga River, dated 9th October 2018, all existing, under-construction, and prospective projects must meet minimal environmental flow. In case of the projects along the Ganga River from the glaciers to Haridwar, environmental flow is a percentage of monthly average flow observed during each 10-daily period during dry, lean and high flow seasons. Dry season is from November to March, lean season is during the months of October, April and May and the high flow season is from June to September. The environmental flow has been given in cumec (m^3/s) for projects from Haridwar to Unnao in Uttar Pradesh for the monsoon (June–September) and non-monsoon (October–May) seasons. For the proposed river valley/hydropower projects to receive environmental clearance (EC), the relevant standard Terms of Reference (ToR) must be followed, which stipulates distribution of 90% dependable year flow into four parts with 30% of it in monsoon season, 20% in lean season and 25% in each of non-monsoon & non-lean seasons. The Terms of Reference (ToR) adopted by the working group to advise the Water Quality Assessment Authority (WQAA) of Ministry of Water Resources, Government of India on the minimum flows in the rivers was to include water quality aspects in the study for fixing the minimum flows of the rivers in India. The working group suggested using a method like Tennant Method as there is not enough data to implement sophisticated methods. Compared to other widely used approaches, this method is simpler in terms of assessment. The report[14] considered flushing and low flows, which are the two out of the four components of minimum flows, the others being special purpose and impoundment level maintenance. The same research recommends using naturally occurring minimum flow with 99% exceedance to sustain the in-stream environment. A range of minimum flushing flows may be advised during floods. Working group study recommends differing minimum flow recommendations for Himalayan and other rivers due to the former's increased snow melt contribution. For non-Himalayan rivers with 10 daily flow data, low flow in any ten-day period should not be less than observed flow with 99% exceedance. If ten daily flow data are unavailable, 0.5% of 75% dependable annual flow in cumec (m3/s) is used. There should be one monsoon flushing flow of at least 600% of 75% reliable annual flow in cumec (m3/s). River flow must be sufficient for self-purification during religious mass gatherings and sewage treatment facility discharges.

While implementing the minimum flow, the working group has identified following constraints.

1. Water for ecological needs (minimum flow) must be managed by not destroying the existing irrigation system.
2. Irrigation use should be given priority over ecological needs.

These are because India has a predominantly agriculture-based economy.

Bargi Dam

220 56' 30'N latitude and 790 55' 30 E longitude are the locations of the Bargi dam. Bargi is a 5374.39 m earth-masonary dam. The dam is 43 km downstream of Jabalpur City and has a 14556 Sq.km. watershed. The reservoir can hold 3.92 billion cubic meters (BCM) in gross storage, 3.18 BCM in live storage, and 0.740 BCM in dead storage. The masonry dam could reach 69.80 meters in height, compared to the earth dam's maximum height of 29 meters. The reservoir has three levels: 425.70 meters at its maximum, 422.76 meters when full, and 403.55 meters at dead storage. The project report[15] states that the reservoir should last for 100 years. 1988 saw the opening of the Bargi Dam and the dam administration has constructed two important irrigation projects: the Bargi Diversion Project and the Rani Avantibai Lodhi Sagar Project.[15] This dam project is intended to have multiple uses, including irrigation, hydropower production, and the supply of water for residential and industrial uses. It is the first significant dam completed in the Narmada River Basin[16] and it features a 90 MW riverbed power plant and a 15 MW canal-based power station on the left bank canal system. As a result, the project's total installed capacity vis-à-vis power production is 105 MW. 2574 and 1570 Sq.km are the left bank canal's

gross and culturable command areas respectively. The right bank canal's yearly water supply for home usage is intended to be 116 million cubic meters (MCM). 54 MCM of water is required yearly for domestic water supply from the left bank canal. Table 2 presents the Bargi dam's water balance scenario.

