Environmental flow in the context of dams and development with special reference to the Damodar Valley Project, India: a review

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Abstract
Environmental flow is the minimum flow required in a fluvial system to maintain its ecological health and to promote socio-economic sustainability. The present work critically examines the concept of the environmental flow in the context of dams and development using a systematic methodology to find out the previous works published during the last 3 decades (1990–2020) in different search engines and websites. The study reviews that structural interventions in the form of dams, barrages, weirs, etc. impede the natural flow of the rivers. Moreover, other forms of development such as industrialization, urbanization, and expansion of modern agriculture also exacerbate the problems of environmental flow across the world, especially in monsoon Asia. The present case of the environmental flow for the Damodar River portrays that the construction of dams and barrages under the Damodar Valley Project have significantly altered the flow duration, flood frequency, and magnitude (high-frequency low magnitude events in the post-dam period), while urban-industrial growth in the basin has polluted the river water (e.g., lower dissolved oxygen and higher biological oxygen demand). This typical alteration in the flow characteristics and water quality has threatened aquatic organisms, especially fish diversity and community structure. This review will make the readers aware of the long-term result of dam-induced fluvial metamorphosis in the environment through the assessment of environmental flow, species diversity, flow fluctuation, and river pollution. The study may be useful for policy-making for ushering in the sustainable development pattern that will attract future researchers, planners, and stakeholders.

Keywords Minimum flow · Structural interventions · Ecosystem productivity · Damodar River · Water pollution · Fish diversity

Introduction
Assessment and maintenance of the environmental flow of a river are essential to upholding sustainable development. It emphasizes the sustainability of the freshwater and estuarine ecosystem, along with the livelihood, and the well-being of people depending on these ecosystems (The Brisbane declaration 2007). It helps in reducing wastewater discharge and minimizing the effects of streamflow alteration in downstream aquatic, floodplains, and coastal ecosystems (WCD 2000). Besides, it conserves water quality for maintaining public health and water-related ecosystem (Patsialis et al. 2014; Chen and Wu 2019).

The river basins have cradled civilizations and maintained cultural heritage from the ancient to the modern period through the provisions of livelihoods of local communities. Hence, basin water resource management is vital for balancing the uses of water between the environment and socio-economic demand (Overton et al. 2014). Nowadays, water resource management is a global challenge in various branches of hydrology, hydraulics, biology, ecology, environmental, socio-economic, and engineering disciplines (Verma et al. 2015). Water resource management needs environmental flow assessment for the sustainability of the river and to meet the societal needs of water. Environmental flow
assessment is an important technique for maintaining environmental sustainability, and sustainable management of river ecosystems in the world (Hazra et al. 2015). For that, regular monitoring of natural river flow is needed (Mitra and Singh 2018). The river flow regime is an important component for analyzing the environmental flow and assessing riverine ecology (Mitra and Singh 2018). Environmental flow assessment and its maintenance play a vital role to protect and improve the structure, and function of the downstream ecosystems. For example, the environmental assessment model of the Connecticut River, USA inspects reservoir management for ecological benefits with dynamic systems and hydropower generation (Bernstein 2013).

All over the world, the environmental flow concept has been applied widely in the fluvial system. It tries to strike balance between the use of river water for socio-economic developments and delivering ecosystem services (Jain 2015). Environmental protection and sustainable water resource management are very crucial for living organisms and non-living objects. Sustainable water resource management is essential to protect the environment and mitigate the rising demand for water (both surface and ground). It is also the global development agenda due to a decline in water quality and quantity for growing population and economic development (Mahammad and Islam 2021a). As sustainable water resource management is essential to protect the environment, dams are regulated on the river for water resource management and mitigating human needs of water (Mitra and Singh 2018). Dams are very important construction tools for river water management for socio-economic development as well as improvement of the degraded ecological condition of the river system and their services.

In the twentieth century, large dams arose as significant and noticeable tools for water resource management. The installation of large dams had increased tremendously from the 1930s to the 1970s for development and economic progress, and the large dam installation trend peaked in the 1970s (WCD 2000). However, in the context of environmental flow, dams play both negative and positive roles depending on the space and time (Dwivedi et al. 2010). For example, the riparian area downstream of a dam may increase and non-native species may also increase (Zeiringer et al. 2018). On the other hand, the river loses flow due to the water holding structure of the dam that impedes the natural river flow regime which impacts the environment, ecology, aquatic life, and river morphology (Mitra and Singh 2018). The natural river flow is important for fluvial communities and their ecological integrity, because the evolution, adaptation, development, and maintenance of river habitats depend on water supply (McManamay and Bevelhimer 2013).

Flowing water is the engine of improvement and protection of the habitat of the river species and sediments movement (Jalón et al. 2017). However, dam reduces sediment and nutrient movement downstream that affects channel, floodplain, and morphology of the coastal area resulting in the loss of aquatic habitats. Fluvial habitats are not only the result of water flow but also interaction among the water, sediment, organic material, and riverine vegetation communities (Jalón et al. 2017). Dynamic interactions of floods and sediments are important for downstream riparian communities, but the reduction of annual floods water impacts the natural productivity of riparian areas, floodplains, and delta. That is why, sediments’ movement and dynamic interaction of floodwater are important criteria for environmental flow design in the ecosystem. Environmental flow design requires the freshwater quantity, quality, and timing of water flow for improving the natural biogeochemical process, and for diverse aquatic communities. Therefore, for minimizing the negative impacts of dams and sustaining freshwater and estuarine ecosystem, there is a need to manage the environmental flow for recovering and maintaining the socially, environmentally, and economically viable option (The Brisbane Declaration 2007). Environmental flow management in the river system is one of the ways to decrease the rising impacts from the hydrological alteration in the world’s rivers (Tonkin et al. 2014). Hence, water flow management needs the establishment and enforcement of environmental services (Arthington et al. 2010). Integrated environmental flow management in the river systems is a decision-making with dialog on water resource policy, legislation on industrial reforms, river basin planning, new infrastructure investment, and rehabilitation or reoperation of existing infrastructure to supply and promote sustainable development (World Bank 2008).

In the context of Damodar Valley Corporation (DVC), huge socio-economic benefits are manifested in the form of controlling the colossal floods, checking soil erosion, developing irrigation systems, supplying domestic and industrial water, generating hydropower, boosting fishing, tourism, and recreation (Damodar Valley Corporation, 2021). The installation of this multipurpose river valley project has led to regional as well as national economic development with an increasing standard of living of people of the concerned region. For example, before dam construction, several devastating floods (1730, 1823, 1848, 1856, 1882, 1898, 1901, 1916, 1923, 1935 & 1943) occurred in the Damodar valley region (Damodar Valley Corporation 2021). However, in the post-dam period, flood probability has been reduced substantially as the DVC created 1.85 million cu. M water storage and 1292 million cu. M flood reserve capacity (Damodar Valley Corporation 2021). About 680 cusecs of water from storage is supplied to meet industrial, municipal, and domestic needs in the states of West Bengal and Jharkhand in India. About 3640 km² of land with irrigation potential has been created. Reservoirs supply water through the canal of 2494 km length in agricultural fields.
drastically changing agricultural land use and cropping pattern (Damodar Valley Corporation 2021). Cropping intensity and diversity have been increased. In 2015–2016, the DVC project also has generated 187.20 million units of hydro-power, an eco-friendly source of energy. Besides, the benefits of the massive engineering projects are also noted on other dimensions such as an increase in crop productivity and a flourishing farming economy (e.g., Kundu and Chattopadhyay 2017; Lahiri-Dutt 2012) and flood moderation and economic development (e.g., Bhattacharyya 2011; Ghosh and Mistri 2013).

Although a large number of works are found to document the dam-induced socio-economic progress, it is rare to find works concentrating on the environmental flow in the context of the DVC and its future consequences. Thus, the prime purpose of this paper is to assess the environmental flow which is the water provided within a river or any wetland to maintain ecosystems and their benefits where there are competing water uses and where flows are regulated. After the construction of the DVC dams and barrages, the fluvial modification of the active channel area is evident in the downstream channel, and anthropogenic intervention is escalating in the active river bed, hampering the free flow of the river. The holistic benefits of water resource management are fruitfully enjoyed by the mass population of the Damodar Floodplain without bothering the future of the sustainable fluvial environment and ecosystem functionality. The dams were once considered as the pillar of economic development, but now in the study area, the dams are not able to continue the direction of sustainable development strategies to keep pace with the growing demand of population, cities, industries, and agriculture. Unfortunately, the sustainability of the fluvial environment is not getting the right attention from the planners and developers. At present, the database shows that the Damodar River is heavily polluted upstream of the Durgapur Barrage, and the riparian area of the river is reduced mainly due to in-channel sedimentation, settlement, agriculture, and sand mining (De et al. 1980, 1985, 1993).

The main flow of the river is now maintained, but it is checked within the narrow range of active channels, not sufficient for environmental flow requirements. Alongside, the peak or bankfull flow, regulated by dams, is persisted for 3–4 days only to save the low-lying downstream area of Damodar during monsoon. Giving importance to the benefits of dams (especially to humans), it is needed to save the species of Damodar from the point of view of environmental ethics. Thus, we have placed more attention on current environmental problems observed in the river due to the DVC project and other structural interventions in the form of check dams, barrages, weirs, and bridges. Our prime aim is to make the readers aware of the long-term result of dam-induced fluvial metamorphosis in the environment, through incorporating the ideas of environmental flow, species diversity, flow fluctuation, and river pollution. Thus, the review will be helpful for academicians, researchers, regional planners concerned with the environment, development, and sustainability.

**Methodological procedure for selection of articles**

The present study is based on the articles and reports accessed from various web-based search engines such as Research Gate, Academia.edu, Google Scholar, Web of Science (WoS), and Scopus. For a systematic review, keeping the research topic in mind, four key terms such as (a) Environmental flow, (b) Dams and development, (c) Environmental flow in the context of Dams and development, and (d) Environmental flow of the Damodar River were selected. These terms were searched in the web-based search engines to find journal articles and reports published in the last 4 decades (1980–2020). The search strategy and article selection processes are shown in Fig. 1. All the articles gathered from the search engines were initially screened for in-depth review concerning the key terms as defined in this study. Hence, this study reviewed those articles primarily focused on the environmental flow assessment, environmental flow for sustainable development, structural interventions like dams and barrages altering environmental flow at a global scale in general, and Damodar river in particular.

