Heliyon 8 (2022) e09857

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Environmental Flow Assessment of Gorai River in Bangladesh: A comparative analysis of different hydrological methods

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ARTICLE INFO

Keywords:
Environmental flow requirement
Mean annual flow
Mean monthly flow
Flow duration curve
Constant yield

ABSTRACT

The purpose of the study is to assess the Environmental Flow Requirement (EFR) of Gorai River in Bangladesh and to evaluate the change in flow characteristics in recent time compared to past. Daily discharge data of Gorai railway bridge station were collected from Bangladesh Water Development Board and analyzed for two periods. Mean Annual Flow (MAF) in G2 period (2000–20166) is found about 13% lower than G1 period (1984–1999). The Mean Monthly Flow (MMF) in low flow season is increased by 99%, and that of high flow is decreased by 20% in G2 period compared to G1. In this study, EFR was determined considering various methods including Tennant, Tessmann, Variable Monthly Flow, Modified Constant Yield, FDCA Q_{50}-Q_{90}, FDCA Q_{50}-Q_{75} and Smakhtin Method. The average EFR for low, high and intermediate flows were found as 89, 915 and 273 m^3/s, which is 9, 61 and 27% of MAF and 96, 23 and 61% of mean seasonal flow, respectively. The overall annual EFR for the river is found as 295 m^3/s or 29% of MAF. It is observed that when the EFRs are expressed as percent of mean seasonal flow, the Low-Flow Requirements (LFR) were found higher than High-Flow Requirements (HFR). However, when the EFRs are expressed as percent of MAF, the LFR is lower than HFR. Among all the EFRs predicted by 8 methods, Smakhtin predicts the smallest HFR (6% of MAF) and FDCA Q_{50}-Q_{90} have the lowest LFR value (1.2% of MAF). The Tennant method is not found to be capable to capture the temporal change of MMF of different seasons. The Average Annual EFR was found to be reduced by 14% in latter period. A deficient flow situation was observed from December to May. The findings can be used for future reference in management of flows in Gorai river.

1. Introduction

The Rivers provide important habitat for native plants, countless species of fish, birds and other animals that live in and along rivers and nourish the entire ecosystems. The river comprises a source of water used for the purpose of domestic, agricultural and trade, a resource of power generation and unwanted discarding, directions for navigation and locates for recreational and religious accomplishments (Zarfl et al., 2014). In the current time, river flow system in freshwater discharge is reflected as a main parameter by the river researchers due to its durable guidance on the ecological and environmental aspects. But hydrologic systems show a foremost task in shaping the biotic configuration, purpose of aquatic, wetland, and riparian ecologies (Richter et al., 1997; Mcmanamay and Frimpong, 2015). The Environmental Flow Requirement is an assessment for how much of the upstream flow of a river should endure to flow down it and onto its floodplains in order to sustain indicated valued geographies of the ecosystem, hydrological commands for the rivers. Instream Flow Requirement (IFR), Environmental Flow (EF), Environmental Flow Requirement (EFR), or Environmental Water Demand (EWD) are the terms used by different researchers to describe the amount of water needed to keep aquatic ecosystems and ecological processes functioning as intended (Karimi et al., 2012; Smakhtin et al., 2004; Dyson et al., 2003; Davis and Hirji, 2003; Lankford, 2002). Environmental Flow Assessment is the name of the procedure used to determine these fluxes.

According to Baghel et al. (2019), one of the most difficult problems that result from altering the river flow to accommodate the daily rise in human needs is the reduction of the riverine environment. The ecosystem's future conditions are heavily reliant on the need for environmental flow. In this study, the EFR for Gorai River has been estimated; it is a river in south west region of Bangladesh that carries its flow from Ganges River. The upstream part of the Gorai River carries freshwater and then saline water in the estuary. It is the main source of upland freshwater supply in this region. The Environmental Flow Requirement varies from region to region. In addition, the impact of the identical flow requirement is different for different areas. However, for the awareness and protection

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https://doi.org/10.1016/j.heliyon.2022.e09857
Received 8 August 2021; Received in revised form 1 January 2022; Accepted 28 June 2022

against threat as well as for the mitigation of danger, it is necessary to assess the temporal and spatial changes in flow characteristics of Gorai River and to estimate the Environmental Flow Requirement (EFR) of the river that can be used for future orientation in management purposes. The river discharges into the Bay of Bengal through the Madhumati and Baleswar Rivers and thus attends as an essential appliance for conserving both the environment and economy of the region (Islam and Gnauck, 2011). Due to excessive extraction from the Ganges River in its upstream inside India, its distributaries inside Bangladesh are gradually drying up for not receiving their dry season flow. Implementation of the Farakka Barrage in 1974 results in reduction in dry flows in the Ganges distributaries to the southwest region that causes two types of environmental impacts in the Gorai catchment area. It shows a continuous process of siltation progressing generally from the northwest (NW) toward the southeast (SE). The south-western coastal zone is in a state of transition from an active developing delta to a semi-moribund delta. On the other hand, Saline intrusion has increased due to tidal penetration and reduction in freshwater flows (Ali and Hossen, 2022). An electric pumping station of irrigation project (GK project) is situated at about 12 km upstream of Gorai Offtake at Ganges River. Recently, Khulna Water Supply and Sanitation Authority (KWASA) has been implementing a project to use the water from this river to meet the additional demand of domestic water in Khulna city (third largest city of Bangladesh). The second largest port of the country (Mongla) is situated at the downstream of the river that demands a sustainable upstream flow for maintaining a sustainable navigation depth (Zhang et al. 2021). However, due to reduction of transboundary flow in Ganges and progressive siltation at the *Gorai offtake*, the flow in Gorai River is not sustainable to meet up its downstream requirement. According to Goes et al. (2020), low dry-season river flow episodes at Farakka are predicted to become more frequent as a result of an increase in the likelihood of droughts and less snowmelt to support the dry-season flow. It is expected that the Ganges Treaty between Bangladesh and India will be renewed in 2026, where EF of Gorai River can be considered as a key parameter to ensure the minimum flow at downstream. Although some researches on environmental flow are available for other rivers of Bangladesh (Smakhtin and Anputhas, 2006; Hossain, 2010; Hossain et al., 2016; Bari and Marchand, 2006; Rahman, 1998; Pal et al., 2009; Zobeyer, 2004; Akter, 2010), EF has not been extensively studied for Gorai River. Due to geographical position, the rivers in Bangladesh have to face huge volume of flows in wet season and very low flow in dry season. Since the future circumstances of the river ecosystem are largely dependent on the Environmental Flow Requirement (EFR), its estimation for the rivers is censoriously important for Bangladesh. The main objective of this study is to assess the flow characteristics of Gorai and to estimate the Environmental Flow Requirement (EFR) of the river that can be used for future reference in management purposes.

For environmental flow analysis, there are four available method categories: Hydrological, Hydraulic, Habitat simulation and Holistic (Pastor et al., 2014). Since the time series of stream flow data are available for most of the important rivers though out the globe, Hydrological approaches for the estimation of EFR are still the extensively used methods worldwide (European Commission, 2015; Linnansaari et al., 2013; Rodríguez-Gallego et al., 2012; Speed et al., 2012; Benetti et al., 2004). However, the period of the hydrological dataset has a significant effect on the estimation (Caissie et al., 2007; Linnansaari et al., 2013). A data set of at least 15 years duration is suggested by Kennard et al. (2010) as appropriate for statistical integrity in EFR estimation. In this paper, the change of flow characteristics of Gorai Railway Bridge station in Gorai River of Bangladesh has been analysed by comparing the results of recent times with the past, and the Environmental Flow Requirement was estimated to sustain natural ecosystem using hydrological approach. Mean Annual Flow (MAF), Mean Monthly flow (MMF), Median Monthly Flow (MeMF) and Flow Duration Curve (FDC) are the four characteristic parameters that were used in this study to determine the EFR based on different available methods.