Table 2: Water Balance Scenario of Bargi Dam

	Per Annum in BM^3
Total 75% Dependable Yield	5.4471
Quantity Reserved for Irrigation	2.08
Return Flow from Irrigation	0.21
Therefore, total yield for planning	3.5769
Uses	
From the Reservoir	
Hydropower	3.115
Evaporation Loss	0.295
From the Canals	
Domestic & Industrial	0.17
Groundwater Utilisation	0.808
TOTAL	4.388

The dam of concern has the discharges in the form of hydropower plant discharges (from the riverbed power plant) and the dam releases during the rainfall season. The volumetric capacity of the Bargi reservoir is analysed as reducing at the rate of 1% per annum and the total design life span of the dam has been estimated as 100 years.[15]

Range of Variability Approach

Range of Variability Approach considers a comprehensive set of 33 parameters called as Indicators of Hydrologic Alteration (IHA)[17,18] parameters. These parameters include the rate at which water conditions fluctuate, the frequency and length of high or low flow episodes, the timing of extreme water conditions throughout the year, and the magnitude of monthly and annual water conditions. Daily discharge values during ante- and post-impact are the only inputs required for applying this approach. To exclude the effects of natural runoff and climate changes from stream flows,[19] recommend using the same time-period for both baseline and developed conditions, which is in the range of 10–20 years. Indicators of Hydrologic Alteration (IHA) software was used to apply this approach.[17] The Range of Variability Approach (RVA) has been used to quantify the alteration of the hydrological regime, and the Indicators of Hydrologic Alteration (IHA) parameters have been known to possess considerable ecological significances.[20]

IHA parameters and their Ecological Significances

The study[13] demonstrated that, monthly water conditions severity affects aquatic species habitat availability and plant soil moisture availability. They limit predator access to breeding places and terrestrial animal water supply. They affect photosynthesis, oxygen, and water temperature. Annual severe water conditions influence competitive, ruderal, and stress-tolerant species. They facilitate plant colonization, structure aquatic ecosystems, and shape river channel morphology, while reducing soil moisture stress, animal dehydration, and plant anaerobic stress. They affect nutrient transfers between rivers and floodplains and aquatic stressors such low oxygen and concentrated pollutants. They also help distribute plant populations in lakes, ponds, and floodplains and aerate channel sediment spawning beds. Organism life cycles are affected by annual severe water conditions. They assist species procreate and avoid predators. High and low pulse frequency and duration provide aquatic creature habitats and aid river-floodplain nutrient transfers. The frequency and rate of water condition adjustments prevent plant drought stress.

Range of Variability Approach

Each of the five IHA parameter groups—which address (i) magnitude, (ii) timing, (iii) frequency, (iv) duration, and (v) rate of change—is ecologically significant in relation to the river ecology. Comparing post-impact IHA parameter fluctuation to ante-impact natural fluctuation assesses the degree to which natural flow regimes have been altered. The Hydrologic Alteration Factor (HAF) for post-impact stage flow values is estimated by the IHA software, as follows

Hydrologic Alteration Factor = (observed frequency – expected frequency) / (expected frequency)

Expected frequency = No. of values in the specific RVA category in the ante-impact stage x (post-impact years/ante-impact years)

The three RVA categories are
Low: any value less than or equal to 33 percentile value

Middle: any value falling between the 34 and 67 percentile values

High: any value greater than 67 percentile value

In case of Indian rivers, the water year is considered from 1st June to 31st May. For conducting Range of Variability analysis using Indicators of Hydrologic Alteration (IHA) software, two time periods have been considered

Ante-impact stage (baseline condition): 01-06-1971 to 31-05-1984 (13 years)

Post-impact stage (developed condition): 01-06-1994 to 31-05-2007 (13 years)

Since the ante-impact daily discharge data from Jamtara gauging station, which is located at about 16 km downstream of the dam was not available, catchment ratio method has been adopted here. As per this method, the daily discharge values recorded at the Barmanghat gauging station, which is the next gauging station along Narmada River after Bargi, have been reduced by 56% as the ratio of catchment area from the origin of Narmada River upto Barmanghat is 1.78 times of that up to Bargi dam site.