**Environmental flow: a concept**

The concept of environmental flow has traveled over time and space (Blaney 2013). It emerges from the concept of ‘minimum flow’ which needs to be maintained in the river systems for sustaining their ecological stability including maintaining the function, process, and resilience of the system. However, in the last 40 years, the environmental flow concept has changed from ‘stable minimum flow’ to ‘progressive dynamic flow’ elements (Chen and Wu 2019). However, standard environmental flow is still exercised to control the flow regime in a dammed river. Streamflow that ensures the flow regime in aquatic habitat and ecosystem process is referred to as “environmental flow”, “environmental water requirement”, “environmental flow requirement”, “environmental water demand”, etc. (Knights 2002; Lankford 2002; Dyson et al. 2003; Smakhtin et al. 2004a, b, 2006). Environmental flow is also considered as “water for nature” or “environmental demand” (Eriyagama and Jina-pala 2014) that is the non-consumptive water needed for the aquatic systems and economic uses (Hazra et al. 2015) (Fig. 2).
A certain volume of water flow is required for improving the river ecosystem and the protection of rivers for supporting riverine ecology and the environment (Richter et al. 2006). Environmental flow also refers to the flow regime that maintains the quality, quantity, and duration of river water flow which are crucial for the protection, and restoration of the degraded ecological condition of a river system (Chen and Wu 2019; Sarkar and Islam 2020; Tharme 2003). Moreover, it maintains the natural biogeochemical process and habitat suitability of the different aquatic species (Arthington et al. 2010). And they destine to set and maintain the science of environmental flow which provides essential environmental services through saving and recovering ecologically and socially sustainable flow regimes (Duvali and Hamerlynck 2003). Generally, environmental flow refers to the flow regime of the river that controls all functions and structures of the river system and its floodplain and wetland (Poff et al. 2009). Besides, it also maintains a healthy ecosystem and upholds the essential process of ecosystems (Smakhtin and Anupthas 2006). The term ‘environmental flows’ is also extensively used to describe the hydrological regime that needs to maintain and sustain the aquatic ecosystems, the human livelihood, and the well-being that rely on them (Acreman 2016). However, many ecologists, water practitioners, and policymakers perceive that this flow not only maintains freshwater and estuarine ecosystems but also provide benefits to human (Eriyagama and Jinapala 2014). This environmental flow tries to balance between the uses...
of river water for meeting socio-economic requirements and providing to ecosystems (Jain 2015), or the balancing between social consumptive demands and ecological sustainability of water which affect the livelihood and ecosystem services (Hazra et al. 2015; Sarkar and Islam 2021). Therefore, the protection of environmental flow is vital for the conservation of aquatic biodiversity in dammed river systems (Grantham et al. 2014), because it is a management tool of ecosystem integrity and biodiversity conservation (Karr 1991; Silk and Ciruna 2005). Thus, amelioration of environmental flow requires increasing the potentiality of the river, conservation of aquatic biodiversity, and reducing ecosystem alteration (Grantham et al. 2014). Environmental flow sustains rivers by maintaining their natural ecological flow. That is why, environmental flow is very important for rivers, because it is the biological engine of aquatic ecosystems of our planet. Environmental flow also allows the river to flush out salinity, encourage biodiversity, improve fish habitat, and help the process of cleaning up water, and provides mankind with ectotype services which are very significant for us in terms of provision of fresh and clean water (Chen and Wu 2019).

According to International Union for Conservation of Nature (IUCN), environmental flows are integrating river flow management for supplying water to meet the requirements of people, agriculture, industry, energy, and ecosystems. However, climate poses a threat to the available supply of water. Water allocation in rivers performs the natural function of the river environment (Jain 2015), sediment movement, and flow management. In Italy, these flows are taken into account as integrated water resource management and its main principle is sustainable development with environmental protection (Maran 2004). At present, water and its flow have been used for meeting public desire by supplying water, food, energy, also sustaining ecological services, and maintaining a healthy ecosystem through sustainable water resource management (Overton et al. 2014). However, environmental flow assessment in the recent decade focuses on the heavily modified hydel-system for releasing flow from dammed reservoir downstream (Tegos et al. 2018).

In this context, various methodologies have been developed for hydrological, hydraulic, biological, water-quality inputs, and socio-economic issues of the dammed river. In Europe, many methodologies, from simple hydrological records to modeling approaches, have been used to estimate environmental flow requirements of the rivers in the downstream segment of a dam for ecological viability (Godinho et al. 2014), and several environmental flow estimation methods and hydrological techniques have been extensively used for assisting regional flow management (Poff et al.
At present, 207 separate environmental methodologies exist in 4 countries among six regions in the world, but Hydrological, Hydraulic rating, Habitats simulation, Holistic method (Tharme 2003), and biological and water-quality inputs approach (Tegos et al. 2018) are the most important. These methodologies and approaches try to reconnect the flow regime which is needed for the whole riverine ecosystem, and it depends on clear relationships between flow regime alteration and impacts on the biophysical environment (Tharme 2003). For example, building block methodology, based on flow requirements for riverine flora, fauna, social and cultural water requirement, groundwater recharge, and coastal water requirement, can be used (Jayasiri et al. 2017). In the last 50 years, various methodologies have been proposed, indicating that minimum flow is needed to mitigate the effects on downstream hydrosystem (Efstratiadis et al. 2014).

**Ecological criteria of environmental flow**

Smakhtin and Anupthas (2006) have mentioned that the environmental flow (EF) is considered as an ecologically satisfactory flow regime premeditated to sustain a river in the present era of global climate change and Anthropocene. The major decisive factors for determining EF should comprise the continuance of both spatial and temporal patterns of channel flow, i.e., variation of flow in different seasons, affecting morphological and functional diversity of rivers (including floodplains, tributaries, and distributaries), and the species of the river are influenced by feedback mechanisms (Smakhtin and Anupthas 2006). The necessary components of the hydrological regime have certain ecological significance in a year—(1) channel maintenance or hydrological recovery, the breeding ground for avian fauna, flooding of wetlands, and preservation of floodplain plants need high regime flows (mainly in monsoon); (2) cycling of organic matter from main channels to floodplains and for seasonal fish migration (mainly for breeding) need a moderate regime of flow; and (3) algae or fungi control, environmental preservation of water quality and human utilization of river need normally low regime of channel flow. Thus, EF should not “only include the quantity of water required but also when and how this water should be flowing” in the river for healthy ecological services (Smakhtin and Anupthas 2006). Due to the interdisciplinary movements of environmentalists, the ideas of EF shift away from a ‘minimum flow attitude’ to the aquatic environment.

Bunn and Arthington (2002) have postulated four basic principles in the domain of EF that call attention to the function of flow regime in developing aquatic life and explain the link between channel flow variation and environmental changes:

1. Channel flow is a key factor of physical habitat in and around the active river valleys, which is consecutively the major determinant for the healthy composition of biotic life. The composition, morphology, and diversity of aquatic communities are very sensitive to any modifications of river flow.
2. In response to the natural flow regimes of the river, the aquatic species (both flora and fauna) have evolved through life. Therefore, the loss of biodiversity of native species is very much linked with the alternatives of the flow regime.
3. Local extinction of species is escalating due to disconnection in the longitudinal and lateral connectivity in between river and floodplain (Sarkar and Islam 2020). The ability of many aquatic species, to move between the river and floodplain or between the main river and its other fluvial components, is determined and controlled by the sustainable maintenance of longitudinal and lateral connectivity in river floodplains.
4. The invasion of exotic and introduced species in the rivers is increased by the variation of flow regime.

**Environmental flow in the context of dams and development**

One of the most controversial issues in dam construction is that it promotes development on the one hand and degrades the environmental ecosystem on the other. Dams are installed for sustainable water resource management based on the principle of economically viable, socially equitable, environmentally sustainable (WCD 2000). Dams induce development by supplying water and hydropower in irrigation fields, industries, and domestic uses (Altinbilek 2002; Loomis 2002). Moreover, it creates potentiality for development as serving beneficiaries such as flood control, flow regulation, irrigation, water usage, hydropower generation, drought mitigation, recreation, fisheries, and navigation (WCD 2000; Ghosh and Mistri 2013; Tortajada 2014). Moreover, storage of these flood water through a dam leads to the development of the navigation system and fishing ground with the help of increasing water levels. Productive wetlands are also created around the reservoir. Thus, dam construction has been associated with the multipurpose project (Bhattacharyya and Wiley 2014; Patsialis et al. 2014). More than half of the world’s large dams have been built for irrigation purposes and about 30 to 40% of irrigated lands out of 268 million hectares depend on them (WCD 2000). About 12% of large dams have also been built for supplying water in various sectors in the world. In the last 2 decades, electricity production is more than twice and its demand has increased rapidly as economic development is spreading and emerging economies in the world (Yüksel 2009).
For the technical, economic, and environmental benefits, demand for pollution-free water has increased especially in developing countries (Yüksel 2009). Dams can also produce non-polluting hydropower for socio-economic development. However, it is challenging to balance water requirements for hydropower generation and ecological restoration (McManamay and Bevelhimer 2013).

Though a dam reservoir gives us several benefits to improve our lives and livelihood, it also renders several negative environmental and social impacts (Richter and Thomas 2007a, b). The most important social consequences of dam reservoirs are resettlement and displacement (Tortajada 2014). About 40 to 80 million people have been displaced. Millions of people across the world have been suffering from large dam failure, due to loss of properties and life downstream. Periodically, change in water level in monsoon season leads to submergence of the surrounding area of reservoir causing loss of properties including houses, agricultural fields, and crops. Although some social amenities and compensation for the livelihood to the displaced households around the dam are provided, dams induce some negative consequences (Ndirangu 2014). For example, siltation is the major problem in the reservoir that reduces the volume of the reservoir and submerges surrounding areas. Every year, about 0.5 to 1% of the reservoir’s volume is diminishing due to sedimentation in the reservoir (WCD 2000). Storage of sediment and heavy metals such as manganese, iron, and hydrogen sulfide lead to the killing of living organisms (Arthington et al. 2010; Kametani et al. 2017). Various types of algae grow in the reservoir that reduce the oxygen level in the water and increase biological oxygen demand (BOD). Consequently, the death of these algae changes water quality and emit greenhouse gas, such as methane, NO₂, and CO₂ from the reservoir. Greenhouse gasses also emitted from reservoirs trigger the rotting of vegetation and carbon inflow from catchment areas (WCD 2000). Living organisms cannot get essential nutrients for the loss of biodiversity. Sedimentation in reservoirs leads to a decrease in nutrients in water in the downstream segment that reduces flood plains' fertility. Besides, the sediment-starved water accelerates the riverbank erosion and perturbs the delta-building process (Fred 2006). Dam reservoir alters flow regimes and sediment budget that affect agriculture, river, and coastal erosion (Van et al. 2018). Moreover, aquatic flora and fauna species are strongly affected by flooding and lack of water. Thus, the lack of floodwater in the dammed downstream impacts soil fertility, quality, and agricultural production, and also increases the salinity of soil (Davidson and Brooke 2006).

Moreover, dam construction is the main factor for physical degradation, fragmentation, and diversion of the aquatic and terrestrial watershed ecosystem (WCD 2000) which affects human well-being, aquatic life, and the environment due to decreasing ecosystem services in the river, wetlands, and floodplains (Overton et al. 2014). The impact of dams includes closure of major river mouths, salt intrusion, destruction of mangroves, and loss of wetland. The construction and operation of dam reservoirs change the flow regime and morphology of rivers that degrade the ecological function and reduction of species diversity of the river. The degradation of the ecological function and reduction of species diversity affects the floodplain agriculture, fisheries, pasture, and forest which are the sources of community livelihood. Dam changes water quality by the process of trapping sediments and nutrients and thermal lamination and decreasing oxygen in the reservoir (Winton et al. 2019). It also changes water turbidity, temperature, and chemistry as a result of water storage, diversion, and the timing of downstream water flow that impacts biota directly (Krchnak and Thomas 2009). The changing water-quality parameters recover slowly after releasing water from the dam and the oxygen level recovers within 1 or 2 km downstream of the dam. However, the changing temperature may even exist a hundred km downstream where it does not allow the recovery of natural levels of biological tolerance and affects many aquatic communities for hundreds of kilometers (WCD 2000).

According to the World Resources Institution (WRI), 46% of 106 main watersheds in the world are modified by more than one large dam (WCD 2000). Besides, at least 60% of the world’s rivers are blocked by over 50,000 large dams (Akmetshin and Kovalenko 2019). However, 60% of the world’s rivers are affected by the diversion of their water (Altinbilek 2001). As dam fragments and stops the natural flow of the river to meet the needs of domestic and industrial water (WCD 2000), it hinders the ‘flushing out mechanism’ to clean up various pollutants which emerge from industries (Dudgeon 2000). The inadequate flow downstream also restricts organic carbon flow leading to greenhouse gas emissions such as CO₂ and methane resulting in climate change (WCD 2000).

