Environmental flow requirements of river Sone: impacts of low discharge on fisheries

K. D. Joshi[1,*], D. N. Jha[1], A. Alam[1], S. K. Srivastava[1], Vijay Kumar[1] and A. P. Sharma[2]

[1]Allahabad Regional Centre, Central Inland Fisheries Research Institute (ICAR), 24 Panna Lal Road, Allahabad 211 002, India
[2]Central Inland Fisheries Research Institute, Barrackpore, Kolkata 700 120, India

Environmental flow of the river Sone at Indrapuri barrage was estimated using 36 years discharge data and the Global Environmental Flow Calculator Software. To maintain the river in moderate condition and to keep basic ecosystem functions intact, at least 18.9% of mean annual runoff (MAR) has been estimated, while the actual discharge of the river was merely 5.16% of MAR. The river presently holds 89 fish species, but 20 species reported in an earlier study were not observed, while 14 new fish species were encountered. Sediments, water and macro-benthic biota of the river were also studied to know the effect of low discharge.

Keywords: Environmental flow, fish diversity, Indrapuri barrage, river Sone, water discharge.

MOST of the Indian rivers are excessively exploited to fulfil ever-increasing demand from power, agricultural, industrial and municipal sectors. Damming of rivers or tributaries is the root cause of river obstructions causing severe modifications and perturbations to the river flow, velocity, depth, substratum, pools, ecology and fish habitats[1]. Each river system has an individual flow regime with particular characteristics such as seasonal pattern of flows, timing, frequency, predictability and duration of extreme events (e.g. floods and droughts), rates of change and other aspects of flow variability[2–5]. Each of these hydrological characteristics has individual as well as interactive regulatory influences on the biophysical structure and functioning of the river and floodplain ecosystems. This also includes physical nature of river channels, sediment regime and water quality, biological diversity/riverine biota and key ecological processes sustaining the aquatic ecosystem[6]. Deviations from natural flow regime result in drastic change in the riverine ecosystems and fishery structures in the downstream.

Disruption of the natural flow regime can alter the entire river ecosystems and socio-economic activities that depend on them[7–9]. Because of altered natural flow regimes, species in freshwater ecosystems are endangered at rates far higher than those in terrestrial and marine ecosystems[3,10]. The cumulative effect of hydrological degradations has also resulted in severe fishery decline in River Ganges and its tributaries[1,11–13]. Freshwater and freshwater-dependent ecosystems provide different services for humans, including fish, flood protection, wildlife, etc.[14,15]. To maintain these services, water needs to be allocated to ecosystems, as it is done to other users like agriculture, power generation, domestic use and industry. The assessment of water requirements of freshwater-dependent ecosystems represents a major challenge due to the complexity of physical processes and interactions between the components of the ecosystems. Environmental flow requirements are often defined as a suite of flow discharges of certain magnitude, timing, frequency and duration. These flows ensure a flow regime capable of sustaining a complex set of aquatic habitats and ecosystem processes and are referred to as 'environmental flows', 'environmental water requirements', 'environmental flow requirements', 'environmental water demand', etc.[16–18].

A global review of the status of environmental flow methodologies revealed the existence of some 207 individual methodologies recorded for 44 countries[19]. These methods are based on various criteria, including hydrological, hydraulic rating, habitat simulation and holistic methodologies. The United States has been at the forefront of the development and application of methodologies for prescribing environmental flows[19]. In the South Asian region, developments in understanding environmental flows and their assessments have been initiated since the beginning of the 21st century[20]. River management issues, including estimation of environmental flows and their effective implementation are still in the developing stage in India; hence limited literature is available on environmental flow studies in Indian rivers[21–25].

It is a general apprehension among environmentalists, planners and the common masses that the construction of dams and barrages causes great loss to the rivers; so the consequences need to be estimated or quantified. The fish fauna of some selected stretches of the river Sone have been studied and documented[26,27] during 1949–53, before construction of Indrapuri barrage. Hence, the present study has been carried out to estimate the environmental flow status in river Sone after construction of the barrage

*For correspondence. (e-mail: kdjoshi.cifri@gmail.com)

and to assess the impact of flow regulation on downstream ecology, fish diversity and fisheries.