Results and Discussion

The IHA parameters from the groups I to V (Table 3) were compared between the ante-impact (01-06-1971 to 31-05-1984) and post-impact (01-06-1994 to 31-05-2007) stages for the daily discharge values at the Jamtara gauging station. The flow variations due to Bargi dam have been shown across the five groups of the IHA parameters.

Flow Variations due to Bargi Dam

Group I: Monthly Water Conditions Magnitude

The median flow values for each calendar month are referred to as the monthly water conditions, and there will be 13 of these values for every month in each stage. Its coefficient of dispersion (C.O.D.) and median, minimum, and maximum values have been determined based on these series of median values for the pre and post dam stages. These are shown in Table 3. In the ante-impact stage, with values of 4.65 cumec and 691.2 cumec, respectively, May had the lowest median monthly flow value while August had the highest. The C.O.D. value for March and June were the lowest at 0.55, while the values for July and October were the highest at 1.75. In the case of May, the minimum thresholds of the maximum and minimum values (2.5 and 11 cumec, respectively) were observed. Conversely, maximum thresholds for the minimum and maximum values (99.6 cumec and 1190 cumec, respectively) were observed in the month of August. The operation of the storage-based hydropower station during the post-impact stage has resulted in a median monthly water condition of 178 cumec. In April, the minimum threshold of the minimum value was recorded as 47 cumec, and in August and December, the maximum threshold of the minimum value was recorded as 178 cumec, which is different from the pattern observed in the ante-impact stage. As far as the maximum value is concerned, the month of June (181 cumec) saw the lowest threshold and the month of September (1229 cumec) saw the highest threshold.

The month of May had the lowest low and high RVA boundaries (3.46 and 5.62 cumec, respectively), whereas the month of August had the highest low and high RVA boundaries (446.3 and 884.5 cumec, respectively). In case of the hydrologic alteration, except in the case of July, for all the other months, in the middle category (values falling within the range from 34 percentile to 67 percentile), the HAF had (-) values indicating that the values within this category have reduced in the post-impact stage in comparison to the ante-impact stage.

With reference to the Figure 3, in the high RVA category, months excluding July, August and September have shown positive hydrologic alteration factor (HAF) indicating rise in the number of such flow values. The trend observed in case of the middle RVA category has been the same as that in the low RVA category with the HAF recording a value of (-1.0) for the months from October – June. The range of HAF values were (-0.75 – +1.5) for the low RVA category and (-0.5 - -0.1) for the high RVA category. The HAF values within the high RVA category was +2.25 for all the three summer months.

Group II: Severity and Duration of Annual Water Extremes

Extreme water conditions refer to maxima, minima, zero flow and base flow index. From the Table 3, the median values of the all the maximum values have shown a reduction to the extent of 50.86%, 51.96%, 57.84%, 52.2% and 46.03% respectively. With reference to Figure 3, in case of 30-day and 90-day minimum values, 100% of them were falling within the high RVA category and for 1,3 and 7-day minimum, 61.54%, 84.62% and 92.31% of the values were falling within the high RVA category. For 1,3-,7-,30- and 90-day maximum values, only about 10% of the values were falling within the high RVA category and remaining were distributed across the other two RVA categories viz. low and middle.

In case of the parameters within group 2, except for 30 and 90-day minimum values, rest all parameters have shown an increase in the C.O.D value. The base flow index has shown a rise between the ante and post dam stages primarily due to the increase in 7-day minimum value, which is used in its calculation. The minimum values show shift towards high RVA categories. On the other hand, the maximum values show a shift towards low RVA categories. Consistent with the median monthly discharge of July - September, the maximum values show a shift towards low RVA category. The range of HAF values within the low RVA category were (+0.5 - +1.0) and the same within the high RVA category were (-0.5 - -0.75). On the other hand, the minimum values show shift towards high RVA category. The range of HAF values within the high RVA category were (+1 - +2.25) and the same for the low RVA category were (+0.25 - -1.0).