The changing ecological flow due to alteration in the biogeochemical cycle impacts fishes, water flow species, flora, fauna, and other species in the aquatic system that depends on the healthy river system. The altering flow also interrupts the connection between upstream and downstream of the river and its floodplains that modify hundreds of kilometers of the downstream ecosystem (Krchnak and Thomas 2009). The changing downstream flow damages the endemic aquatic ecosystem and declines the power of endemic species (Bernstein 2013). Although dam reservoir promotes fisheries upstream, in the lower stretch of the river, delta, estuary, marine fish production is reduced due to decreased freshwater and nutrient flow. Besides, it also interrupts the species movement, decreases species composition, and results in the loss of some species in the downstream and upstream segments. Several species cannot complete their life cycle. For example, the decline of Salmon fish is due to
the altering of hydrological regimes by dam construction (Rothfeder 2001; Pitzl 2007).

**Human intervention on environmental flow in the monsoon Asia**

The maximum rivers of monsoon Asia are rain-fed as indicated by the term “monsoon” (seasonal). As the Asian climate is influenced by the monsoon regime, drought and floods are common phenomena. Therefore, mitigating their negative impacts, water resource management plays a vital role in this continent, especially in the dry period and dry areas (Patsialis et al. 2014). Many river basins in the southern and western states of India face physical or economic water deficiency triggering drought (Casadei et al. 2016), while the basins in the east receive surplus water resulting in flood conditions (Smakhtin and Anputhas 2006). That is why, the river water stock, altering and diverting flow for utilization of water are needed to meet socio-economic needs (Jain and Kumar 2014). To meet these demands of water and control floods, structural intervention as the water resource management tools came into existence. Structural interventions like dams try to manage river water resources for mitigating the effects of drought and floods. Moreover, they play a key role in their water holding capacity and providing water where it is needed for societal and environmental development (Ajenikoko and Ashafa 2017).

The downstream of river systems face no flow as a result of water holding structures for hydropower production, the water supply for irrigation fields, and bridge construction that induce a remarkable impact on the aquatic ecosystem (Mitra and Singh 2018). Flow characteristics are responsible for changes in the dam’s downstream hydrological, sedimentological, and geomorphological characteristics (Pal 2015). Several hydropower plants in the Himalayan region alter river flow regimes which affect the riverbank, river bed, and its ecology, especially in the dry season. Diversion of Amu and Syr Rivers for irrigation purposes changed the flow regime and led to 80% volume losses of the Aral Sea (Barlow and Clarke 2002). Moreover, massive diversion and alteration of upper Damodar River water into canals lead to a reduction in the natural flow regime of the lower Damodar, and practically, it becomes a dry and timid channel (Ghosh 2011, 2014). Hence, the diversion and alteration of the natural river flow of Asian rivers led to the degradation of the environment. Inadequate flow in the river system is detrimental to the endangered ecosystem.

The creation of dam reservoirs also stops the natural river flow which changes the natural flood cycle resulting in the alternation of the sediment budget and sediment transport capacity in the downstream floodplain, and delta. Current water flow in the Sundarban’s river systems is incapable to sustain their ecosystem function, because decreasing flow degrades the ecosystem services and separates river reach. Therefore, the flow is needed in rivers' upper reach to enhance the ecosystem services and function of the Sundarban mangrove region (Hazra et al. 2015). For the improvement of the present ecosystem service in the Asian rivers, there is a need to maintain environmental flow and to reduce the disturbance on the freshwater regime of a particular region. For example, water resource assessment and developmental projects in the Damodar river basin need to maintain rules and regulations to serve the environmental flow in the Damodar river basin (Verma et al. 2015). Thus, structural interventions in the monsoon Asia’s river systems lead to regional development through water resource management and developmental project, but improper management of water resources hinders the downstream ecosystem, hydromorphology, and communities resulting from their negative impact on flow volume, pattern, and quality (World Bank 2008).

The other developmental projects (e.g., hydropower, thermal power, industries, and agricultural lands) destroy water quality and interrupt natural water flow leading to degrading the environment that hinders the aquatic biodiversity and their services. The process of hydropower generation is harmful to water quality, because it increases water temperature and traps nutrients and sediments. Polluted water with various harmful elements coming out of various industries mixes into river water depleting water quality. The thermal power plant needs a huge amount of water for power generation. For that, it extracts water from the river and depletes river water quantity and quality. An excess of river water extraction for other purposes also intervenes in environmental flow. The increase in population, and booming of consequent economic growth, and the rising demand for freshwater accelerate river water extraction without consideration of environmental sustainability that pushes back the system to cross the biogeochemical limits leading to ecosystem degradation (Karakaya and Evrendilek 2013; Jain 2015). Mining activities also trigger erosional processes due to deforestation that leads to sedimentation in the reservoirs. They destroy river water quality, because a large amount of dust and various intoxicants mix into river water from mining sectors (Kumar et al. 2016), and decrease in streamflow and water quality in reservoirs and rivers. The downstream water quality is also damaged due to the standstill condition of flow in the summer season and polluted water mixes into river water from industries and agricultural fields. Hence, a minimum flow needs to be restored as a natural flow. Besides, implementing environmental flow needs the due

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consideration of these types of developmental projects (Kumar et al. 2007).

Environmental flow requirements of Indian rivers

Rapid urbanization, industrialization, and intensification of agriculture are very pertinent issues in India and these anthropogenic factors together affect deeply the hydrogeomorphic and environmental structure of Indian Rivers, creating major environmental concerns in Anthropocene. Hundreds of multi-purpose dams and reservoirs, like Damodar Valley Corporation (DVC), for water supply, irrigation, hydropower, flood management, and fisheries have been developed. Besides, in the Indo-Gangetic Plains many floodplains (viz., Ganga, Ghaggar, Kosi, Yamuna, Bhagirathi-Hooghly Rivers, etc.) have been detached from the main rivers by elevated embankments, and remaining riparian lands are under intensive agriculture, urbanization, and grazing pressure (Smakhtin and Anputhas 2006). Human settlements and anthropogenic activities (like mining, damming, deforestation, and pollution generation) have degraded the environmental quality of river valleys and increased sedimentation in all rivers of India. All the affected riverine biota and species composition have been altered, and many species have nearly been vanished or endangered (like Fishing Cat, Smooth-coated Otter, Gangetic Dolphin, Gharial, Ganges Shark, Sarus Crane, etc.). In India, the river basins, mainly Ganga–Brahmaputra–Meghna Delta, are now strongly affected by flow fragmentation and regulation due to high demand and global climate change (Smakhtin and Anputhas 2006). Central Pollution Control Board (CPCB) data show that the ten dirtiest river stretches in 2018 were found on river Vasishtha (Tamilnadu), Ghaggar (Haryana and Punjab), Bhadra (Gujarat), Mithi (Maharashtra), Sabarmati (Gujarat), Hindon (Uttar Pradesh), Sutlej (Punjab), Khori (Gujarat), and Thirumanimuthar (Tamil Nadu). CPCB is currently monitoring 445 rivers in India and the number of polluted stretches (in the category of 3–6 mg l−1 of BOD level) increases from 36 (2009) to 175 (2018). West Bengal Pollution Control Board (WBPCB) identifies 17 stretches of river as polluted based on BOD, DO, and total Coliform (Table 1).

The expressions such as ‘environmental flows’ and ‘water for nature’ mean an allocation of river water must be made for nature at first, then allocating water for different uses (Smakhtin and Anputhas 2006). It is found that the status of environmental flow research is not very satisfactory in India and this research is now under a growing stage of development. The National Commission for Integrated Water Resource Development Plan (NCIWRDP) efficiently established that it was not achievable to calculate approximately the amount of water required for different environmental purposes (Smakhtin and Anputhas 2006). The Supreme Court of India had made a judgment on the issue of minimum flow. In 1999, the Supreme Court of India directed the central government to guarantee a minimum flow of 10 m³ s⁻¹ in the Yamuna River as it flows through New Delhi for improving its water quality (Smakhtin and Anputhas 2006). The EF of the Baitarani River has been estimated based on the need to sustain 7-day minimum and 1-day maximum channel flows in the river. The entire country has an environmental flow of about 476 km³ which constitutes

| Sl no. | River                | Polluted stretch               | BOD (mg l⁻¹) when identified as polluted | BOD (mg l⁻¹) at present | DO (mg l⁻¹) at present | Total Coliform (MPN/ 100 ml) at present | Fitness comment       |
|-------|----------------------|--------------------------------|------------------------------------------|-------------------------|-----------------------|-----------------------------------------|-----------------------|
| 1     | Vindyadhari          | Haroa bridge to Manlancha burning ghat | 26.7–45.0                               | 14.69                   | 1.8                   | 130,000                                 | Class D, not fit for bathing |
| 2     | Mahananda            | Siliguri to Binaguri           | 6.5–25                                   | 21.0                    | 4.8                   | 220,000                                 | Class D, not fit for bathing |
| 3     | Churni               | Santipur town to Majhadia      | 10.3–11.3                                | 3.1                     | 4.0                   | 35,000                                  | Class D, not fit for bathing |
| 4     | Dwarka               | Tarapith to Sadhak Bamdeeb ghat | 5.6–17                                   | 3.15                    | 7.3                   | 54,000                                  | Class D, not fit for bathing |
| 5     | Bhagirathi-Hooghly   | Tribeni to Diamond Harbour     | 5.0–12.2                                 | 4.5                     | 7.1                   | 170,000                                 | Class D, not fit for bathing |
| 6     | Damodar              | Durgachakhm to Dishergarh      | 4.4–8.2                                  | 3.95                    | 7.1                   | 12,000                                  | Class D, not fit for bathing |
| 7     | Jalangi              | Lal Dighi to Krishnanagar      | 8.3                                      | 3.8                     | 6.5                   | 17,000                                  | Class D, not fit for bathing |

WBPCB (2020)
approximately 25% of total renewable water resources in India (Smakhtin and Anputhas 2006).

**Environmental flow of Damodar River**

**River of agony**

Damodar River plays a key role in providing a source of drinking water, water for irrigation and power, industrial needs, and coal mining activities in the basin. The River once known as the ‘River of Sorrow’ because of the severity of the flood (Mahammad and Islam 2021b) has now turned into a ‘River of Agony’ due to the environmental degradation of the river resulting from the indiscriminate discharge of domestic, industrial, and mining wastes from the basin (Patra 2008). The agony side of DVC dams is now evidenced by the inhabitants of Damodar Floodplain. After dam construction, each person expected that the extreme floods would completely have vanished from this region, but the flood is now modified its character, promoting low peak but longer duration (more than 1 week), due to drainage congestion, delinking of palaeochannel from the main river, and the inability of regulated discharge due to reservoir siltation. Moreover, the river stretches about 68 km from the downstream of Panchet Dam to the

![Damodar river valley with principal industries](image1)

![Damodar river valley with principal industries](image2)
upstream of Durgapur Barrage in West Bengal passing through the main industrial belt of eastern India and covering important cities like Kulti, Barakar, Asansol, Raniganj, and Durgapur has been affected due to environmental stress and water pollution (Fig. 3). The stretch is receiving a large number of point and non-point sources of pollution from thermal power plants, collieries and coal-based industries, steel, cement, fertilizers, chemical, and other plants as well as domestic and agricultural areas that lead to the water pollution to the river either directly or through numerous drains and nullahs (Patra 2008).