Study area

The river Sone originates at an elevation of 600 m above msl near Amarkantak plateau in Madhya Pradesh (MP) and debouches in the river Ganga near Patna, Bihar. The total length of the river is 784 km, out of which about 500 km lies in MP, 82 km in Uttar Pradesh and the remaining 202 km in Bihar. The important tributaries of the river Sone are Rihand, Kanhar, Ghaghar and Koel. The total catchment area of the river is spread over 71,259 sq. km. The river has a steep gradient with quick run-off and ephemeral regimes, becoming a roaring river with the rainwater in the catchment area, but turning quickly into a formidable stream. The river being wide and shallow leaves disconnected pools of water during summer (lean period). The river was once notorious for changing course, but this tendency has been checked by the formation of anicut at Dehri in 1873–74 and construction of Indrapuri barrage in 1968. The Rihand Dam was also constructed in the upstream catchment of the river Rihand, a tributary of Sone in 1962. Further, the Bansagar Dam in MP was constructed and commissioned in the river in 2008.

Methodology

The river Sone was studied at four sampling sites on a seasonal basis for water discharge, ecology and fishery parameters from April 2010 to March 2012. The sampling sites were Tilauthu (84°4′57″E, 24°48′2″N), Dehri-on-Sone (84°11′35″E, 24°54′8″N), Andhari (84°30′35″E, 25°12′54″N) and Koilwar (84°47′44″E, 25°34′17″N). Of these, Tilauthu is situated upstream of Indrapuri barrage and the rest are in the downstream stretch (Figure 1). The sites were selected on the basis of reasonable distance, accessibility and habitat variability. Incoming and discharge data of Indrapuri barrage has been collected for the period January 1976 to December 2011 from Indrapuri Barrage Authority. The incoming and discharge data were collected in cusecs and converted into cumecs and million cubic metres (MCM) for analysis purpose. The Global Environmental Flow Calculator (GEFC) was used to calculate environmental flow requirement of river Sone.

The GEFC[28] is a software developed for desktop rapid assessment of environmental flows (EFs). The calculator uses monthly time series flow conditions and its corresponding flow duration curve (FDC) – a cumulative distribution function of flows for EF estimation. The FDC is represented by 17% points on the probability (*X*) axis. EFs aim to maintain an ecosystem or upgrade it to some prescribed or negotiated condition – ‘environmental management class (EMC)’. The higher the EMC, the more water is needed for ecosystem maintenance. Six EMCs are used in GEFC ranging from ‘unmodified’ to ‘critically modified’. Each EMC is represented by its unique FDC. The FDC for each class is determined by the lateral shift of the original reference FDC to the left along the probability (*X*) axis by one percentage point. Each EMC is effectively an EF scenario. The EMC best suited for the river in question may be selected based on expert judgement. A FDC established for each EMC can be converted into an EF time series. Using this software, monthwise discharge from the barrage has been estimated and recommended for moderately modified class (class C) of EMC of the river.

Analysis of variance (ANOVA) has been used to show the significant variation between upstream and downstream values of soil and water parameters. Mean differences of the parameters over locations and periods were tested at 5% level of significance. The ecological parameters were studied following standard methods. The information on piscine diversity was collected through experimental fishing conducted at the selected sites using cast, gill and drag nets, fishes caught by the local fishers, market survey at fish landing centres, published data and opinions of the active fishers and experts along the course. The fishes were identified[29,30] and taxonomic discrepancies were resolved based on the available literature[31] and also using the FishBase database[32]. In addition to primary data on fish diversity collected from different centres, the secondary data from available publications[26,27] have also been used to know the timescale change in availability of fishes.

Results and discussion

Water discharge in the river

The incoming water in the river Sone registers strident annual variations, which was recorded at the Indrapuri barrage, discharge from the barrage also varied accordingly. In general, the incoming water registered depletion during the time period between 1977 and 2010. The highest flow was registered in 1978 at 1,255,407 MCM and minimum 167,829 MCM in 2010 (Figure 2). There was almost declining trend in incoming flow after 1999 till 2010. But it drastically increased to the tune of 829,014.5 MCM in 2011 due to heavy rains in the upper catchment area.