2. Methodology

2.1. Study area

The Gorai River (located between 21°30′N to 24°0′N latitude and 89°0′E to 90°0′E longitude) is originated from Ganges at Talbaria, north of Kushtia town and 19 km downstream from the Hardinge bridge and ends at Bardia Point after traveling 199 km in southwestern part of Bangladesh. After this point, the river became tidal and reaches the Bay mainly via the Passur and Sibsa Rivers. The Gorai has a catchment area of 15160 km^2. The second largest sea-port of the country (Mongla Port) is situated about 93 km downstream from Bardia. The flow of Gorai is very important for the sustainable draft of the navigation route of the port. The flow characteristics at Gorai railway Bridge station have been studied in this study, which is about 12 km downstream of Gorai Offtake point. Figure 1 shows the Gorai River indicating different important locations.

The physical features of the study area have been dominated by surface water systems, the proximity of the sea in the south, the dynamic morphology that is greatly governed by sedimentation processes, and the human induced influence on the entire hydro-geophysical characteristics of the region. The region is endowed with surface water systems. Main River systems of this region consist of the Gorai-Modhumoti-Baleswar river system and the Gorai-Bhairab-Pussur river system. In the Gorai-Modhumoti-Baleswar, the upper course is called the Gorai River, in its lower course it is known as the Baleswar river and its estuary mouth which is 14 km wide is called the Haringhata River. The length of Baleswar river is 57 km, and the Nabganga river from Bardia point to Gazirhat is 29 km. The length of Gorai-Modhumoti-Baleswar rivers is 371 km (37 km in Kushtia, 71 km in Faridpur, 92 km in Jessore and 104 km in Khulna and 67 km in Barisal in the eastern border of Sundarbans). The length of Bhairab river is 250 km and it runs Jessore and Khulna region, the length of Chitra river is 170 km, The length of Nabaganga is 230 km (26 km in Kushtia and 204 km in Jessore).

Most of the rivers in southern zone contain much higher salinity as compare to the drinking water standard or domestic use (Hossain et al., 2016). Moreover, most of the rivers in this region has almost no flow in dry season due to Farakka effect (Ali and Saifullah, 2017).

At Bheramara, 12 km upstream of the Gorai Offtake at the Ganges River, there is an electric pumping station for the irrigation project (GK project). In the main irrigation canal, river water is pumped. The Ganges River and the pumping station are connected by a 740 m intake channel. About 142,560 acres of arable land are included in the project (Mirza and Hossain, 2004). The main pump house can produce 147.9 m^3/s at its highest capacity.

Khulna is the third largest city of Bangladesh, situated at the bank of Bhairab-Rupsha River (Figure 1). At present KWASA (Khulna Water Supply and Sanitaion Authority) uses ground water as the only water source. However, to minimize ground water depletion and to meet the future water demand, alternate source of water is necessary. To meet the additional demand of domestic water in Khulna city and to reduce the dependency on ground water, KWASA has planned to use river water and already chosen Mollahat point of Modhumoti river as the surface water collection point. The feasibility study of KWASA, 2010 assumed that safe amount to intake water from the river is less than 5%. This water withdrawal point is about 20 km downstream of Bardia.

Mongla Port is the second gateway of Bangladesh situated at the bank of Pussur River about 131 km upstream from the Bay of Bengal and about 30 km from khulna. For the opeartion of the port, the river requires to maintain a navigable channel of about 10.0 m draft. The siltation in the Pussur river increases due to the reduction of flows in Gorai river (Rahman and Ali, 2018, 2022).

2.2. Methods for environmental flow analysis

In this study, the Environmental Flow Requirement (EFR) of Gorai River is calculated by eight different approaches based on Mean Annual

Figure 1. Location of study area and Gorai River in Bangladesh.

Flow (MAF), Mean Monthly flow (MMF), Median Monthly Flow (MeMF) and Flow Duration Curve (FDC) concept. The methods used for determining the EFR are: (i) Tennant method (Option-I: Good habitat quality) (ii) Tennant method (Option-II: Fair habitat quality) (iii) Tessmann method (iv) Variable Monthly Flow (VMF) Method (v) Modified Constant Yield (MCY) method (vi) FDCA Q_{50}-Q_{90} (vii) FDCA Q_{50}-Q_{75} and (viii) Smakhtin Method. Among these, MCY and FDCA Q_{50}-Q_{75} methods are newly introduced in this study. In this study, average EFR represents the average of eight EFRs (calculated by 8 methods) for a particular season. The mean EFR is the Annual EFR determined by a particular method.

Mean Annual Flow (MAF) Method is commonly acknowledged as Tennant method (Tennant, 1976). It is the popular method used or accepted by 16 states in the USA and 25 countries all over the world (Akter, 2010). According to this method, EFR was set at different percentage of the Mean Annual Flow and the percentages were varied from 10% to 200% of the mean annual flow. The percentage has been set considering the anticipated habitat quality as presented in Table 1. The highest percentage of mean annual flow (200%) is required for 'flushing' type of habitat quality regardless the seasonal variations. The flow requirement decreases with the lowering of status of habitat quality. For the 'good' habitat quality 20% of the MAF is required and for the 'Fair' habitat quality 10% of the MAF is required for LFS. For HFS, 40% and 30% of MAF are required for 'good' and 'fair' quality, respectively. 'Severe degradation' will be occurred if the flow is less than 10% for both the seasons.

Table 1. Flow requirement according to habitat quality.

Habitat quality	Flow Requirement (% of MAF)
Flushing flow	200%
Optimum range	60–100%
Outstanding	60% at HFS, 40% at LFS
Excellent	50% at HFS, 30% at LFS
Good	40% at HFS, 20% at LFS
Fair	30% at HFS, 10% at LFS
Poor	10%
Severe degradation	$<$10%

In Tessmann method (Tessmann, 1980), The EF values were considered as equal to the 100% of MMF for Low flow months and 40% of MMF for high and intermediate flow months. In Variable Monthly Flow (VMF) method (Pastor et al., 2014), EF for low, high and intermediate months were taken as 60%, 30% and 45% of MMF, respectively. The definition of low flow, high flow and intermediate flow seasons are presented below in Section 2.4.

In the Constant Yield (CY) method, Environmental Flow Requirement are generally set at 100% of the median monthly flows (MeMF) for each month. In this study, CY method is modified based on the concept of Tessmann method. In this Modified Constant Yield (MCY) method, Median monthly flow is used instead of MMF with the same percent of flow for seasonal variations used in Tessmann. Therefore, in MCY method the EF values were considered as equal to 100% of MeMF for low flow months and 40% of MeMF for high flow months. Following Tessmann method, 40% of MAF was considered for Intermediate Flow Season (IFS).