Environmentalists often said that the industrialists exploiting the area’s resources are not willing to make a positive change in the physical environment. It was informed by public media that about 200,000 L of furnace oil spilled into the water of Damodar from the Bokaro Steel Plant (BSP) on 2nd April 1990. To check that disaster the authorities of BSP and government took at least 4 days. It was informed that the spilled oil was reached up to Durgapur (150 km from BSP) after a week and five million people of this area used the contaminated water of Damodar. That disaster was not noticed by any pollution control authorities of India. That incident was first noticed by a downstream thermal power plant which abruptly found the inefficiency of the cooling process in its boilers, raised the alarm. That event of 1990 gave us a vulnerability alarm of industrial accidents in the river, because more than 50 major industries and more than 400 industrial units have developed on the banks of the Damodar River. The states of Jharkhand and West Bengal depend on the river water and the power plants developed in the valley. The thermal power plants of DVC alone generate about 1800 MW of electricity. Considering the environmental concern, the biggest threat to the Damodar River is the vast mineral resources of the Chottanagpur Plateau which are intensively exploited due to the mounting demand of the Indian economy. The River is badly affected both physically and ecologically by dumping urban waste material with extensively industrial effluents discharge and siltation with reducing river water flow (Fig. 4). The River Course is also influenced by changing land use and cropping pattern, creating fluvial metamorphosis. Thus, the river tends to become an ecological desert.

**Controlled river**

Damodar is a typical flashy river that primarily derives its flow from immediate surface runoff resulting from rainfall and it is notorious for its flash floods in the past. Its annual mean discharge is 12,210 million m$^3$ and about four-fifths of its flow are recorded during the monsoon period (June–September) (Patra 2008). There is a wide seasonal fluctuation in the river flow depending on the variation of rainfall, occasional storms, intense cyclones, and resultant surface runoff. One of the perfect examples of anthropogenic intervention on the physical environment is the engineering control of the Damodar River system through the building of large dams and barrages (under Damodar Valley Corporation), expanding urban areas, and delinking the main channel from the floodplain. The total length of Damodar is 871 km, encompassing the basin area of 26,200 km$^2$. In this span of the river valley, about 49 towns and cities, 732 live coal mines, and 131 major industrial establishments have an indirect or direct impact to modify the physical environment of Damodar as per the estimate of the Central Inland Fisheries Research Institute (CIFRI 1988). To minimize floods and to enhance water resource management, five reservoirs and one barrage have been constructed across the rivers of Damodar Basin to store 1270 million m$^3$ of water (Table 2). During 8 dry months (November to June), the River Damodar is allowed to sustain a perennial flow by regulating the reservoir sluices of DVC and IWD. Efforts of DVC are made to maintain the flow rate of 16.14 m$^3$ s$^{-1}$ above Panchet Dam, and 12.17 m$^3$ s$^{-1}$ for the next stretch up to Durgapur and below Durgapur 2.83 to 5.66 m$^3$ s$^{-1}$.

**Quantifying environmental flow using flow regime**

The first approach to quantifying environmental flow only focuses on minimum flow, based on the idea that all river health problems are associated with low flow. In environmental flows, (1) flow regime should be considered and (2) level of conservation for the ecosystem is intended in Damodar River. Environmental flow includes the discharge of a particular magnitude, frequency, and timing which are necessary to ensure that a river system remains environmentally, economically, and socially healthy. The flow regime of Damodar, comprising the five key components of variability, i.e., magnitude, frequency, duration, timing, and rate of change, is recognized as central to sustaining biodiversity and ecosystem integrity. In FDC, the 17 percentage of points is used on the probability axis: 0.01, 0.1, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95, 99, 99.9, and 99.99 percentage which covers whole ranges of flow (Fig. 5). Any shift of an FDC

![Fig. 4 Choking of environmental flow by anthropogenic activities](image-url)
Based on the hydrological EF assessment methodologies, the flow duration curve links EFs with environmental management classes (EMCs) which are used to illustrate the hydrological situations of the river (Jain and Kumar 2014). The anticipated situation of the river is termed EMC. The higher EMC denotes that the river needs more water with greater water flow to maintain the river ecosystems. The monthly flow duration curves of EF of each EMC shift to the left concerning percentages flow as determined by the lateral shift of the original reference FDC (Fig. 5).

According to the reference flow duration curve, any shift of an FDC to the left means that this loss (part of variability is lost) is due to the reduced assurance of monthly flows, i.e., the same flow will be occurring less frequently.

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According to the reference flow duration curve, any shift of an FDC to the left means that this loss (part of variability is lost) is due to the reduced assurance of monthly flows, i.e., the same flow will be occurring less frequently. The flow duration curve has shifted left from the pre-dam period to the post-dam period at Rhondia of Damodar River (Fig. 6a). Therefore, the analysis of flow and presentation of the flow duration curve indicates that the variability is lost due to reducing flows in the river. The flow analysis at Rhondia in pre-dam (1940–1950) and post-dam (1993–2008) periods of Damodar River reveals that the flow discharge corresponding to 85% exceedance probability is 0.7 m³/s and 2 m³/s in the pre and post-dam periods, respectively, while the corresponding flow to 1% exceedance probability is 3575 m³/s and 2460 m³/s in the pre-dam and post-dam periods, respectively (Fig. 6b). The corresponding flow to 1, 5, 10, 20, and 30% exceedance probability is found to reduce indicating a decrease in daily high flow, while corresponding flow to 40, 50, 60, 70, 80, and 85% exceedance probability is found to increase implying an increase in daily low flow (Table 3).

The downstream variability of environmental flow is obvious due to longitudinal disconnectivity by installing dams and barrages (Verma et al. 2015). After satisfying the water demand of large-scale industries and collieries (from Dhanbad to Durgapur region, nearly 115 km stretch of Damodar River), the minimum flow of lean period (mainly summer), deriving from stochastic FDCs of 60-day daily mean flows, ranges in between 1.14 and 0.79 m³s⁻¹ which can be recognized as the predicted environmental flow of lower Damodar River up to the Durgapur Barrage. The intensive anthropogenic withdrawal of groundwater, from the Damodar valley, can act as catalysts for the minimum base flow of lean period (promoting dryness of riverbed), because the loss of aquifers (declining pre-monsoon groundwater depth of > 4 m bgl in between 2006 and 2015 in Paschim and Purba Barddhaman) reduces lateral connectivity of river with groundwater at the time summer to sustain...
flow. Surely, it is a critical issue for the survival of riverine flora and fauna under the direct influence of water crisis, urban-industrial pollution, and climate change. For making India’s rivers free-flowing again, the National Green Tribunal (NGT) of India has advised maintaining a minimum or optimum environmental flow of 15–20% of the average lean season course in all rivers of all states. In the study of the Yamuna River Basin, Smakhtin et al. (2007) estimated that a minimum flow of 10 m$^3$s$^{-1}$ is essential to maintain the ecological balance of a highly polluted river. Our study reveals that in this monsoon-dominated and dam-induced Damodar River Basin, the minimum flow varies widely from 2.04 to 16.81 m$^3$s$^{-1}$ (based on 7Q10 and 7Q100), which is situated at a critical level in respect of all Indian rivers.

Moreover, a paradigm shift of streamflow is observed from August to September after the dam was installed on the Damodar River (Fig. 7). It has an immense impact on the breeding functionality and monsoonal movement of fishes upstream of Damodar River. The fishes have to adjust to this altered peak condition after dam construction. Besides, maximum annual floods or overbank flows were essential conditions in the pre-dam period for the distribution of fishes throughout the wetlands of the Damodar floodplain. After dam construction, the physical barriers hampered the fish movement, and uncertainty of peak flood flows (controlled by reservoirs) occurred throughout the year, providing problems to breeding movement and egg-laying period of fishes. The peak attenuation of flow now recorded in September is not suitable for the growth of many fishes, because it intentionally increases the timing of the breeding or egg-laying period of fishes (Hayes et al. 2018). This condition directly poses threat to the fish species population toward extinction, and it indirectly affects the livelihood of inhabitants.

Furthermore, several devastating floods with more than 18,000 m$^3$ s$^{-1}$ peak discharge occurred with high peak streamflow in the pre-dam periods (1823–1957) of the Damodar River (Fig. 8a). The mean peak discharge was 9,504 m$^3$s$^{-1}$ in the pre-dam period as per the observed year’s data of floods. In this context, DVC came into being to regulate the flow of the Damodar River to fulfill its primary objective of flood control and management of water resources in the basin. After the construction of dams, the magnitudes of floods and their frequency reduced substantially. The average peak discharge floodwater is 3,598 m$^3$s$^{-1}$ in the post-dam period (Table 4). The analysis based on the daily streamflow of the Damodar river at Rhondia in the pre-dam (1940–1949) and the post-dam (1993–2007) period indicates that in the pre-dam periods, 62.60% (229 days/year) days of streamflow was below 283.2 m$^3$s$^{-1}$ which has increased to 71.92% (261 days/year) days.
in the post-dam period. Therefore, the streamflow of more than 566.4 m$^3$ s$^{-1}$ has been decreased after the construction of dams on the Damodar River (Table 5). Besides, seasonal streamflow characteristics of Damodar at Rhondia in pre-dam (1934–1956) and post-dam (1959–2007) periods indicate that regarding all the seasons except monsoon, the average percentage of streamflow has increased with higher SD and CV (Table 5; Fig. 8b).

The analysis of discharge characteristics into four climatic seasons, i.e., summer, monsoon, autumn, and winter, reveals that there is a sharp change in streamflow characteristics of each season from pre-dam to post-dam periods. The total annual discharge is found to decrease from the pre-dam to the post-dam periods. Besides, the mean discharge has decreased in the monsoon season, but the other three seasons portray increases from the pre-dam to the post-dam periods. Therefore, the presence of a dam in the system brought regulated discharge in the off-monsoon season and reduced the flow in monsoon due to the catch/filling of water in the monsoon period. However, the absolute reduction in flow due to damming and eventual distribution of dammed river water to the agricultural fields through the irrigation canal poses a threat to environmental flow and aquatic ecosystem (Dickens et al. 2019). Moreover, rivers need water (annual fluctuation of flow), debris, and sediment to ensure that aquatic ecosystems stay healthy and provide benefits to people (Dickens et al. 2019).
et al. 2019). Integrating flow management into river basin development provides the means to make consensus-based decisions on how to manage trade-offs between infrastructure development (including agriculture and hydropower), livelihoods, and ecosystems. Loss of natural flow regimes (i.e., seasonal fluctuation of streamflow) disrupts the productivity of freshwater and estuarine fisheries and flood-recession agriculture (Dickens et al. 2019). Thus, flow fluctuation is needed for species diversity; however, the DVC dams have controlled the fluctuation for the benefit of industry, agricultural irrigation, and the water demand of cities.

**Water quality status and industrial effluents**

Water pollution both surface and sub-surface is the main environmental issue in India. The water resource is being polluted due to various sources from different activities, both directly or indirectly. The sources of water pollution in India are untreated municipal sewage and its unplanned waste disposal, improper treatment of industries effluent (Sarkar et al. 2021) and its waste disposal, intensive use of agro-chemical in irrigation, excessive exploitation of ground and river water, and agricultural effluent (Fig. 9a–f).