The water discharge from Indrapuri barrage also showed similar declining trend over the period. It was 839,206 MCM in 1976 and 1,111,996 MCM in 1978, but reduced to a mere 31,408 MCM in 2010 (Figure 3). There was almost declining trend in discharge values since 1999 onwards till 2010. Time-series data of monthly discharge from Indrapuri barrage showed almost similar annual trend

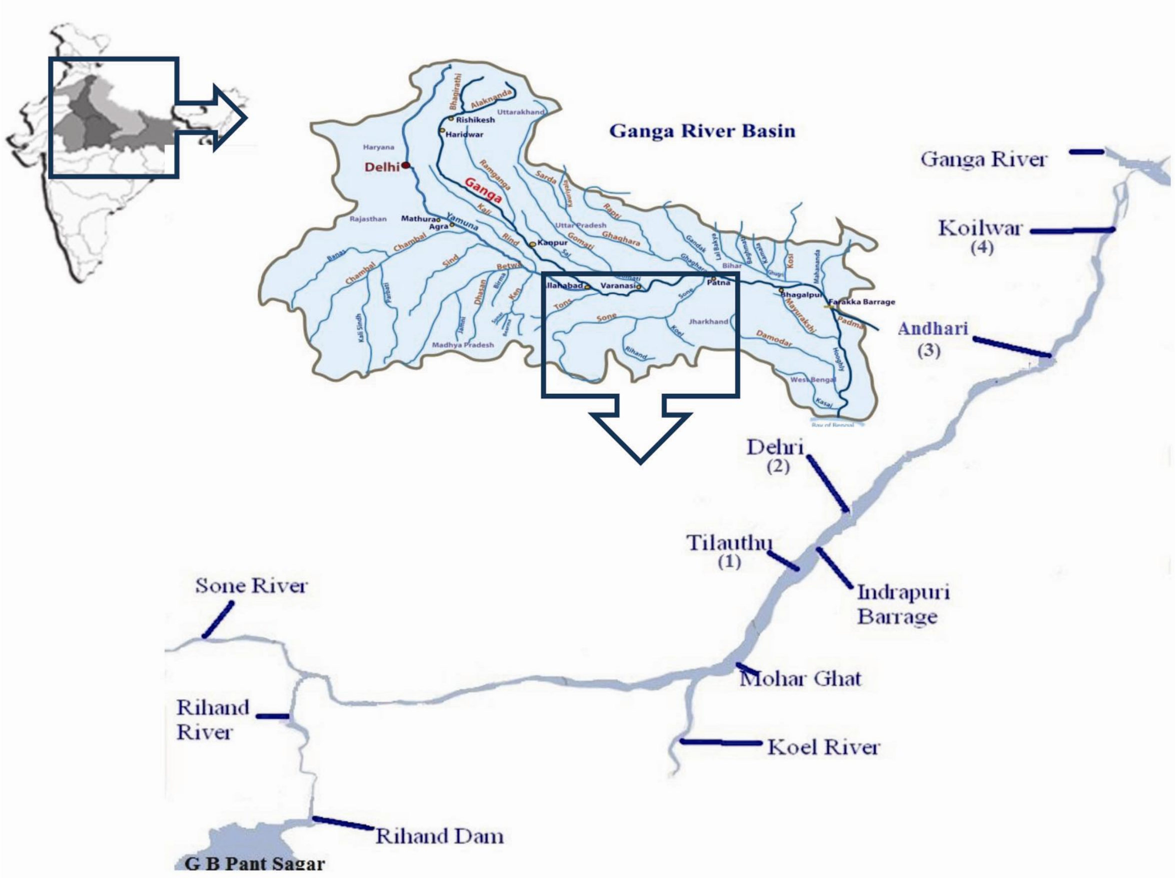

Figure 1. Schematic map of the Sone river and sampling sites.