Between the ante and post dam stages for the Jamtara river gauging station, the median flow values have shown increase in case of the yearly minimum flow values viz. 2.85 cumec and 99 cumec in case of yearly 1-day minimum, 2.95 cumec and 99 cumec in case of yearly 3-day minimum, 3.157 cumec and 99 cumec in case of yearly 7-day minimum, 4.715 cumec and 113 cumec in case of yearly 30-day minimum and 6.354 cumec and 170.2 cumec in case of yearly 90-day minimum, all values being the ante-impact and post-impact stage values respectively. To the contrary, in case of the yearly maximum flow values, the median flow values have shown a reduction, viz. 6188 cumec and 3041 cumec in case of the yearly 1-day maximum, 4380 cumec and 2104 cumec in case of the yearly 3-day maximum, 3079 cumec and 1298 cumec in case of the yearly 7-day maximum, 1277 cumec and 586.5 cumec in case of yearly 30-day maximum and 642.4 cumec and 346.6 cumec in case of yearly 90-day maximum, all values being the ante-impact and post-impact stage values respectively.

Group III: Annual Extreme Water Conditions Timing

The timing of yearly extreme water conditions, referring to the Julian date when the yearly 1-day maximum and yearly 1-day minimum flows have taken place, is referred to as the yearly extreme water conditions timing.[13] In group 3, there is an increase (from 31% to 38%) in the values falling within the high RVA category for the date of minimum value, which implies that in the post dam stage, the 1-day minimum flow has occurred more beyond the median value (Julian date of 153) when compared to the ante-impact stage. In the case of high RVA category, the HAF of the timing of minimum flow was equal to (+0.25). But, in case of the timing of maximum flow, more values were in the low RVA category in comparison to the ante-impact stage (46.15% and 30.76% respectively), with the HAF being (+0.5). From the Table 3, the timing of minimum flow has remained almost the same but the minimum threshold of timing of minimum flow has shown a shift of 133 days towards the beginning of the year in the post-impact stage.

Table 3: Non-parametric statistics for IHA parameters during Ante and Post Impact Stages in case of Bargi Dam

	Ante-impact stage: 1972-1984				Post-impact stage: 1995-2007				Boundaries of RVA Categories		Hydrologic Alteration
	Median Value	Coefficient of Dispe -rsion	Minimum Value	Maximum Value	Median Value	Coefficient of Dispe -rsion	Minimum Value	Maximum Value	Low RVA Category	High RVA Category	Middle RVA Category
Group I											
June	5.20	0.55	3.10	99.60	178.00	0.47	87.50	181.00	4.60	6.26	-1.00
July	201.90	1.75	48.60	619.60	178.00	0.00	91.00	203.80	130.80	350.80	1.40
August	691.20	0.91	99.60	1190.00	178.00	0.18	178.00	563.00	446.30	884.50	-0.80
September	403.80	1.11	44.00	724.90	178.00	0.32	178.00	1229.00	243.40	477.80	-0.80
October	96.30	1.75	13.85	273.40	178.00	0.09	178.00	201.00	69.36	155.20	-1.00
November	38.68	1.00	8.90	99.60	178.00	0.13	178.00	255.00	30.57	55.17	-1.00
December	22.25	0.91	7.65	43.10	178.00	0.16	178.00	212.00	16.83	35.49	-1.00
January	17.65	0.71	5.75	26.55	178.00	0.59	99.00	208.00	14.65	23.03	-1.00
February	16.05	0.74	5.00	41.53	178.00	0.12	99.00	207.00	11.17	20.38	-1.00
March	8.65	0.55	4.20	20.25	178.00	0.10	82.00	203.00	7.49	10.33	-1.00
April	5.88	0.87	3.50	12.50	178.00	0.08	47.00	199.00	5.20	8.44	-1.00
May	4.65	0.70	2.50	11.00	178.00	0.04	99.00	188.00	3.46	5.62	-1.00
Group II											
1-day minimum	2.85	0.67	0.00	5.35	99.00	1.22	0.00	178.00	2.55	3.41	-1.00
3-day minimum	2.95	0.66	1.57	5.45	99.00	0.96	0.00	178.00	2.56	3.48	-1.00
7-day minimum	3.16	0.60	1.68	5.60	99.00	0.74	0.00	178.00	2.79	3.60	-1.00
30-day minimum	4.72	0.71	2.48	10.90	113.00	0.66	46.13	180.00	3.46	5.74	-1.00
90-day minimum	6.35	0.69	3.35	12.75	170.20	0.17	83.96	191.00	5.68	8.35	-1.00
1-day maximum	6188.00	0.98	99.60	10330.00	3041.00	1.72	178.00	9834.00	3040.00	7627.00	0.20
3-day maximum	4380.00	1.01	99.60	6668.00	2104.00	1.93	178.00	7188.00	1843.00	5534.00	0.20
7-day maximum	3079.00	0.84	99.60	4114.00	1298.00	1.91	178.00	4431.00	1385.00	3318.00	0.00
30-day maximum	1227.00	0.72	99.60	2186.00	586.50	1.73	178.00	1955.00	907.20	1496.00	-0.40
90-day maximum	642.20	0.91	99.60	1154.00	346.60	1.28	176.00	920.80	470.10	845.30	-0.20
Zero-day count	0.00	0.00	0.00	1.00	0.00	0.00	0.00	10.00	0.00	0.00	-0.33
Index of base flow	0.02	0.66	0.01	0.10	0.41	0.87	0.00	0.99	0.01	0.03	-1.00