In the upstream area of Panchet Dam, River Damodar when flows through the coal belt of Jharkhand gets polluted seriously due to the discharge of industrial effluents from fertilizer factories, cement factories, coal washeries, mica factories, steel plants, etc. National Environmental Engineering Research Institute (NEERI) had prepared a pollution report of Damodar in 1994. In general, the river of West Bengal is said to be polluted, if the river water is polluted with organics (BOD > 3 mg l⁻¹). It was found that

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**Table 3** Frequency analyses for pre-dam and post-dam flow at Rhondia of Damodar River

| EF  | Pre-dam (1940–1950) | Post-dam (1993–2008) | Change | Pre-dam (1933–1957) | Post-dam (1959–2010) | Change |
|-----|---------------------|----------------------|--------|---------------------|----------------------|--------|
| %   | (m³/s)              | (m³/s)               | (%)    | (m³/s)              | (m³/s)               | (%)    |
| 1   | 3575                | 2460                 | −1115  | 0.2                 | 17,682               | 11,542 | −6140  |
| 5   | 1977                | 1139                 | −838   | 0.5                 | 16,950               | 10,742 | −6208  |
| 10  | 1263                | 681                  | −582   | 1                   | 16,271               | 10,029 | −6242  |
| 20  | 577                 | 322                  | −255   | 2                   | 15,456               | 9209   | −6247  |
| 30  | 200                 | 168                  | −32    | 5                   | 14,104               | 7926   | −6178  |
| 40  | 85                  | 99                   | 14     | 10                  | 12,797               | 6772   | −6025  |
| 50  | 38                  | 66                   | 28     | 20                  | 11,129               | 5415   | −5714  |
| 60  | 19                  | 37                   | 18     | 50                  | 79,126               | 3164   | −75,962 |
| 70  | 9                   | 16                   | 7      | 80                  | 50,529               | 1577   | −48,952 |
| 80  | 3                   | 6                    | 3      | 90                  | 3816                 | 1024   | −2792  |
| 85  | 0.7                 | 2                    | 1.3    | 95                  | 29,517               | 691    | −28,826 |

Source: Bhattacharyya and Wiley 2014

*EF* exceedance frequency (% of time the flow indicated is equalled or exceeded in the period of record)

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**Fig. 7** Hydrographs of the Lower Damodar River in pre-dam (1934–1956) and post-dam (1959–2007) periods (Based on Bhattacharyya 2011)
in between Santhaldih and DTPS, the BOD level of river water exceeds the critical limit (i.e., greater than 3 mg l\(^{-1}\)) (Table 6). NEERI reported significant results at selected locations of the study area presented in Table 6.

Table 7 shows that DO ranges from 1.0 to 7.9 mg l\(^{-1}\) which exceeds CPCB (Central Pollution Control Board, India) standards (4 mg l\(^{-1}\) or more) and BOD ranges from 3 to 48 mg l\(^{-1}\) which also exceeds CPCB standards (3 mg l\(^{-1}\) or less). In most of the sites, the free ammonia is found to exceed the value of 1.2 mg l\(^{-1}\) (critical). According to the CPCB standard, the water of Damodar is categorized as ‘Water Class D’ (propagation of wildlife and fisheries only). In the River, \(pH\) value ranged from 7.5 to 8.9 mg l\(^{-1}\) during monsoon and 7.7 to 8.8 mg l\(^{-1}\) during post-monsoon seasons (Ghosh and Banerjee 2012). The \(pH\) in the water samples exceeds the FAO standards (6.5–8.0) for agricultural application but within the recommended IS irrigation limiting standards (5.5–9.0). Lead is an extremely pervasive

![Streamflow of the Lower Damodar River at Rhondia: a. magnitude of streamflow; b. monthly average streamflow (Based on Bhattacharyya 2011)](image-url)
and toxic environmental contaminant in water; and its values range from 0 to 0.071 mg l\(^{-1}\) during monsoon and 0 to 0.092 mg l\(^{-1}\) during post-monsoon (Ghosh and Banerjee 2012). The concentrations of Pb in the River are within the recommended FAO standards (5.0 mg l\(^{-1}\)) for agricultural application. Iron ranged from 0.12 to 1.52 during monsoon and 0.052 to 3.55 during post-monsoon. It is well within FAO standards (5.0 mg l\(^{-1}\)), but exceeds IS irrigation standards (3 mg l\(^{-1}\)) (Ghosh and Banerjee 2012). The presence of heavy metal pollutants and the concentration of metals is in order of Fe > Mn > Pb.

There are several coal washeries, coke-oven, and soft-coke plants on both banks of the Damodar River. The traditional industries, chiefly supported by coal, iron, and steel, have undergone a rapid diversification and new industrial ventures, which include mainly heavy engineering, fertilizers, coal-based chemicals, current plants, and thermal power generation, are making a dominant impact on the water resources of the Damodar. The major industries have their treatment facilities, but they have discharged many pollutants into the river system. Those industries having a direct impact on Damodar are identified as: (1) Santaldih Thermal Power Station (STPS), (2) Bhojudih Coal Washeries, (3) Dishergarh Thermal Power Station, (4) Indian Iron and Steel Company Ltd. (IISCO) Burnpur, (5) Bengal Paper Mill Co. Ltd. Raniganj, (6) Alloy Steel Plant (ASP) Durgapur, (7) Durgapur Steel Plant (DSP), (8) Durgapur Chemicals Ltd. (DCL), (9) Durgapur Thermal Power Stations (DTPS), and (10) Hindustan Fertilizer Corporation Ltd. (HFC) Durgapur (Patra 2008) (Table 8; Fig. 9c, d).

De et al. (1980, 1985) studied the impact of industrial effluents on the Damodar River near Durgapur and found that Tamla Nullah, which carried the waste of major industries like DPL and DCL, constantly contaminated the river and the barrage. High values (beyond the limit of BIS) of mixed oxides, ammonia, calcium, magnesium, total water-soluble exchange cation, and anion and COD were noted in the Bengal Paper Mill, Singaron Nullah, and HFC drain confluence, but maximum values were found at Tamla Nullah confluence where the pollution load from Durgapur region appeared to be maximum (De et al. 1985). The levels of toxic elements (e.g., arsenic, cadmium, chromium, lead, and zinc) were significant at 30 and 40 km downstream of the River from the Bengal paper Mill, Raniganj (De et al. 1985). A similar study was done by De (1993) to monitor the effects of pollution on aquatic plants and paddy husk in the Asansol–Durgapur industrial belt. He found that Asansol–Durgapur region contaminated the barrage water, while Tamla Nullah and industrial drains of the Durgapur region contaminated directly the River. River water is not safe for drinking purposes as

| Class unit in m\(^3\)/s | Percentage of total number of day | Percentage change |
|------------------------|----------------------------------|------------------|
|                        | Pre-dam                          | Post-dam         |
| < 283.2                | 62.6                             | 71.92            | 14.89 |
| 283.2–566.4            | 7                                | 9                | 28.57 |
| 566.4–849.6            | 5.3                              | 4.9              | – 7.55 |
| 849.6–1132.8           | 3.7                              | 2.5              | – 32.43 |
| 1132.8–1416            | 2.8                              | 1.6              | – 42.86 |
| 1416–1699.2            | 2.2                              | 1.23             | – 44.09 |
| 1699.2–1982.4          | 1.5                              | 0.75             | – 50 |
| 1982.4–2265.6          | 1.5                              | 0.3              | – 80 |
| > 2265.6               | 3.44                             | 1.2              | – 65 |
| No flow days           | 9.96                             | 6.5              | – 34.74 |
| –                     | 100%                             | 100%             | – |

Total number of days in pre-dam period = 3653, total number of no flow days = 364. Total number of days in post-dam period = 5425, total number of no flow days = 367. Data not available = 53 days (Source: Bhattacharyya 2011).

| Class unit in m\(^3\)/s | Percentage of total number of day | Percentage change |
|------------------------|----------------------------------|------------------|
|                        | Pre-dam                          | Post-dam         |
| < 283.2                | 62.6                             | 71.92            | 14.89 |
| 283.2–566.4            | 7                                | 9                | 28.57 |
| 566.4–849.6            | 5.3                              | 4.9              | – 7.55 |
| 849.6–1132.8           | 3.7                              | 2.5              | – 32.43 |
| 1132.8–1416            | 2.8                              | 1.6              | – 42.86 |
| 1416–1699.2            | 2.2                              | 1.23             | – 44.09 |
| 1699.2–1982.4          | 1.5                              | 0.75             | – 50 |
| 1982.4–2265.6          | 1.5                              | 0.3              | – 80 |
| > 2265.6               | 3.44                             | 1.2              | – 65 |
| No flow days           | 9.96                             | 6.5              | – 34.74 |
| –                     | 100%                             | 100%             | – |

Table 5 Seasonal streamflow characteristics of Damodar River at Rondia in pre-dam (1934–1956) and post-dam (1959–2007) periods (% of streamflow with respect to annual average streamflow total)

| Period | Parameter | Summer | Monsoon | Autumn | Winter | Mean annual total (m\(^3\)/s) |
|--------|-----------|--------|---------|--------|--------|-----------------------------|
| Pre-dam| Years     | 21     | 21      | 21     | 21     | 4061.05                     |
|        | X         | 1.4    | 83.7    | 12.23  | 2.6    | 1186.9                      |
|        | SD        | 1.32   | 7.04    | 6.49   | 2.27   | 29.23                       |
|        | CV        | 94.29  | 8.41    | 53.07  | 87.31  | 55.97                       |
| Post-dam| Years    | 48     | 48      | 48     | 48     | 2836.02                     |
|         | X         | 5.07   | 75.58   | 14.6   | 5.22   | 1587.34                     |
|         | SD        | 6.67   | 13.81   | 12.11  | 4.58   | 55.97                       |
|         | CV        | 131.56 | 18.27   | 82.95  | 87.74  | 55.97                       |

N No of years, X Average percentage of stream flow, SD standard deviation, CV coefficient of variation, Summer-March—May, Monsoon–June–September, Autumn- October–November, Winter- December–February. (Source: Bhattacharyya 2011)
it has lost its self-purification capacity. Damodar River sediments, between Raniganj and Panagarh, were polluted with toxic elements (Cd, Cr, Hg, Pb, Zn, Ni, etc.) and water is unfit for domestic purposes. Patra (2008) monitored the River and TamlaNullah, which had the COD in the range of 40–80 mg l⁻¹; BOD of 11–25 mg l⁻¹ and TSS as 50–160 mg l⁻¹. Fluvial sediments of the River, the downstream of the confluence of Tamla Nullah, was having a maximum iron content of about 21,000 mg kg⁻¹, zinc 45 mg kg⁻¹, copper 16 mg kg⁻¹, total chromium 28 mg kg⁻¹, nickel 17 mg kg⁻¹, and lead as 5 mg kg⁻¹ (Patra 2008).

Moreover, municipal waste is an important source of water pollution. The water is polluted due to the urban

Fig. 9 Dams and development in the Damodar Valley. a Negligible water flow 500 m downstream of Durgapur Barrage. b Sandy river bed of Damodar downstream of Durgapur Barrage. c Singharan Nala contributing industrial effluents to the Damodar River near Waria, West Barddhaman. d Singharan Nala passing along the ash pond of Durgapur Steel Plant, West Barddhaman. e Agricultural practice on Damodar char (mid-channel bar) near Purnia, Bankura District. f Sand mining on the river bed of Damodar near Waria (Source: Field Photographs, February 2021)
disposal and their effluents discharge into the river through the canal and tributaries. In the basin area, there have 49 (CIFRI 1988) such sources and their huge amount of effluents with pollutant mix into the river. Most of the town is an industrial or mining-based town in the basin area. According to CIFRI (1988), the basin with a 5.65 million urban population, and the river from Berom to Burdwan receives per day 273.134 MLD of municipal effluent with 174.43 tons BOD.