The Flow Duration Curve Analysis (FDCA) is another commonly used hydrology-based methodology applied worldwide. EFR are generally set at the 50th percentile (denoted as Q_{50}) for high flow season and 90th percentile (denoted as Q_{90}) for low flow season of annual flow (Smakhtin et al., 2004; Pastor et al., 2012; Gao et al. 2012, 2018). According to certain researchers, an FDC's design low-flow range varies between 70% and 99.9%, symbolized by Q_{70} and Q_{99}, respectively (Karimi et al., 2012; Smakhtin, 2001). In a comparative analysis, Karimi et al. (2012) suggested a minimum flow rate corresponding to Q_{80} depicted from FDC for Shahr Chai River in Iran. According to Gao et al. (2018), the eco-deficit, which measures the quantity of water lacking compared to the requirements of the river ecosystem, can be calculated using the 25th percentile FDC. In this study, by FDCA, EFR is calculated considering two methods: Q_{50}-Q_{90} and Q_{50}-Q_{75}; where Q_{50} was taken as HFR for both the methods and LFR were calculated using Q_{90} and Q_{75} for first and second method, respectively.

Smakhtin et al. (2004) recognized four potential ecological river statuses: Good, Moderate, Fair and Degraded. He proposed Q_{50}, Q_{75} and Q_{90} as the low flow component for good, moderate and fair ecological status. For high flow, EF varied from 0 to 20% of MAF based on the value of Q_{90} (0 for $Q_{90} > 30\%$ MAF and 20% for $Q_{90} < 10\%$ MAF). In this analysis, Smakhtin method is used considering moderate ecological status for low flow and LFR is taken as Q_{75}.

2.3. Data and time span of analysis

Data on mean daily discharge (m^3/s) from the Bangladesh Water Development Board (BWDB) for the years 1984–2016 have been gathered. The daily hydrologic data were processed using IHA (Indicators of Hydrologic Alteration) software (Version 7.1) for the analysis in order to characterize the natural water conditions and assist analyses of human-induced changes to flow regimes. A comparison of flow regimes between earlier and more recent times is a common strategy for evaluating hydrologic change. In this study, the flow for last thirty years was analysed for three periods: Total period (1984–2016), G1 period (1984–1999) and G2 period (2000–2016).

Very few flow regimes in the majority of river basins can be regarded as completely natural, that is, free of anthropogenic influences like abstractions, discharges, or storage effects from impounding reservoirs. Therefore, the existing flow records must be "naturalized" before any significant evaluation of the water resource can begin. According to Brandt et al. (2017), the flow naturalization typically does not adjust for anthropogenic influences such urbanization or changes in land use. According to Caissie et al. (2014), the value of EF in hydrological methods depends on the specified characteristic flow. These techniques, which are suggested as acceptable for EF pre-assessment in the water management planning phase, are based on monthly or daily hydrological records. If time series of daily average flows are given, it is reasonably simple to establish the flow characteristics. The fundamental issue with hydrological approaches that rely on flow characteristics is naturalization of flows (Książ ek et al., 2019). In the present study, the upstream diversion of water has been occurred in the source river Ganges through Farakka barrage and through GK project at 12 km upstream of *Gorai offtake* (Figure 1). The EFR is calculated for Gorai River at an about 12 km downstream of *Gorai offtake*. Therefore, EF assessments have been performed based on daily hydrological records and the anthropogenic effects are neglected.

2.4. Flow seasons

According to the concept that all problems with ecosystem health are caused by low flows, some studies on EFR concentrated on the perception of a minimal low level (Zappia and Haycs, 1998). But it is widely acknowledged that each component of a flow regime, including high, medium, and low flows, is crucial (Poff and Zimmerman, 2010; Tharme, 2003; Acreman and Dunbar, 2004). Smakhtin et al. (2004) and Tennant (1976) considered the low flow months as those having Mean Monthly Flow (MMF) lower than Mean Annual Flow (MAF); and if the MMF is greater than MAF, the months are high flow months. On the other hand, according to Tessmann method (Tessmann, 1980) and VFM method (Pastor et al., 2014), low flow months are those where MMF is less than 40% of MAF and for high flow months the MMF is higher than 80% of MAF. In last two methods, Intermediate flow seasons (IFS) are defined for a smooth transition between high and low flow months.

3. Results and discussions

3.1. Temporal change of Gorai River flow

The river data had been analysed using IHA software in two different ways, first is single period analysis (1984–2016) and second as a two-period analysis: G1 period (1984–1999) and G2 period (2000–2016). The river characteristics of G1 period were compared with G2. Figure 2 shows the time series of daily discharge for G1 and G2 period. It is observed that though there is no significant slope in the linear trend line for G1 period, it shows decreasing trend in latter period. Figure 3 depicts the comparison of mean monthly flows for different time spans. Relatively high discharges were observed in August and September and very low discharges from January to May.

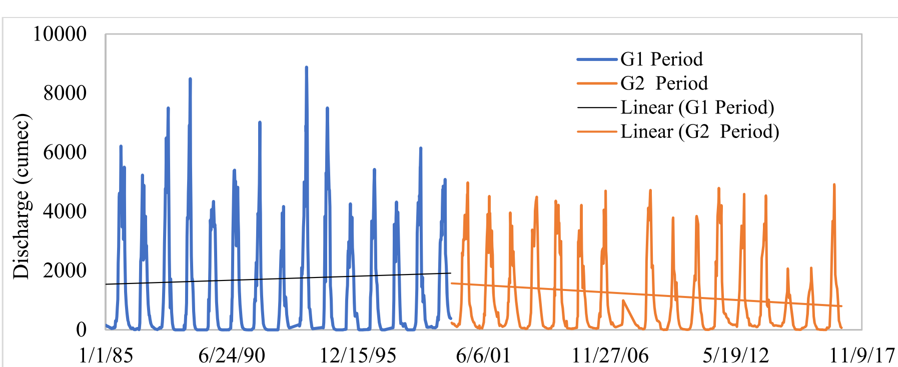

Figure 2. Time series of discharge at Gorai Railway Bridge station for two periods.

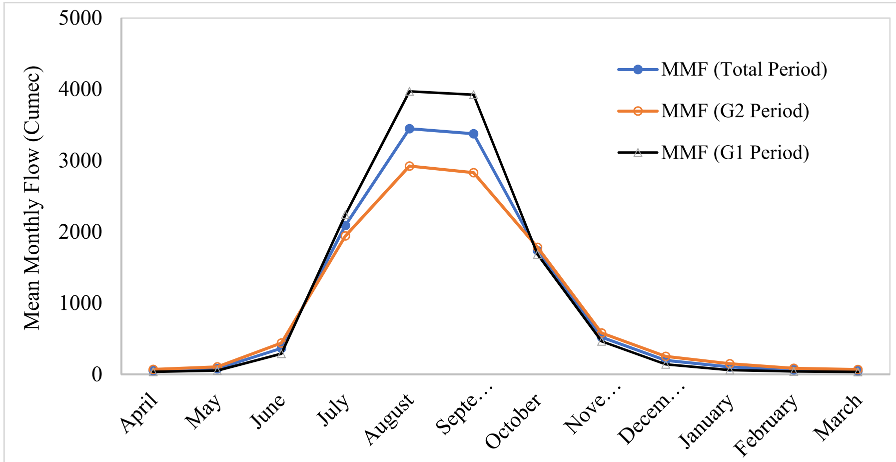

Figure 3. Comparison of Mean Monthly Flows for different time spans at Gorai Railway Bridge station.