Group III											
Date of minimum	154.00	0.04	138.00	305.00	153.00	0.34	5.00	315.00	150.90	158.80	-0.20
Date of maximum	231.00	0.07	153.00	253.00	236.00	0.19	153.00	262.00	222.20	238.70	-0.60
Group IV											
Low pulse count	3.00	1.17	1.00	8.00	0.00	0.00	0.00	5.00	2.62	4.38	-1.00
Low pulse duration	12.00	1.88	1.00	90.00	1.50	1.50	1.00	4.50	3.62	19.28	-0.80
High pulse count	3.00	0.83	0.00	6.00	2.00	2.50	0.00	11.00	2.00	4.00	-0.63
High pulse duration	9.50	5.01	1.00	121.00	54.50	1.85	3.00	126.00	6.65	39.75	-0.75
Group V											
Rise rate	2.90	1.29	0.35	7.93	78.00	3.57	2.44	1416.00	1.49	3.95	-0.80
Fall rate	-0.95	-1.11	3.40	-0.25	-78.00	-2.04	-1416.00	-4.00	-1.21	-0.68	-1.00
Number of reversals	138.00	0.25	55.00	182.00	12.00	15.25	1.00	207.00	130.70	155.40	-0.80

*(-) sign indicates a decrease in value, C.O.D is Coefficient of Dispersion

Group IV: Frequency and Duration of High and Low Pulses

While formulating the analysis criteria, since the type of statistical analysis conducted was non-parametric in nature, the threshold of high and low flood pulses has been set as median ± 25 percentile.[13] The low pulse count has considerably got shifted to the low RVA category with the HAF being estimated as (+2.0) This points to decline in this parameter in comparison to the ante-impact stage. There has not been much difference in case of the low pulse duration between both the stages with (30.76%) of the values falling within the low RVA category in both the stages. Of the remaining values, there was only (7.69%) of them falling with in the high RVA category in comparison to (38.46%) in case of the ante-impact stage. In the case of high pulse count, there has been an increase in number of values falling within the high and low RVA categories, with the increase in the percentages being 15.28% and 23.08% respectively between the pre and post dam stages.