Table 6 Critical BOD status of Damodar River in between Santhaldih and Durgapur Thermal Power Stations (West Bengal)

| Sl. No. | Pollutant status | Site | Reason |
|---------|------------------|------|--------|
| 1       | BOD = 3.2 mg l⁻¹ | Confluence of Kadamda Nullah and Damodar | Effluent from Bhojudih coal washeries and Santhaldih Thermal Power Station (STPS) |
| 2       | BOD = 5.2 mg l⁻¹ | Damodar at Raniganj | Discharge of domestic waste from the township |
| 3       | BOD = 5.6 mg l⁻¹ | Confluence of Tamla Nullah and Damodar | Effluents from steel plants and chemical industries |
| 4       | BOD = 5.0 mg l⁻¹ | DTPS outfall | Effluent discharge from power station |

Source: Patra 2008

Table 7 Key Effluents entering into the Damodar River in selected locations in between Burnpur and Durgapur (West Bengal)

| Sl. No | Sites | TDS mg l⁻¹ | TSS mg l⁻¹ | pH | DO mg l⁻¹ | BOD mg l⁻¹ | COD mg l⁻¹ | NH₄⁺-N mg l⁻¹ |
|--------|-------|------------|------------|----|-----------|------------|------------|---------------|
| 1      | Drain from Burnpur IISCO & Township | 600 | 19 | 7.7 | 4.3 | 28 | 108 | 3 |
| 2      | Nunia Nullah before Damdoar | 540 | 29 | 7.9 | 6.4 | 5 | 48 | 8 |
| 3      | Singaran Nullah before Damodar | 480 | 19 | 8.2 | 7.9 | 26 | 160 | 0 |
| 4      | Outlet of DTPS Ash Pond | 180 | 1889 | 8.0 | 7.1 | 4 | 52 | 1.2 |
| 5      | Tamla Nullah-Channel siphon crossing | 300 | 662 | 8.5 | 5.2 | 48 | 360 | 8 |
| 6      | Ningha colliery near Raniganj | 900 | 37 | 7.8 | 1.9 | 22 | 90 | 2 |
| 7      | Ricket & Colman Ltd, Asansol | 780 | 9 | 7.8 | 7.7 | 3 | 20 | 0.5 |
| 8      | DTPS colony discharge, Durgapur | 240 | 12 | 7.6 | 1.0 | 30 | 224 | – |

Source: Patra 2008

Table 8 Identified toxic effluents of major industries entering into the river system of Damodar

| Sl. No | Industry | Major Pollutants | Receiving water body (impact) | Type of treatment available (adequacy of facilities) |
|--------|----------|------------------|-------------------------------|--------------------------------------------------|
| 1      | Santaldih Thermal Power Station | TSS, O & G | Kadamda Nullah (significant) | Settling tank (inadequate) |
| 2      | Bhojudih Coal Washeries | TSS, TDS, COD | Damodar River (significant) | Settling tank (inadequate) |
| 3      | Dishergarh Thermal Power Station | TSS | Damodar River (insignificant) | Settling tank (adequate) |
| 4      | Indian Iron & Steel Co. Ltd., Burnpur | Fe, TSS, O & G | Damodar River (significant) | ETP with lagoons (inadequate) |
| 5      | Bengal Paper Mill Co. Ltd., Raniganj | TSS, BOD, COD | Damodar River (significant) | Only lagoon (inadequate) |
| 6      | Alloy Steel Plant, Durgapur | pH, TSS, COD, O & G, Cr, Ni | Tamla Nullah (significant) | Sludge pit, Pre-neutralization with settler (adequate) |
| 7      | Durgapur Steel Plant | TSS, BOD, COD, O & G, Phenol, Cyanide | Tamla Nullah (significant) | BOD plant, settling ponds, ash ponds, oil catch pit (adequate) |
| 8      | Durgapur Chemicals Ltd | TSS, BOD, Phenol, COD, O & G | Tamla Nullah (significant) | Hg controls (inadequate) |
| 9      | Durgapur Thermal Power Stations | TSS, BOD, COD, O & G | Damodar River | Ash ponds (inadequate) |
| 10     | Hindustan Fertilizer Corporation Ltd., Durgapur | Cr, As, NH₄⁺-N | Tamla Nullah (significant) | Removal plant for As and Cr (inadequate) |

Source: Patra 2008
load. The river becomes polluted day by day due to a large amount of municipal effluent with various toxicant pollutants discharged into the river. Wastewater from industrial complexes and livestock farms contributes more of NH$_4$-N, COD, Cu, and Pb into the river.

Environmental stress

CIFRI (1988) categorized the ecological zones of Damodar River into four types—(i) Zone 1: Upstream of Tenughat Reservoir, (ii) Zone 2: Tenughat-to-Panchet Reservoir, (iii) Zone 3: Panchet-to-Durgapur Barrage, and (iv) Zone 4: downstream of Durgapur Barrage (Appendix A). A detailed study was carried out by the CIFRI during 1993–1995 to relate the level of river water pollution to the structure and functions of the aquatic organisms (CIFRI 1988). For example, in Zone 3, the plankton populations were significantly lower compared to the upstream population, especially at Chirakurhi confluence, ISSCO confluence, and Nulia Nullah discharge points (CIFRI 1988).

The suppression of these organisms may be attributed to the toxic effect of the effluents brought in through these respective sources. All 33 species inclusive of 25 phytoplanktons and 9 zooplanktons were identified from this zone in which Anacystis sp. dominated contributing 47.24% of the total plankton population. The dominance of Cyanophyceae and rotifers among plankton populations revealed a high organic load in the system in zone 3. A high density of plankton is 16 to 604 u l$^{-1}$ (average 269.56 u l$^{-1}$), observed in the river stretch which is influenced by the Asansol and Durgapur Industrial Complex (ADIC). Paria and Konar (2003) observed the highest percentage of phytoplankton and the lowest percentage of Bacillariophyceae diatom and Desmidiaceae algae among the total organisms in the Damodar River. The species diversity reflects the healthy condition of the fluvial habitat and the ideal environmental flow of the river. In the downstream of Durgapur Barrage, the species diversity of the planktonic flora and fauna gradually declined as the number of species recorded was only 18 in this river stretch (CIFRI 1988). The population density also declined (30 to 99 u l$^{-1}$; average 50.11 u l$^{-1}$). These changes of Zone 4 in the plankton population are primarily due to the mixing of industrial effluents mainly from ADIC which to some extent reflects the pollution stress in the river. Benthic organisms which are an integral part of the biocommunities and a vital component of the food chain are highly sensitive to ecological changes.

Nesemann et al. (2017) have mentioned that the use of macrobenthic invertebrates as bioindicators is more accurate than chemical and microbial analyses and this species inventory is the most popular biological method to understand environmental impact assessment of aquatic pollution. Molclusa taxu, viz., Haitia Mexicana, Digoniostomaperulchella, Digoniostomaceremepopoma, Bellamyabengalenis, Thiara lineate, Pisidiumnevillianum, etc., can be used as a pollution indicator in the Damodar River. Oligochaete and Chironomid worms both being indicators of eutrophication, this center appears to be organically polluted. However, the complete absence of mollusks and other benthic fauna does indicate the unsuitability of the river bed for colonization of diverse benthic fauna. It is needed to mention that rigorous sand mining (Fig. 9f) has modified the channel morphology to a great extent, and as a result, the population of mollusks is drastically reduced. Despite that, a positive hope can deduce in the present COVID-19 pandemic situation of 2020. The countrywide lockdown due to the COVID-19 pandemic has brought remarkable changes to the water quality of Damodar within 4 months, and it acts as a catalyst to turn a positive condition of nature’s restoration potentiality (Chakraborty et al. 2021). During the lockdown, the eutrophic zones have been significantly modified throughout the industrial stretch of Damodar River (Chakraborty et al. 2021).

Ecological stress with special reference to fish community

Physical habitat consists of channel and floodplain landforms and other geomorphic features. In this regard, ecological parameters (i.e., parameter of river water) of the Damodar River should be considered.

Changes in discharge are a form of disturbance, but a moderate level of hydrological variability enhances biological diversity. River biota has evolved adaptive mechanisms to cope with habitat changes that result from natural flow variation, and indeed, many species rely on regular or seasonal changes in river flows to complete their life cycles. Diversity of fish types, and size of fish, presence of mollusks are good indicators of river health and good environmental flows. A study carried out by the CIFRI during the early 50 s before the installation of the DVC indicates that a total of 89 species of fish were found in different stretches of the Damodar river that has decreased to only 56 species during 1993–1995 (CIFRI 1988). Moreover, a study conducted by the CIFRI (2013) and Dey et al. (2013) represent the polluted condition of the river at the Durgapur Barrage site (Appendix B). This has corresponding effects on the fish community structure (Table 9). The analysis of fish species in the Durgapur barrage, Burdwan (Krisaksetu, Barsul, and Palla sites), and Mundeshwari bifurcation sites of river Damodar reveals 46 fish species in 2013 (Table 9).