To study the seasonal variability, annual flow has been categorized in three dispersed seasons based on the amount of mean monthly discharge. Table 2 shows the general flow characteristics of Gorai River. For the total time span, the mean annual flow is calculated as 1012 m^3/s, which is 1086 and 943 m^3/sec for G1 and G2 Period, respectively. In July to October, the MMF are higher than MAF and hence those months are under the category of High Flow Season (HFS). December to May are categorized as Low Flow Season (LFS) as the MMF of these months are less than the 40% of MAF (as defined by Pastor et al., 2014; Tessmann 1980). The November and June are the transitional months and under the category of Intermediate Flow Season (IFS). The high flow comes to decrease at the month of November after which low flow season starts. Whereas low flow comes to increase at the month of June after which high flow season settles. It is observed that the flow in pre-monsoon starts increasing in June. The peak highest flow is found in monsoon period in the month of August, and then it again starts decreasing in the month of October. After the monsoon, the flow comes to a minimum level in the month of March. As shown in Table, in LFS the MMF is only 93 m^3/s, i.e., 9.2% of MAF. MMF in HFS is 262% of MAF. Mean Annual Flow in G2 period is found about 13% lower than that of G1 period.

Table 3 shows the comparison of Mean Monthly Flow (MMF) for different time spans for Gorai River. It is observed that the March is the lowest flowing month and the MMF is 35 m^3/s in G1 period, 69 m^3/s in G2 period, and for total period the lowest MMF is 52.2 m^3/s in March. August is the highest flowing month and the MMF is 3972 m^3/s in G1 period, 2925 m^3/s in G2 period, and for total period the MMF in August is 3432 m^3/s. In the LFS the discharge is very low in the Gorai River system compared to HFS; the MMF of August is about 66 times higher compared to the flow in March. Interestingly, though the MMF in HFS is decreased in G2 period compared to G1, it is increased in LFS. It can be further explained by comparing the flow duration curves for G1 and G2 period (Figure 4). At the exceedance probability of about 64%, the FDC curves for total period, G1 period and G1 period met or crossed each other. Before that point, flows in G1 period is higher than those in G2 and the scenario is reversed for exceedance probability greater than 64%. The MMF in LFS is increased by 99%, and in HFS it is decreased by 20% in G2 period compared to G1.

Table 2. Mean Annual Flow (MAF) for different time spans in Gorai Railway Bridge stations.

MAF with LF-HF range (m^3/s)			Seasonal mean Flow (Total Period)		
Total period	G1 Period	G2 Period	LFS (Dec. to May)	IFS (Jun & Nov.)	HFS (July to Oct.)
1012 (52–3432)	1086 (35–3972)	943 (69–2925)	93 m^3/s (9.2% of MAF)	446 m^3/s (44% of MAF)	2654 m^3/s (262% of MAF)

Table 3. Mean Monthly Flow (MMF) for different time spans in Gorai Railway Bridge stations.

Season	Month	Mean Monthly Flow (MMF)			Seasonal Average		
		G1 Period (m^3/s)	G2 Period (m^3/s)	Change	G1 Period (m^3/s)	G2 Period (m^3/s)	Change
LFS	December	142	253	79%	62	123	99%
	January	60	151	151%			
	February	42	87	105%			
	March	35	69	96%			
	April	37	71	90%			
	May	54	107	97%			
HFS	July	2239	1942	-13%	2956	2371	-20%
	August	3972	2925	-26%			
	September	3925	2831	-28%			
	October	1686	1784	6%			
IFS	November	465	581	25%	395	489	24%
	June	325	397	22%			

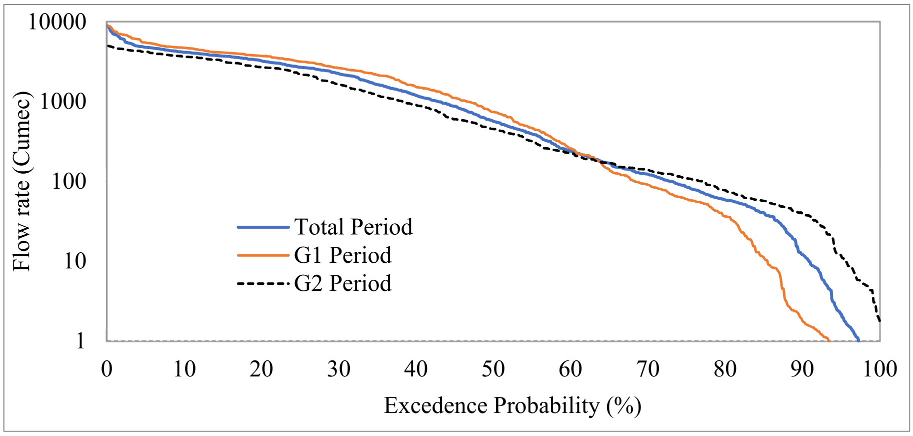

Figure 4. Flow Duration Curve for Gorai Railway Bridge station for Total, G1 and G2 period.

3.2. Environmental Flow Requirement of Gorai River

The EFR calculated by different methods are presented below.

3.2.1. EFR based on mean annual flow (MAF)

In this study, Tennant method is used to calculate the EFR using Mean Annual Flow. Table 4 shows the Flow requirement according to habitat quality for Gorai Railway Bridge. Here the flow requirement according to habitat quality are calculated both for high and low flow seasons. Considering the habitat quality, it is found that, for Gorai Railway bridge station the severe degradation is occurred if the flow is less than 101.2 m^3/s. According to Tennant, the severe degradation is occurred if the flow is less than the lowest flow after which the river can lost its environmental habitat quality.

Table 4. Flow requirement according to habitat quality for Gorai River (for total period).

Habitat quality	HFS & IFS (m^3/s)	LFS (m^3/s)
Flushing flow	2024	2024
Optimum range	607.2–1012	607.2–1012
Outstanding	607.2	404.8
Excellent	506	303.6
Good	404.8	202.4
Fair	303.6	101.2
Poor	101.2	101.2
Severe degradation	<101.2	<101.2

Since the assessment of EFR depends on the methodology employed, the season of the river flow, and the intended habitat quality that the management seeks to achieve and/or maintain, the large range of EFR is clearly evident (Bari et al., 2006). In the present study, the EFR has been evaluated for two different habitat quality: *'good'* and *'fair'*. Figure 5 represents the Comparison of Mean Monthly Flows with EFR in MAF method at Gorai Railway Bridge station during 1984–2016. In the figure Option-I and Option-II represent the *'good'* and *'fair'* habitat quality. Under these conditions the EFR in LFS according to the Tennant method comes out to be 202 m^3/s and 101 m^3/s for the *'good'* and *'fair'* habitat quality, respectively. The values are 405 and 304 m^3/s for HFS.

It is observed that the mean EFR for *'good'* and *'fair'* habitat quality are 304 and 202 m^3/s, that corresponds to the 30% and 20% of the MAF, respectively. The EFR for different seasons are given in Table 5. The table also shows the comparison of EFR calculated by different methods.