Group V: Rate and Frequency of Water Condition Change

As per[13] the hydrologic record is divided into rising and falling stages in order to identify reversals as given in group 5. These stages indicate instances of positive or negative daily fluctuations in flows. The rise rate values have increased within the high RVA category with the change being 61.54%. On the other hand, the fall rate values within the low RVA category have shown an increase to the extent of 96%. Both were in comparison between the ante and post dam stages, with the trend showing clear gain in the daily flow values in the post-impact stage. From Table 3, the median value of rise rate and fall rate in the ante-impact stage were +2.90 and (-)0.95 respectively. But this has significantly increased to +78.00 and (-)78.00 in the post-impact stage. Number of reversals have also shown drastic reduction from 138 to 12 between the pre and post dam stages.

With reference to Figure 2, showing the flow duration curves (FDCs) representing the temporal flow regime changes, following inferences can be made: The graph depicting FDC of November month in the ante-impact stage is consistently lower when compared to same in the post-impact stage. Same can be observed in case of the graphs depicting the months of December and February in the post-impact stage (1995-2007). But, in case of January, in the post-impact stage, the flow values have merged with those of ante-impact stage values beyond >90% exceedance probability. In the case of August, in the post-impact stage, the values go higher when compared to the ante-impact stage beyond 90% exceedance probability. In case of July, the post-impact stage values are higher than the ante-impact stage values upto 10% exceedance probability, after that they go below the ante-impact stage values upto 80% exceedance probability, beyond which the post-impact stage values again go higher. In case of June, upto 15% exceedance probability, the ante-impact stage values are higher when compared to the corresponding post-impact stage values. But this trend reverses beyond this threshold. In case of March, April and May, the post-impact stage values are considerably higher when compared to the corresponding monthly values in the ante-impact stage. In case of September, the post-impact stage values are higher when compared to the ante-impact stage values upto around 15% exceedance probability, beyond that the ante-impact stage values are higher upto around 72% exceedance probability, after that both the graphs get merged with each other. In case of October, the post-impact stage values are higher when compared to the corresponding ante-impact stage values up 15% exceedance probability, then the ante-impact stage graph goes higher upto around 28% exceedance probability. Beyond this point, the post-impact stage values are consistently higher when compared to the ante-impact stage values.

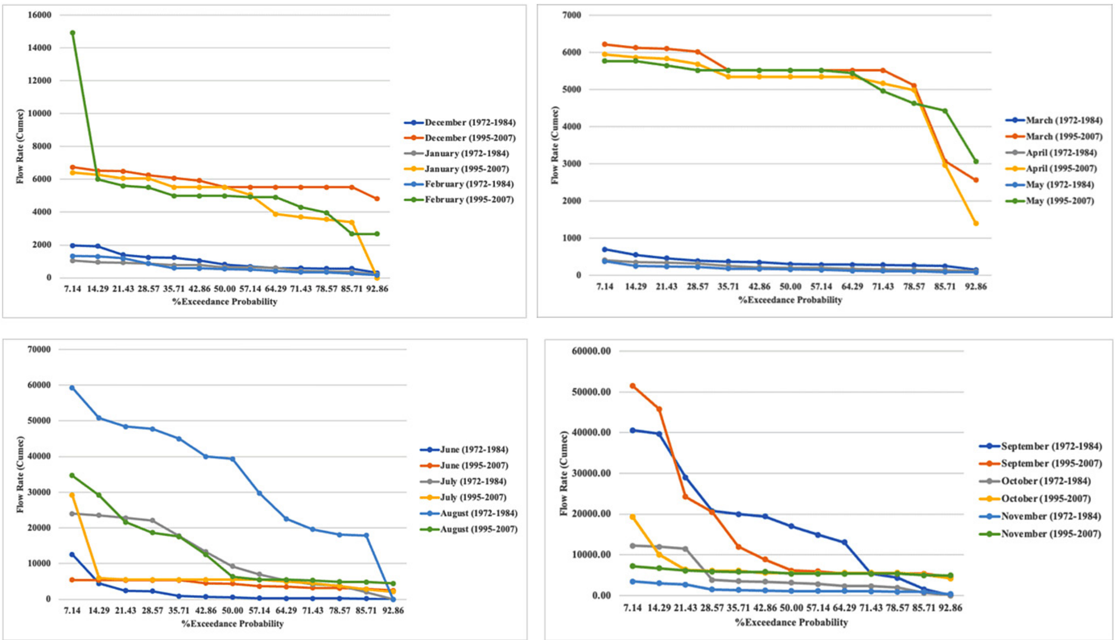

Fig. 2: Pre (1972–1984) and Post (1995–2007) Impact Stage flow duration curves (FDCs) in case of Bargi Dam