Among the 19 families of fish species, the dominant family is the Cyprinidae in all sites of river Damodar. In brief, Cyprinidae is the dominant family of fish species in all three sites of Durgapur barrage, Burdwan (Krisaksetu, Barsul, and Palla sites), and Mundeshwari bifurcation with
| Order                  | Family                        | Sl No | Scientific Name            | Local Name | Durgapur barrage | Burdwan (Krisak setu, Barsul and Palla) | Mundeshwari Bifurcation |
|-----------------------|-------------------------------|-------|---------------------------|------------|------------------|----------------------------------------|------------------------|
|                       |                               |       |                           | Durgapur   |                 | IUCN: category | Population | IUCN: category | Population | IUCN: category | Population |
|                       |                               |       |                           | Barrage    |                 |             |           |             |           |             |           |
|                       |                               |       |                           | Burdwan    | Krisak setu,   | LC           | DE         | LC           | DE         | LC           | DE         |
|                       |                               |       |                           | Barsul, Palla |               |              |           |             |           |             |           |
|                       |                               |       |                           | Mundeshwari | Bifurcation    |              |           |             |           |             |           |
| Beloniformes          | Belonidae                     | 1     | Xenentodon cancila        | Kakia      | –               | –           | LC         | DE         | LC         | DE         |
| Cyprinodontiforms     | Aplocheilidae                 | 2     | Aplocheilus panchax       | Kanpona    | –               | –           | DD         | UN         | –          | –          |
| Cyprinidae            |                               | 3     | Amblypharyngodon mola     | Mourola    | LC              | ST          | LC         | ST         | LC         | ST         |
|                       |                               | 4     | Danio devario             | Techokha   | LC              | ST          | LC         | ST         | LC         | ST         |
|                       |                               | 5     | Danio ticto               | Techokha   | LC              | DE          | NT         | DE         | NT         | DE         |
|                       |                               | 6     | Puntius ticto             | Punti      | LC              | UN          | LC         | DE         | LC         | DE         |
|                       |                               | 7     | Puntius sophore           | Punti      | LC              | UN          | LC         | UN         | LC         | UN         |
|                       |                               | 8     | Puntius phutumio          | Punti      | LC              | UN          | LC         | UN         | LC         | UN         |
|                       |                               | 9     | Puntius conchonius        | Punti      | LC              | UN          | VU         | ST         | –          | –          |
|                       |                               | 10    | Salmostoma bocalia        | Chela      | LC              | ST          | LC         | ST         | LC         | ST         |
|                       |                               | 11    | Labeo calbasu             | Kalbose    | –               | –           | LC         | ST         | LC         | ST         |
|                       |                               | 12    | Labeo bata                | Batla      | LC              | UN          | LC         | UN         | LC         | UN         |
|                       |                               | 13    | Labeo rohita              | Rui        | LC              | UN          | LC         | UN         | LC         | UN         |
|                       |                               | 14    | Cirrhinus mirgala         | Mrigel     | LC              | ST          | LC         | ST         | LC         | ST         |
|                       |                               | 15    | Catla catla               | Katla      | NE              | UN          | NE         | UN         | NE         | UN         |
|                       |                               | 16    | Amblypharyngodon mola     | Mourola    | –               | –           | LC         | ST         | LC         | ST         |
| Cobitidae             | Lepidocephalichthys guntea    | 17    | –                          | Guntey     | –               | –           | LC         | UN         | LC         | UN         |
| Clupeiformes          | Clupeidae                     | 18    | Gudusia chapra            | Khaira     | LC              | DE          | LC         | DE         | LC         | DE         |
| Osteoglossiformes     | Notoperidae                   | 19    | Nototerus chitala         | Chital     | EN              | UN          | EN         | UN         | EN         | UN         |
|                       |                               | 20    | Nototerus notopterus      | Pholui     | LC              | DE          | LC         | DE         | LC         | DE         |
| Perciformes           | Ambassidae                    | 21    | Chanda ranga              | Chanda     | NA/C            | UN          | NE         | DE         | NE         | DE         |
|                       |                               | 22    | Chanda nama               | Chanda     | NA/C            | UN          | LC         | UN         | LC         | UN         |
|                       |                               | 23    | Channa punctata           | Lata       | NA/Nc           | UN          | LC         | UN         | LC         | UN         |
|                       |                               | 24    | Channa marulias           | Sal        | LC              | UN          | LC         | UN         | LC         | UN         |
|                       |                               | 25    | Channa gachua             | Chang      | LC              | UN          | LC         | UN         | –          | –          |
|                       |                               | 26    | Channa striatus           | Sol        | NE              | UN          | NE         | UN         | NE         | UN         |
| Gobiidae              | Glossogobius giuris           | 27    | Bele                      | NA/C       | UN              | LC         | DE         | LC         | DE         |
| Nandidae              | Nandus nandus                 | 28    | Bheda                     | –          | –               | LC         | DE         | LC         | DE         |
| Osphronemidae         | Colisa fasciata              | 29    | Khalisa                   | –          | –               | LC         | DE         | LC         | DE         |
|                       | Colisa lalia                 | 30    | Khalisa                   | NA/Nc      | UN              | NE         | DE         | NE         | DE         |
Table 9 (continued)

| Order         | Family       | Sl No | Scientific Name | Local Name       | Durgapur barrage | Burdwan (Krisak setu, Barsul and Palla) | Mundeshwari Bifurcation |
|---------------|--------------|-------|-----------------|-------------------|------------------|----------------------------------------|-------------------------|
|               |              |       |                 |                   | IUCN: category   | Population | IUCN: category | Population | IUCN: category | Population |
| Siluriformes  | Bagridae     | 31    | Mystus cavassius | Tengra            | LC               | DE          | LC            | DE          | LC            | DE         |
|               |              | 32    | Mystus aor      | Aard              | LC               | ST          | VU            | ST          | VU            | ST         |
|               |              | 33    | Mystus seenghala| Tangra            | NE               | UN          | NE            | UN          | NE            | UN         |
|               |              | 34    | Mystus tengara  | Tangra            | LC               | DE          | LC            | DE          | LC            | DE         |
|               |              | 35    | Mystus vittatus | Tangra            | LC               | DE          | LC            | DE          | LC            | DE         |
|               |              | 36    | Rita rita       | Rita              | LC               | DE          | LC            | DE          | –             | –          |
| Clariidae     |              | 37    | Clarias batrachus| Magur             | LC               | UN          | LC            | UN          | LC            | UN         |
| Pangasiidae   |              | 38    | Pangasius pungasi| Pangus            | LC               | DE          | LC            | DE          | LC            | DE         |
| Sisoridae     |              | 39    | Bagarius bagarius| Garua             | LC               | DE          | VU            | DE          | VU            | DE         |
| Siluridae     |              | 40    | Wallago attu    | Bøal              | NT               | DE          | NT            | DE          | NT            | DE         |
| Heteropneustidae |              | 41    | Heteropneustes fossilis| Singi | LC               | ST          | LC            | ST          | LC            | ST         |
| Synbranchiformes | Mastacembelidae | 42    | Macrognathus pancalus| Pankal       | NA/C             | UN          | NT            | UN          | –             | –          |
|               |              | 43    | Macrognathus aculeatum| Ban             | NA/C             | UN          | LC            | UN          | –             | –          |
|               |              | 44    | Macrognathus armatus| Ban             | LC               | UN          | LC            | UN          | LC            | UN         |
| Tetradontiformes | Tetraodontidae | 45    | Tetradon fluviatilis| Potoka       | –                | –          | NE            | DE          | –             | –          |
|               |              | 46    | Tetradon cutovia| Tepa              | –                | –          | NT            | DE          | NT            | DE         |

Based on Dey et al. (2013), Saha and Patra (2013), Environmental and Social Impact Assessment Report (2018) Note: IUCN Category: Least Concern (LC); Near threatened (NT); Vulnerable (VU); Not Evaluated (NE); Data Deficient (DD); NA (this taxon has not yet been assessed for the IUCN Red List); C (this taxon is in the Catalogue of Life); NC (this taxon is not in the Catalogue of Life); Population Trend: Decreasing (DE); Unknown (UN); Stable (ST)
12 (33.33%), 14 (30.43%), and 13 (33.33%) fish species, respectively. This is followed by the Bagridae family with 5 (13.89%), 6 (13.04%), and 5 (12.82%) fish species. The next dominant family is the Channidae with 4 (11.11%), 4 (8.70%), and 3 (7.69%) fish species, respectively, in three sites of river Damodar. Based on the fish species availability at representative sites, Cyprinidontiforms order is the most dominant in all sites of Damodar River followed by Siluriformes and Perciformes. In the dominant Cyprinidontiforms order lies 12 (33.33%), 16 (34.78%), and 14 (35.9%) fish species of Durgapur barrage, Burdwan (Krisaksetu, Barsul, and Palla sites), and Mundeshwari Bifurcation, respectively. The Siluriformes order contains 10 (27.78%), 11 (23.91%), and 10 (25.64%) of fish species in three sites, respectively. Moreover, 8 (22.22%), 10 (21.74%), and 9 (23.08%) fish species belong to the Perciformes order, respectively, in the three sites of Damodar rive.

The composition, diversity of fish, and their present status are good indicators of the aquatic ecosystem and its environment. Based on the study, 24 (66%), 31(67%), and 27 (69%) fish species are the least concern (LC) recorded from of Durgapur barrage, Burdwan, and Mundeshwari Bifurcation sites, respectively. Near threatened (NT) fish species are the Danioticto, Wallagoattu, Macrognathuspancalus, and Tetrodoncutcutia which are present with the strength of 1 (3%), 4 (9%), and 3 (8%) species in the three sites, respectively. Vulnerable (VU) fish species are the Puntiusphutunio, Puntiusconchonius, Mystusaor, and Bagariusbagarius which account for 3 (7%) in Burdwan and 3 (8%) in Mundeshwari Bifurcation site. According to the study, 10 (28%), 6 (13%), and 5 (13%) fish species are not evaluated (NE) in the selective sites. One fish species (Notopteruschitala) is endangered in all three sites and one data-deficient (DD) species is the Aplocheiluspanchax found in the Burdwan site.

The study conducted by the CIFRI (2013) reveals that 9 (25%), 19 (41%), and 17 (44%) fish species population is decreasing in Durgapur barrage, Burdwan, and Mundeshwari Bifurcation sites of river Damodar, respectively. Decreasing fish population in an aquatic system indicates the environmental degradation of that aquatic system. The unknown populations of fish species are 21 (58%), 18 (39%), and 13 (33%), respectively, in three sites of river Damodar, while 6 (17%), 9 (20%), and 9 (23%) fish species are stable in the three sites of river Damodar, respectively.

**Postscript and future direction of research**

**Significance of the study**

The concept of environmental flow can be applied widely to water bodies such as streams, rivers, lakes, estuary, floodplains, and groundwater for increasing and restoring ecosystem health. It needs the volume of water, right frequency, right time, and the right length of flow time for sustaining a healthy river and maintaining the ecological health of river systems (Tremblay 2010). The conservation and recovery of riverine ecosystems depend on releasing of flow regime and exact modeling among the hydrological pattern, fluvial, inconvenience, ecological reaction of river, and floodplains (Arthington et al. 2010). The changing natural flow pattern impacts river hydrology which can recover through releasing environmental flow which can recover through releasing environmental flow (Jayasiri et al. 2017). Better planning, design, and operation of the dam should minimize negative impacts and exhibit where to build or not to build it (King and Brown 2018). Thus, the dam consequences should be minimized through comprehensive environmental flow assessment with Cumulative Impact Assessments (CIAs) (King and Brown 2018). Environmental flow assessment and flow management should be the basic equipment of integrated water resource management, environmental impact assessment, and strategic environmental assessment. They also need certification of industrial development infrastructure and land use, water use, energy production strategies (The Brisbane Declaration 2007). Environmental impacts’ assessment on all developmental projects such as hydropower generation, water extraction for irrigation, industrial, domestic, and other uses including water regulation should be made mandatory for estimating environmental flows (Eriyagama and Jinapala 2014). These development projects must obey environmental protection law and maintain minimum environmental flow in aquatic systems, especially during the dry period.

The implementation and management of environmental flow can be extensively exercised on the ecological limits with hydrological alteration for freshwater sustainability (Poff et al. 2009). The implementation of the environmental flow concept in the river system leaves behind the speed of river ecosystem modification (Grantham et al. 2014). It mitigates the negative impacts of the dam on downstream hydrology and geomorphology, ecology, and the environment and helps for aquatic biodiversity conservation, reducing ecosystem modification and decreasing the negative impacts on the river system (Godinho et al. 2014). To serve the environmental flow, flow needs to be released intentionally from the dam downstream of the river for improving its ecological condition, providing healthy ecosystem services, and also maintaining downstream environmental flows. Its implementation is the main component of Integrated Water Resource Management (IWRM); however, the implementation is still limited on water resource management because of unknown flow regime requirements and interdependence between stakeholder consequences (Overton et al. 2014). It is very difficult to meet environmental goals, because environmental situations are rarely considered for productivity.
goals. However, its implementation has affected waterbody’s hydromorphology (Ramos et al. 2017). However, its implementation is still restricted to many river systems in developed countries and infrequent in developing countries (Eriyagama and Jinaapala 2014). Although its acceptance and implementation are incorporated into water policies and laws of the IUCN, it needs to be integrated into sustainable water management by making the liability of the government, ministries, and other stakeholders (Chen and Wu 2019). Achieving sustainable development downstream requires rising care by countries especially the developing nations, both by the public and private sector investments (World Bank 2008).