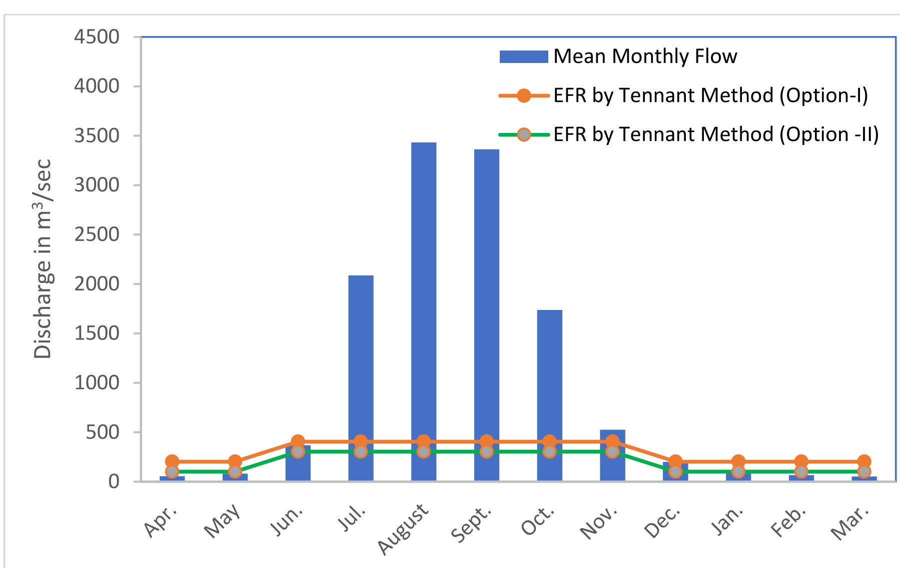

Figure 5. Comparison of Mean Monthly Flows with EFR for Good habitat Quality at Gorai Railway Bridge station (Option-I and Option-II represents the *'good'* and *'fair'* habitat quality).

Table 5. Comparison of EFR values for LF, IF and HF seasons computed by different methods for total time span.

Season	Unit of EFR	Tennant (Option-I)	Tennant (Option-II)	Tessmann	VMF	Q_{75}-Q_{50}	Q_{90}-Q_{50}	Smakhtin	MCY	Average	Median
LFS	m^3/sec	202	101	93	56	85	12	85	81	**89**	**85**
	% MAF	20	10	9	5.5	8.4	1.2	8.4	8.0	**9**	**8**
	% MLF	217	109	100	60	91	13	91	87	**96**	**91**
HFS	m^3/sec	405	304	1062	796	566	566	152	1073	**615**	**566**
	% MAF	40	30	105	79	56	56	15	106	**61**	**56**
	% MHF	15	11	40	30	21	21	6	40	**23**	**21**
IFS	m^3/sec	405	304	405	201	230	85	152	405	**273**	**267**
	% MAF	40	30	40	20	23	8.4	15	40	**27**	**26**
	% MIF	91	68	91	45	52	19	34	91	**61**	**60**
Mean	m^3/sec	304	202	468	327	270	209	118	466	**295**	**287**
(Annual)	% MAF	30	20	46	32	27	21	12	46	**29**	**28**

(MAF = Mean Annual Flow, MLF = Mean Low Flow, MHL = Mean High Flow, MIF = Mean Inter. Flow).

3.2.2. EFR based on mean monthly flow (MMF)

Based on the MMF concept, EFR are determined by two methods: Tessmann method and Variable Monthly Flow (VMF) Method. It is observed that the mean EFR by Tessmann method is found as 468 m^3/s that corresponds to the 46% of the MAF. The Low and High flow seasons' EFR are estimated as 93 m^3/s (9% of MAF) and 1062 m^3/s (105% of MAF), respectively. Among the eight methods, it gives the second highest flow requirement for high flow. But compared to Tennant method it has predicted less EFR for LFS. It can be noted that according to Tennant, 10% of the MAF (Option-II) is considered the lowest and highly undesirable threshold for EF allocations and that at least some 30 % of the total natural MAF may need to be retained in the river throughout the basin to ensure fair conditions of riverine ecosystems (Option-I). For IFS, the EFR is calculated as same as the Option-I (good habitat quality) of Tennant method.

In Tessmann method, 100% and 40% of MMF were considered as the flow requirement of Low and high flow months, however the requirement in variable flow method (VFM) is 60% and 30%, respectively. Therefore, the estimated mean EFR in VFM is found 8% lower than Tessman. The mean EFR by VFM method is found as 327 m^3/s that corresponds to the 32% of the MAF. The low flow requirement is 5.5% of MAF, which is 40% less than the requirement by Tessmann method.

3.2.3. EFR based on median monthly flow (MeMF)

Using the MeMF, the EFR is determined using Modified Constant Yield (MCY) method. EFR values were considered as equal to the 100% of MeMF for Low flow months and 40% of MeMF for high and intermediate flow months. Since the difference between the mean monthly flow and median monthly flow are not so significant, the EFR values predicted by MCY are quite identical with the Tessmann method. Though the mean EFR is 46% of MAF which is same as the Tessmann method, the Low flow requirement in MCY method is 15% lower than the Tessmann method.

3.2.4. EFR based on Flow Duration Curve Analysis (FDCA)

Flow duration intervals are stated as percentage of exceedance with zero corresponding to the highest stream discharge in the record (i.e., flood conditions) and 100 to the lowest (i.e., drought conditions). The Annual Flow Duration curve for the studied location of Gorai River is shown in Figure 4. As described in Art. 2.4, three methods were used for FDCA to determine the EFR; they are Q_{50}-Q_{90}, Q_{50}-Q_{75} and Smakhtin Method. Figure 6 shows the comparison of EFR calculated by all the methods. Since the low flow condition is the main concern in predicting EFR, ccomparison of EFR of LFS is presented along with Mean Monthly Flow (MMF) in Figure 7 in a zoomed view. Among all the EFRs predicted by 8 methods, FDCA Q_{50}-Q_{90} is the bottom most having the LFR value of only 12 m^3/s that coresponds to 1.2% of MAF. On the other hand, LFR predicted by Q_{50}-Q_{75} is 85 m^3/s, which is 8.5% of MAF. This result is consistent with that of other methods. The HFR for both the methods are found as 566 m^3/s or 56% of MAF.

Smakhtin method is used considering moderate ecological status for low flow, which is calculated as Q_{75}. Thus, the LFR in this method is same as FDCA Q_{50}-Q_{75}. However, it shows the lowest requirement for HFS,

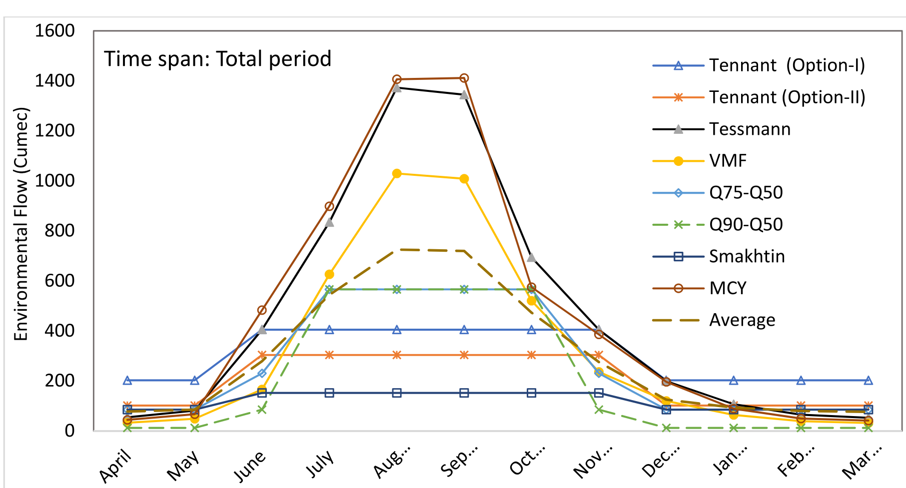

Figure 6. EFR values computed by different methods for Gorai Railway bridge station.