The mean flow values of the months from July-September show a decreasing trend and the same for the months from March to May show an increasing trend between the pre and post dam scenarios (Table 4 and Table 5). If the seasonal stream flow characteristics are analysed (Table 6), the coefficient of variation has reduced by 25%, 92%, 88% and 51% in the cases of mean yearly total, summer, winter and monsoon flows because of flow modifications in the post-impact stage. This points to lesser variation in flow during the post-impact stage. Average % of flow has been reduced by 44% in the monsoon season. The mean yearly flow and the summer flow have increased in the post-impact stage, which are attributed to the continuous release of water after the power production from the riverbed power plant.

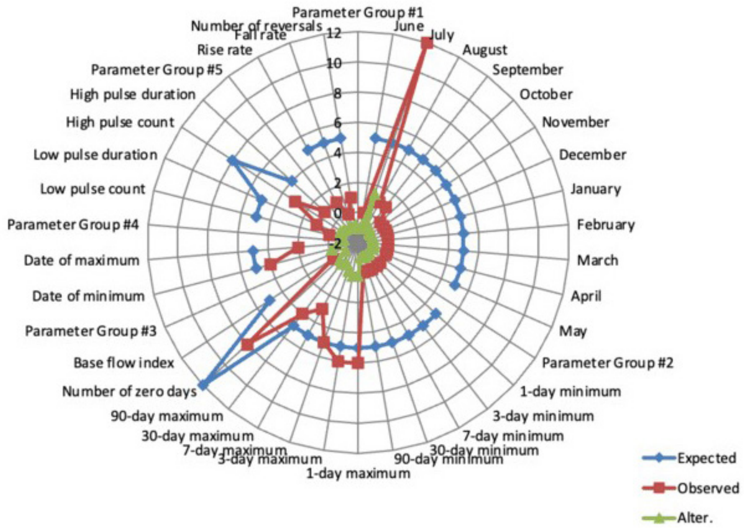

Fig. 3: Representative hydrologic change and expected and observed RVA values for 33 IHA parameters after Bargi Dam construction

Table 4: Hydrological Aspects of the Flows w.r.t. the Case Study Project in the Ante-Impact Stage

Aspect	Average Value (cumec)	Lowest Value (cumec)	Highest Value (cumec)
Daily Flows	205.75	0.00	11568.59
7-day flows	205.70	1.87	4607.70
10-day flows	205.68	1.93	4053.02
Monthly flows	209.74	2.79	1912.04
July	391.16	34.36	774.58
August	1152.21	280.97	1912.04
September	581.96	51.86	1352.97
October	172.21	20.07	393.51
November	56.11	10.11	114.86
December	31.28	9.53	63.44
January	21.91	6.68	33.90
February	24.70	5.72	51.41
March	12.53	4.82	27.68
April	7.59	3.74	13.85
May	5.38	2.79	12.21
June	59.88	4.56	419.91

Both the sudden release and lack of discharges from the dam affect the downstream vegetation adversely. The lack of discharges leads to decreased soil fertility, increased soil salinity and the resultant reduced productivity in the downstream end of the dams.[21] Construction of dams lead to destruction of the natural drainage networks as it stops the flow and diverts it through man-made canals for irrigation needs. The dams also alter the natural diversity of aquatic species, as has been shown in[9,10] and introduces non-native invasive species. It adversely affects the practice of flood-plain agriculture, receipt of sediments and growth of mangroves at the mouth of the rivers.[22] It alters the magnitude and timing of flow events thus hindering the flushing of pollutants and sediments causing habitat destruction of various aquatic flora and fauna in the downstream end. The studies[23,13] have demonstrated that the yearly IHA parameters' values should be kept as close as possible to the ante-impact values. The variability of values of IHA parameters between these two stages must be minimized to the extent possible through implementing the adaptive flow management strategies.