**Future directions**

The present work found that the status of the environmental flow of the Indian rivers especially that of West Bengal is not supportive of the sustainability of the aquatic organisms and the development of the society and economy. Though the consciousness and the measures to protect the environmental flow is getting importance across the world especially in the developed nations, the situation is not at all encouraging for the state of West Bengal, especially for the Damodar River. Therefore, more concentrated research is required in some dimensions. First, identifying typical sources of alteration in river flow regimes concerning dams, barrage, weir, water diversion, urbanization, levees and embankments, sand mining, and groundwater pumping is required. Second, sediment movement and disposition are modified by dam-induced discharges. Coarsening of streambed can, in turn, reduce habitat availability for aquatic species. Changes in flow regimes should be related to dam construction, fragmentation of habitat, and loss of natural connectivity. This perspective should be attempted in the context of the Indian rivers. Third, research may be carried out on alterations of flow components responsible for reduced diversity, loss of sensitive species, dominant taxa, life cycle disruption, reduced species richness, seasonal reproduction, riparian plant growth, loss of floodplain specialists in mollusk assemblage, etc. Fourth, for measuring E. flow of the river of West Bengal, hydrological and ecological data of the more gauge stations are required. This aspect may also encourage other researchers and organizations from physical geography and ecology to focus on these aspects. Finally, multidisciplinary research is also required to comprehend the complexity of the ecological system and dynamics of E. flow.

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**Declarations**

**Conflict of interest** The authors declare that they have no conflict of interest.

**References**

Acreman M (2016) Environmental flows-basics for novices. Wires Water 3:622–628
Ajenikoko GA, Ashafa OA (2017) Development of a flow rate model for retrofitting of dam for hydroelectric power generation. ISJ Theoret Appl 06(50):1–13
Akhmetshin E, Kovalenko K (2019) Construction of large dams: problems and development trends. MATEC Web Conf 265:1–5
Altinbilek D (2001) The role of dams in development. In: Internationl Fieriery Symposim, pp 59–63
Altinbilek D (2002) The role of dams in development. Int J Water Resour Dev 18(1):9–24
Arthington AH, Naiman RJ, McClain ME, Nilsson C (2010) Preserving the biodiversity and ecological services of rivers: new challenges and research opportunities. Special Issue Environ Flows Sci Manag 55(1):1–36
Barlow M, Clarke T (2002) Blue Gold: the fight to stop the corporate theft of the world’s water. The New Press, New York
Bernstein A (2013) Sustainable water management using environmental flows in the connecticut river. Environ Water Resour Eng Masters Projects. https://doi.org/10.7275/FFFN-QA35
Bhattacharyya K, Wiley MJ (2014) Dams, riparian settlement and the threat of climate change in a dynamic fluvial: a case study of the Damodar River, India. Springer Science Business Media Dordrecht, pp 75–100
Bhattacharyya K (2011) The lower Damodar River, India: understanding the human role in changing fluvial environment. Springer Science & Business Media
Blaney D (2013) Environmental flows, political dams. J Polit Sci Public Affairs I(2):1–7
Bunn SE, Arthington AH (2002) Basin principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environ Manage 30:492–507
Casadei S, Pierleoni A, Bellezza M (2016) Integrated water resources management in a lake system: a case study in Central Italy. Water 8(12):570
CIFRI (1988) The River Damodar and Its Environment. Indian Council of Agricultural Research, Barrackpore, Bull. No. 73. http://www.cifri.res.in/Bulletins/Bulletin%20No.79.pdf
CIFRI (2013) Environment and Fisheries of River Damodar. Indian Council of Agricultural Research, Barrackpore, Bull. No. 183. http://www.cifri.res.in/Bulletins/Bulletin%20No.183.pdf
Chakraborty B, Roy S, Bera A, Adhikary PP, Bera B, Sengupta D, Bhunia GS, Shit PK (2021) Eco-restoration of river water quality during Covid-19 lockdown in the industrial belt of eastern India, Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-12461-y
Chen A, Wu M (2019) Managing for sustainability: the development of environmental flows implementation in China. Water 11(3):433
Maran S (2004) Environmental Flows and integrated water resource management: the Vomano River case study. Assessment and provisioning of environmental flows in Mediterranean watercourses, IUCN.unemed.org

McManamay RA, Bevelhimer MS (2013) A Holistic framework for environmental flows determination in hydropower contexts. Oak Ridge National Laboratory, Oak Ridge. http://www.osti.gov/bridge

Mitra S, Singh A (2018) Assessment of environmental flow requirements of damodar river basins by using flow duration indices method – a case study. Int J Hydrol 2(3):281–283

Mahammad S, Islam A (2021a) Evaluating the groundwater quality of Damodar Fan Delta (India) using fuzzy-AHP MCDM technique. Appl Water Sci 11(7):1–17. https://doi.org/10.1007/s13201-021-01408-2

Mahammad S, Islam A (2021b) Identification of palaeochannels using optical images and radar data: A study of the Damodar Fan Delta, India. Arab J Geosci 14(17):1–22. https://doi.org/10.1007/s12517-021-07818-5

Ndirangu SM (2014) The Effects of dam construction process on household livelihoods: a case of Thiba dam in Kirinyaga County, Kenya. A Research Project Report Submitted in Partial Fulfilment of the Requirements for the Award of the Master of Arts Degree in Project Planning and Management, pp 1–73

Nesemann HF, Sharma G, Kumar R, Sheetal A, Roy S (2017) Do the rivers of Chota Nagpur dry forests (Jharkhand), Damodar and Subarnarekha differ in biodiversity of aquatic macrozoobenthos, functional feeding groups, and biological water quality? Aquat Ecosyst Health Manage 20(1–2):116–129

Overton IC, Smith DM, Dalton J, Barchiesi S, Acreman MC, Stromberg JC, Kirby JM (2014) Implementing environmental flows in integrated water resources management and the ecosystem approach. Taylor & Francis 59(3–4):860–877

Pal S (2015) Impact of Massanjore dam on hydro geomorphological modification of Mayurakshi River Eastern India. Springer Science Business Media Dordrecht, pp 921–944

Paria T, Konar SK (2003) Ecological degradation of some rivers in West Bengal: River Pollution in India and Management. APH Publishing Corporation, New Delhi

Patra S (2008) Pollution profile of Damodar River in a particular stretch. Unpublished Report of Master of Technology in Conservation of Rivers and Lakes, Alternate Hydro Energy Centre, Indian Institute of Technology Roorkee. http://shodhbkhabharth.iitr.ac.in:8081/jspui/bitstream/123456789/12088/1/HYDG13946.pdf

Patsialis T, Skoulilakis C, Ganoulis J (2014) Ecological flow for integrated planning of small hydropower plants: a case study from Greece. In: Hydrology in a Changing World, pp 469–474

Pitz G (2007) Colorado River. In Encyclopedia of Environment and society, vol I. SAGE Publications, Thousand Oaks, CA

Poff LN, Richter BD, Arthington AH, Bunn SE, Naiman RJ, Kendy E, Warner A (2009) The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. Freshwater Biol. https://doi.org/10.1111/j.1365-2427.2009.02204.x (Blackwell Publishing Ltd)

Ramos V, Formigo N, Maia R (2017) Ecological flows and the Water Framework Directive implementation: an effective coevolution. European Water 60:423–432

Richter BD, Thomas GA (2007a) Restoring environmental flows by modifying dam operations. Ecol Soc 12(1):1–26

Richter BD, Thomas G (2007b). Dam good operations. https://www.waterpowermagazine.com/features/featuredam-good-operations

Richter BD, Warner AT, Meyer JL, Lutz K (2006) A collaborative and adaptive process for developing environmental flow recommendations. River Res Appl 22(3):297–318

Rothfeder J (2001) Every Drop for sale: our desperate battle over water in a world about to run out. Penguin Putnam, New York

Saha MK, Patra BC (2013) Present status of ichthyofaunal diversity of Damodar river at Burdwan district, West Bengal, India. Int J Scientific Res Publ 3(6):1–11

Sarkar B, Islam A, Das BC (2021) Role of declining discharge and water pollution on habitat suitability of fish community in the Mathabhanga-Churni River, India. J Clean Prod 326:129426. https://doi.org/10.1016/j.jclepro.2021.129426

Sarkar B, Islam A (2020) Drivers of water pollution and evaluating its ecological stress with special reference to macrovertebrates (fish community structure): a case of Churni River, India. Environ Monit Assess 192(1):1–31. https://doi.org/10.1007/s11356-021-17719-5

Sarkar B, Islam A (2021) Assessing poverty and livelihood vulnerability of the fishing communities in the context of pollution of the Churni River, India. Environ Sci Pollut Res 1–24. https://doi.org/10.1007/s11356-021-17719-5

Silk N, Ciruna K (2005) A practitioner’s guide to freshwater biodiversity conservation. Island Press, Washington, DC

Smakhtin V, Revenga C, Döll P (2004a). Taking into account environmental water requirements in global-scale water resources assessments: The Comprehensive Assessment of Water Management in Agriculture. Colombo, Sri Lanka: International Water Management Institute. (IWMI Comprehensive Assessment Research Report 2)

Smakhtin V, Anuphas M (2006) An assessment of environmental flow requirements of Indian River Basins. Int Water Manag Inst Res Rep 107:1–42

Smakhtin V, Revenga C, Döll P (2004b) A pilot global assessment of environmental water requirements and scarcity. Water Int 29(3):307–3017

Smakhtin V, Arunachalam M, Behera S, Chatterjee A, Das S, Gautam P, Unni KS (2007) Developing procedures for assessment of ecological status of Indian river basins in the context of environmental water requirements, vol 114. IWMI

Tegos A, Schlüter W, Gibbons N, Katselis Y (2018) Assessment of environmental flows from complexity to parsimony-lessons from Lesotho. Water 10:1–17

Tharme RE (2003) A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. Wiley InterScience 19:397–441

The Brisbane Declaration (2007) Environmental flows are essential for freshwater ecosystem health and human well-being. In: The 10th International Riversymposium and International Environmental Flows Conference. Brisbane, Australia

Tonkin JD, Tortajada, C. (2014). Dams: an essential component of development. Springer 1:323–330

Tortajada, C. (2014). Dams: an essential component of development. America, A4014005-1-A4014005-9

Tremlay H (2010) The emergence of environmental flow protection in Quebec Law. Les Cahiers De Droit 51(3–4):801–825

Van BD, Kantoush SA, Sumi T, Mai N (2018) Historical changes of flow and sediment budget in Vietnamese Mekong Delta due to upstream dam development. Multi-perspective water for sustainable development. Indonesia, pp 123–131. https://www.researchgate.net/publication/328913347

Verma RK, Murthy S, Tiwary RK (2015) Assessment of environmental flows for various sub-watersheds of damodar river basin using different hydrological methods. Int J Waste Resour 5(4):1–6

WCD (2000) Dams and development: a new framework for decision-making. Earthscan Publications Ltd, London
Winton RS, Calamita E, Wehrli B (2019) Reviews and syntheses: dams, water quality and tropical reservoir stratification. Biogeosciences 16(8):1–25

WBPCB (2020) Revised Action Plan for Rejuvenation of River Damodar Paschim Bardhaman West Bengal. West Bengal Central Pollution Control Board, River Rejuvenation Committee, Kolkata. https://www.wbpcb.gov.in/writereaddata/files/Action%20Plan%20for%20Riverf%20Damodar.pdf

World Bank (2008) Mainstreaming environmental flow requirements into water resources investments and policy reforms. Environment Department Energy, Transport and Water Department. DRAFT, Main Report, vol 1

Yüksel I (2009) Dams and hydropower for sustainable development. Energy Sources Part B 4(1):100–110

Zeiringer B, Seliger C, Greimel F, Schmutz S (2018) River hydrology, flow alteration, and environmental flow. Riverine ecosystem management. Springer, Cham, pp 67–89

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