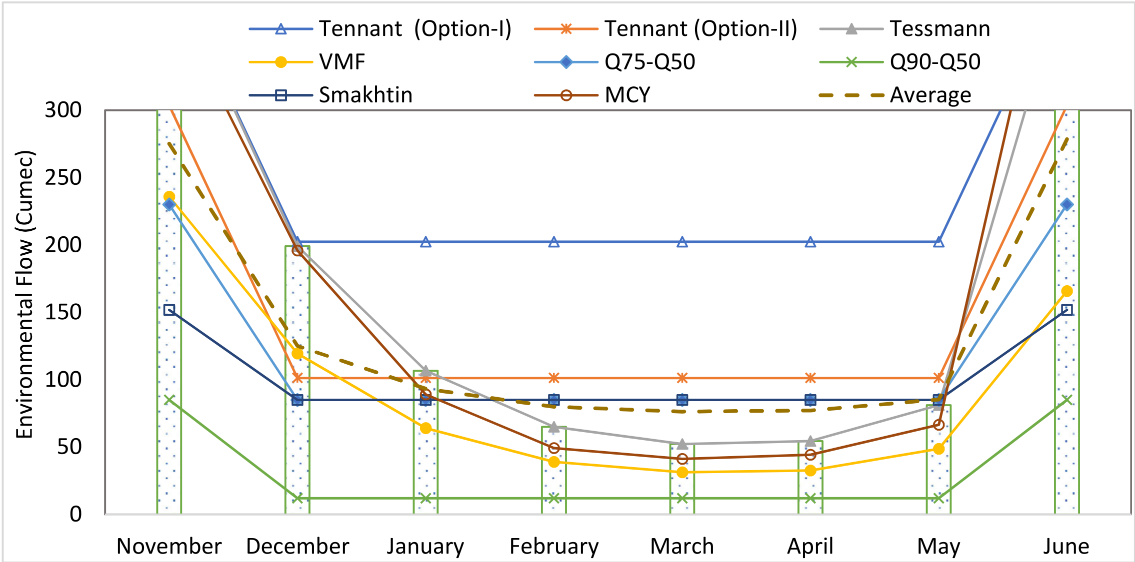

Figure 7. Comparison of EFR of LFS with Mean Monthly Flow computed by different methods.

only 152 m^3/s or 15% of MAF. The average EFR for Q_{50}-Q_{90}, Q_{50}-Q_{75} and Smakhtin Method are found as 270, 209 and 118 m^3/s with 27, 18 and 12% of MAF, respectively.

3.2.5. Overall annual EFR

Among the 8 methods, the EFR for LFS is found to be varied from 12 m^3/s (in FDCA Q_{90}-Q_{50}) to 202 m^3/s (Tennant with '*good*' habitat quality) with an average value of 89 m^3/s. As percent of MAF, LFR varies from 1.2 to 20% with an average of 9%. The HFR varies from 152 (Smakhtin method) to 1073 m^3/s (MCY method), which is 15%–106% of MAF. The average of 8 HFRs is 615 m^3/s or 61% of MAF. The Inter Flow Requirement lies in between and varies from 85 to 405 m^3/s or 8.4–40% of MAF having average of 273 m^3/s (27% of MAF). Combining EFR of different seasons, the mean EFR is calculated for each method. The mean EFR calculated by 8 methods are found to be varied from 118 m^3/s (12% of MAF) to 468 m^3/s (46% of MAF) having the average value of 295 m^3/s (29% of MAF).

Therefore, based on the above analysis, the average EFR for low, high and intermediate flow are 89, 615 and 273 m^3/s, respectively. In terms of MAF, it is 9, 61 and 27% of MAF. On the other hand, low-flow requirement can be expressed as 96% of mean low-flows (average of a range of 13–217% predicted by different methods), while high-flow requirements represent 23% of mean high-flows (average of a range of 6–40%) (Table 5). Therefore, it is observed that when the EFRs are expressed as percent of Mean seasonal Flow (MLF, MHF, MIF), the Low-flow requirements are higher than high-flow requirements. However, when the EFRs are expressed as percent of Mean Annual Flow (MAF), the Low-flow requirements are lower than high-flow requirements. Also, for any method, the LFR as percent of MAF is always less than the percent of mean low flow (MLF), while the HFR as percent of MAF is always greater than the percent of mean high flow (MHF). The overall annual EFR for the Gorai River at Gorai railway Bridge station is found as 295 m^3/s or 29% of MAF. Instead of average if Median value of 8 EFR is considered, the annual EFR can be found as 287 m^3/s or 28% of MAF. In determining annual EFR, the difference between the median and average value is not significant.

3.3. EFR for different time spans

Tables 6 and 7 show the EFR values for LF, IF and HF seasons computed by different methods for G1 and G2 Period, respectively. The percent change in EFR values from G1 to G2 period for different time spans are shown in Table 8. Among the 8 methods, the results of G1 and G2 period computed by Tennant (Option I), Q_{75}-Q_{50} and Tessmann method are compared graphically in Figure 8. It is observed that the EFRs of G2 period are much lower in HFS compared to those in G1. However, it is reversed for LFS i.e., the EFRs of G2 period are higher compared to G1. This is because, in G2 period the MMF is higher in LFS and lower in HFS compared to G1 period.

For G1 period, the EFR for LFS is found to be varied from 2 m^3/s (in FDCA Q_{75}-Q_{50}) to 217 m^3/s (Tennant with 'good' habitat quality) with an average value of 72 m^3/s and a median value of 60 m^3/s. As percent of MAF, LFR varies from 0.2 to 20% with an average of 7%. The HFR varies from 163 (Smakhtin method) to 1183 m^3/s (MCY method), which is 15%–109% of MAF. The average of 8 HFRs is 707 m^3/s or 65% of MAF. The Intermediate Flow Requirement lies in between and varies from 60 to 434 m^3/s or 5.5–40% of MAF having average of 285 m^3/s (26% of MAF). The annual EFR calculated by 8 methods are found to be varied

Table 6. Estimation of EFR values for LF, IF and HF seasons computed by different methods for G1 Period.

Season	Unit of EFR	Tennant (Option-I)	Tennant (Option-II)	Tessmann	VMF	Q_{75}-Q_{50}	Q_{90}-Q_{50}	Smakhtin	MCY	Average	Median
LFS	m^3/sec	217	109	62	37	60	2	60	29	**72**	60
	% MAF	20	10	5.7	3.4	5.5	0.2	5.5	2.7	**7**	6
HFS	m^3/sec	434	326	1182	887	741	741	163	1183	**707**	741
	% MAF	40	30	109	82	68	68	15	109	**65**	68
IFS	m^3/sec	434	326	434	170	257	60	163	434	**285**	291
	% MAF	40	30	40	16	24	5.5	15	40	**26**	27
Mean	m^3/sec	326	217	497	342	320	258	111	524	**325**	323
(Annual)	% MAF	30	20	46	32	29	24	10	48	**30**	30

Table 7. Estimation of EFR values for LF, IF and HF seasons computed by different methods for G2 period.