Table 5: Hydrological Aspects of the Flows w.r.t. the Case Study Project in the Post-Impact Stage

Aspect	Average Value (cumec)	Lowest Value (cumec)	Highest Value (cumec)
Daily Flows	232.79	0.00	9834.00
7-day flows	232.24	0.00	4431.29
10-day flows	232.08	34.20	3586.50
Monthly flows	231.48	46.70	1717.20
June	140.29	83.17	180.03
July	226.78	119.23	943.52
August	427.15	155.35	1119.10
September	514.82	149.03	1717.20
October	224.09	136.48	623.97
November	190.32	163.50	239.60
December	188.35	155.35	217.26
January	163.79	109.19	206.65
February	199.47	99.07	532.75
March	170.33	88.41	200.45
April	165.47	46.70	198.13
May	166.95	99.00	186.06

Table 6: Seasonal Stream Flow Characteristics

		(March-June)	(July-September)	(October - February)
Period	**Parameter**	**Summer**	**Monsoon**	**Winter**
Ante-Impact	Years	13	13	13
	Average % of Flow	2.70	89.56	7.74
	SD	25.86	395.98	52.04
	CV	1.21	0.56	0.85
Post-Impact	Years	13	13	13
	Average % of Flow	22.87	49.78	27.35
	SD	14.73	91.95	18.10
	CV	0.10	0.27	0.10

Conclusion

From the RVA method, it can be concluded that after the dam has been built, the flow regime that has been experienced downstream of the dam have altered in an irrevocable manner. In the RVA, the temporal change analyses of the Narmada River discharge between the ante and post impact stages were determined using an array of 33 indicators of hydrologic alteration (IHA) parameters. During the months from March to June, the median flows show shift towards high RVA categories. On the other hand, values of median monthly discharges during the monsoon season of Madhya Pradesh (July to September) show shift towards the low RVA category. In the ante-impact stage, the C.O.D for the summer months such as March and June were the lowest and that for the rainy months such as July and October were the highest. The same during the post-impact stage show drastic variation with the lowest C.O.D value being observed for the month of July and the highest being in the month of January. From the RVA results for the group 1 of IHA parameters, it can be concluded that all (100%) the values in the post-impact stage for the months from October – June are lying within the high RVA category, 92.31% and 76.92% of the values of August and September respectively are also lying within the high RVA category. But the exception is only in case of July, in this case, 92.31% of the monthly flow values are lying within the middle RVA category. From the RVA results for the group 2 of IHA parameters, conclusion is that the annual maximum water conditions have shown an average reduction of 51.78%. But the annual minimum water conditions have shown a substantial increase to the extent of 2791%. From the group 3 of IHA parameters it can be concluded that the minimum threshold of the Julian date of the annual maximum value remained the same. But for the other thresholds, there were shifts in the Julian dates between the ante and post-impact stages. In case of the group 4 of IHA parameters, there has been a reduction in the low pulse count and an increment in the high pulse count. In case of group 5 of IHA parameters, rise rate in the daily flow values has shown an increase and the fall rate has shown a decrement. In the post-impact stage, the number of recorded zero discharge days has shown an increase (from single occurrence to 24 occurrences) when compared to the ante-impact stage and 92% of these days were in the non-rainy seasons. Therefore, the rationale for providing additional flows as the minimum low flow should be to minimise the ecological impacts as much as pragmatically feasible. By adjusting the releases from the dam and by empirically assessing the resultant ecosystem changes, most optimum values for the IHA parameters can be achieved.

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