Season	Unit of EFR	Tennant (Option-I)	Tennant (Option-II)	Tessmann	VMF	Q_{75}-Q_{50}	Q_{90}-Q_{50}	Smakhtin	MCY	Average	Median
LFS	m^3/sec	189	94	123	74	109	39	109	105	**105**	107
	% MAF	20	10	13	7.8	12	4.1	12	11	**11**	11
HFS	m^3/sec	377	283	948	711	453	453	141	970	**542**	453
	% MAF	40	30	101	75	48	48	15	103	**58**	48
IFS	m^3/sec	377	283	377	230	220	109	141	377	**264**	256
	% MAF	40	30	40	24	23	12	15	40	**28**	27
Mean	m^3/sec	283	189	440	312	242	188	125	439	**277**	262
(Annual)	% MAF	30	20	47	33	26	20	13	47	**29**	28

Table 8. Percent change in EFR values from G1 to G2 period by different methods.

Season	Tennant (Option-I)	Tennant (Option-II)	Tessmann	VMF	Q_{75}-Q_{50}	Q_{90}-Q_{50}	Smakhtin	MCY	Average	Median
LFS	-13	-13	98	100	82	1850	82	262	**44**	**78**
HFS	-13	-13	-20	-20	-39	-39	-13	-18	**-23**	**-39**
IFS	-13	-13	-13	35	-14	82	-13	-13	**-7**	**-12**
Mean	-13	-13	-11	-9	-24	-27	13	-14	**-14**	**-19**

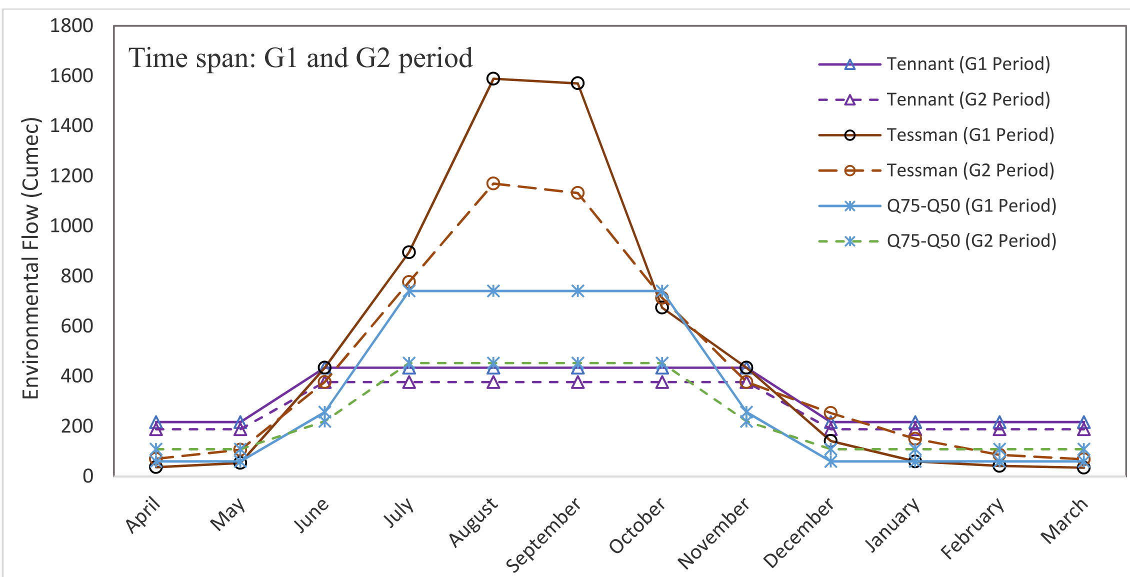

Figure 8. Comparison of EFR values for G1 and G2 period computed by different methods for Gorai Railway bridge station.

from 111 m^3/s (10% of MAF) to 524 m^3/s (48% of MAF) having the average value of 325 m^3/s (30% of MAF) and a median value of 323 m^3/s (30% of MAF). The difference between the median and average value is not significant. The lowest Annual EFR (mean) was predicted by Smakhtin method and the highest by MCY method.

For G2 period, the EFR for LFS is found to be varied from 39 m^3/s (in FDCA Q_{75}-Q_{50}) to 189 m^3/s (Tennant, Option-I) with an average value of 105 m^3/s and a median value of 107 m^3/s. As percent of MAF, LFR varies from 4.1 to 20% with an average of 11%. Comparing with G1 period, it is found that the average EFR in LFS is increased by 44%. This average trend is reflected in the prediction of all the methods except Tennant. Since the Tennant method is based on MAF, the value of MAF for G1 and G2 period decides the EFR for all the seasons. Although the MAF for G1 is higher than G2, the mean flow in LFS is higher in G2 period. Table 8 shows that in Tennant method, for all the seasons the EFR value decreased by 13% in G2 period compared to G1, because the MAF in G2 is 13% lower than G1. Therefore, the Tennant method failed to capture the temporal change of seasonal variations. For high flow season, the EFR for G2 period is found to be varied from 141 m^3/s (Smakhtin) to 970 m^3/s (MCY) with an average value of 542 m^3/s. As percent of MAF, HFR varies from 15 to 103% with an average of 58% in G2 period. Comparing with G1 period, it is found that the average HFR is decreased by 23% (average of 13–39%). The Median EFR for G2 period is found 78% higher in LFS and 39% lower in HFS compared to G1 period.

Since the MMF for HFS are significantly larger than that for LFS, EFR of HFS has a dominating role in determining the mean (annual) values of EFR for each method. Among the all, Smakhtin method predicts the smallest HFR and for that reason the mean EFR by Smakhtin method is dominated by LFS (it is explained earlier that the EFR in LFS is higher for G2 period than G1). Except Smakhtin, all other methods show similar trend, i.e., the mean EFR is decreased in G2 period than G1. The average Annual EFR in G2 period is found to be 14% lower than that in G1 period. In G1 period it was 325 m^3/s that reduced to 277 m^3/s in latter period. However, the median of Annual EFR is found to decrease by 19% in G2 period compared to G1.

For G1 period, the average EFR for low, high and intermediate flows are 73, 707 and 285 m^3/s, respectively. In terms of MAF, it is 7, 65 and 26% of MAF. The overall Annual EFR for the G1 period is

Table 9. Comparison of Average EFR values for LF, IF and HF seasons computed by different methods for G1 and G2 period.

Season	Month	Monthly EFR (m^3/s)			Seasonal EFR (m^3/s)		
		G1 Period	G2 Period	Change	G1 Period	G2 Period	Change
LFS	December	95	146	53%	73	105	44%
	January	71	113	58%			
	February	65	95	46%			
	March	64	89	37%			
	April	72	88	21%			
	May	71	100	42%			
HFS	July	622	489	-21%	707	542	-23%
	August	851	621	-27%			
	September	833	619	-26%			
	October	522	440	-16%			
IFS	November	290	268	-7%	285	264	-7%
	June	280	260	-7%			

Table 10. Comparison of Median EFR values for LF, IF and HF seasons computed by different methods for G1 and G2 period.

Season	Month	Monthly EFR (m^3/s)			Seasonal EFR (m^3/s)		
		G1 Period	G2 Period	Change	G1 Period	G2 Period	Change
LFS	December	87	130	50%	60	107	78%
	January	60	109	82%			
	February	51	90	77%			
	March	47	81	72%			
	April	60	82	37%			
	May	57	100	76%			
HFS	July	706	453	-36%	741	453	-39%
	August	741	453	-39%			
	September	741	453	-39%			
	October	549	453	-18%			
IFS	November	291	272	-7%	291	256	-12%
	June	291	251	-14%			

found as 325 m^3/s or 30% of MAF of G1 period. For G2 period, the average EFR for low, high and intermediate flows are 105, 542 and 264 m^3/s, respectively. In terms of MAF, it is 11, 58 and 28% of MAF. The overall Annual EFR for the G2 period is found as 277 m^3/s or 29% of MAF of G2 period.

However, if the median value of 8 EFRs (by 8 methods) are considered instead of average, the median EFR for G1 period in low, high and intermediate season are found as 60, 741 and 291 m^3/s; in terms of MAF, those are 6, 68 and 27% of MAF, respectively. The median of Annual EFR for the G1 period is found as 323 m^3/s or 30% of MAF. For G2 period, the

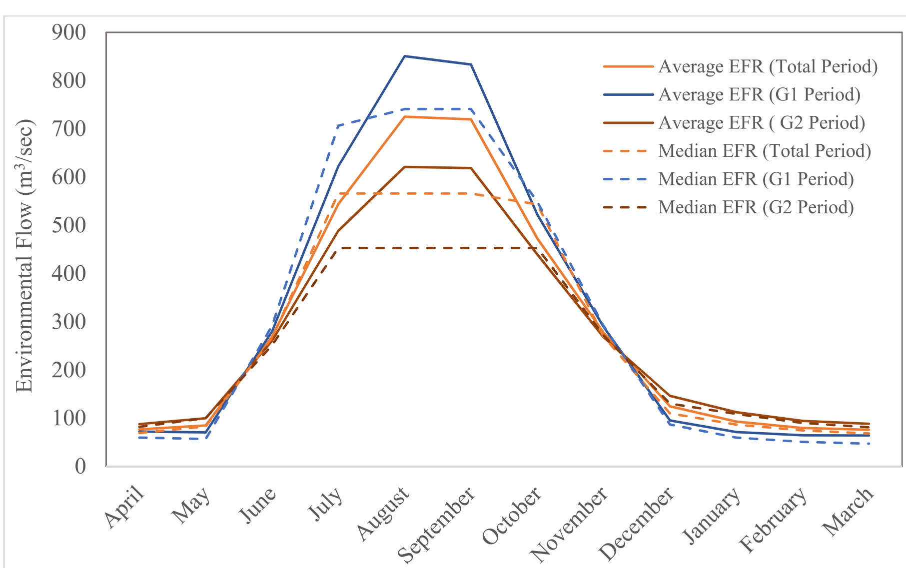

Figure 9. Comparison of Average Monthly EFR for different time spans.

median EFR for low, high and intermediate flow are 107, 453 and 256 m^3/s that correspond to 11, 58 and 28% of MAF, respectively. The median of Annual EFR for the G2 period is found as 262 m^3/s or 28% of MAF of that period.

Averaging the values of 8 methods, the monthly EFR in LFS is found to be increased by 21–58%, however in HFS it is decreased by 16–27% (Table 9). Average EFR in LFS is 73 and 105 m^3/s for G1 and G2 period respectively i.e., LFR is increased by 44%. Average EFR in HFS is 707 and 542 m^3/s for G1 and G2 period respectively, which shows decrease in HFR by 23%. The change in intermediate flow requirement is not so significant, it decreased by 7%.

As shown in Table 10, the monthly median EFR in LFS is found to be increased by 37–82%, however in HFS it is decreased by 18–39%. Median EFR in LFS is 60 and 107 m^3/s for G1 and G2 period respectively i.e., LFR is increased by 78%. Median EFR in HFS is 741 and 453 m^3/s for G1 and G2 period respectively, which shows decrease in HFR by 39%. The change in intermediate flow requirement is not so significant, it decreased by 12%.

The average and median monthly EFR—both are plotted in the same graph and shown in Figure 9. It is observed that, for this river, when the EFR is calculated averaging the values predicted by 8 methods the profile is nearly Gaussian type. On the other hand, when the median of 8 EFR values are plotted, the profile is top-hat type. For all the time spans, the median EFRs are found smaller than the average EFR. The monthly EFR by FDCA Q_{50}-Q_{75} method is found very close to the median monthly EFR for HFS, and for LFS the prediction by Smakhtin method is found very close to Median EFR.

4. Summary and conclusions

The purpose of the study was to assess the EFR of Gorai River in Bangladesh and to evaluate the change in flow characteristics in recent time compared to past. Daily discharge data of selected stations were collected from Bangladesh Water Development Board (BWDB) and analysed for two periods. In this study, EFR has been determined considering eight approaches: two approached based on Mean Annual flow (good and fair habitat quality in Tennant method), two approaches based on Mean Monthly Flow (Tessmann and VMF Method), three approaches of Flow Duration Curve Analysis (FDCA Q_{50}-Q_{90}, FDCA Q_{50}-Q_{75} and Smakhtin Method) and one approaches based of Median Monthly Flow (Modified Constant Yield Method). The average EFR (over all methods) for low, high and intermediate flow are found as 89, 915 and 273 m^3/s, respectively, which is 9, 61 and 27% of MAF and 96, 23 and 61% of mean seasonal flow. The average annual EFR for the Gorai River at Gorai railway Bridge station is found as 295 m^3/s or 29% of MAF. The median of annual EFRs is found as 287 m^3/s or 28% of MAF. In determining annual EFR, the difference between the median and average value is not significant. It is observed that when the EFRs are expressed as percent of mean seasonal flow (MLF, MHF, MIF), the low-flow requirements are higher than high-flow requirements. However, when the EFRs are expressed as percent of Mean Annual Flow (MAF), the Low-flow requirements are lower than high-flow requirements. Also, for any method, the LFR as percent of MAF is always less than the percent of mean low flow (MLF), while the HFR as percent of MAF is always greater than the percent of mean high flow (MHF). Among all the EFRs predicted by 8 methods, Smakhtin predicts the smallest HFR (6% of MAF) and FDCA Q_{50}-Q_{90} have the lowest LFR value (1.2% of MAF). The monthly EFR by FDCA Q_{50}-Q_{75} method is found very close to the median monthly EFR for HFS, and for LFS the prediction by Smakhtin method is found very close to Median EFR.

Mean Annual Flow in G2 period is found about 13% lower than that of G2 period. The MMF in LFS is increased by 99%, and in HFS it is decreased by 20% in G2 period compared to G1. Since the MMF for HFS are significantly larger than the LFS, EFR of HFS has a dominating role in determining the mean annual EFR for each method. The Tennant method is found not to be capable of capturing the temporal change of MMF of different seasons. Among all the methods, Smakhtin predicts the smallest HFR and for that reason the annual EFR by Smakhtin is dominated by LFS. Except Smakhtin, all other methods show similar trend, i.e., the mean EFR is decreased in G2 period than that of G1. The average Annual EFR in G2 period is found to be 14% lower than G1 period. In G1 period it was 325 m^3/s that reduced to 277 m^3/s in latter period. The median of Annual EFRs in G2 period is found about 19% lower than that of G1 period. The median of annual EFR in G1 and G2 periods are 323 and 262 m^3/s, respectively. A deficient flow situation was observed from December to May. The findings can be used for future reference in management of flows in Gorai River. Adoption and implementation require that environmental flows are incorporated into water policies and national legislation.

Declarations

Author contribution statement

Md. Shahjahan Ali : Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Md. Mahmudul Hasan: Performed the experiments; Analyzed and interpreted the data.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability statement

The authors do not have permission to share data.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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