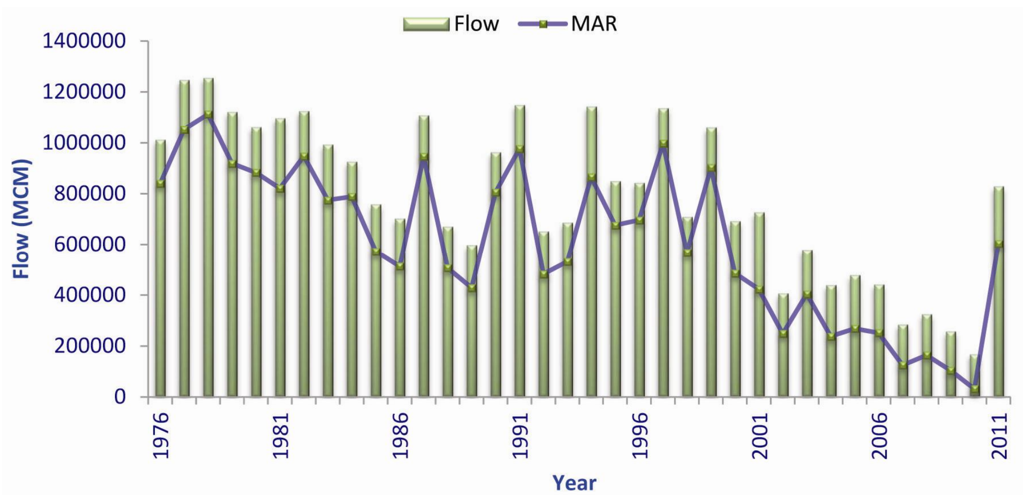

Figure 2. Annual incoming water in the river Sone at Indrapuri barrage (1976–2011).

in different months till 1999, which gradually declined later. Maximum water discharged at 221,991 MCM was recorded in September 1987, while there was no discharge during several other months (Figure 4).

Due to severe reduction in flow and meagre discharge during most of the years (1999–2010), the river has completely lost its riverine character below the barrage and reduced to pools and pockets of water. The wetted perimeter reduced to mere 2–5% of the original span. Even during flood season, the river was in pathetic condition with a maximum wetted parameter of 5% and velocity 0.2–0.4 km hr^{-1}. Observations on past discharge data

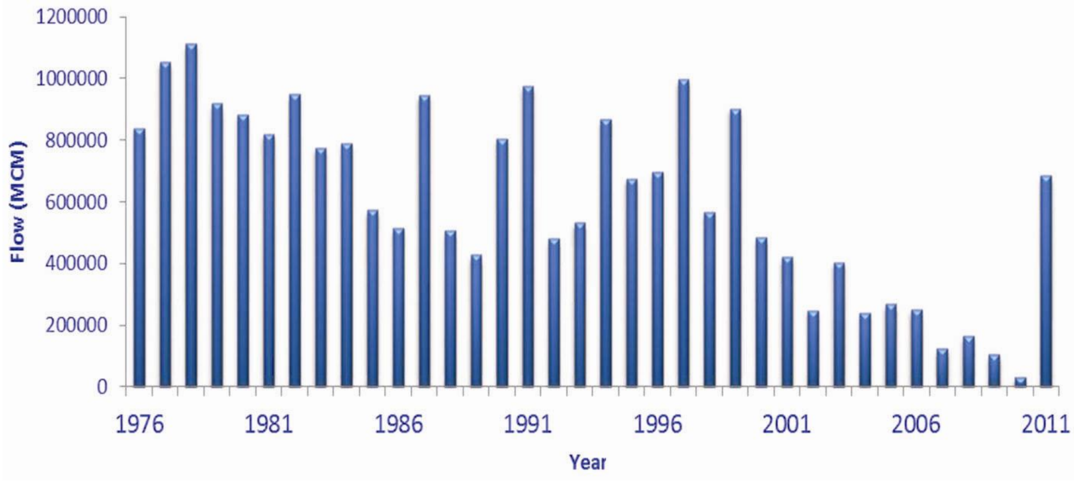

Figure 3. Annual water discharge from Indrapuri barrage (1976–2011).

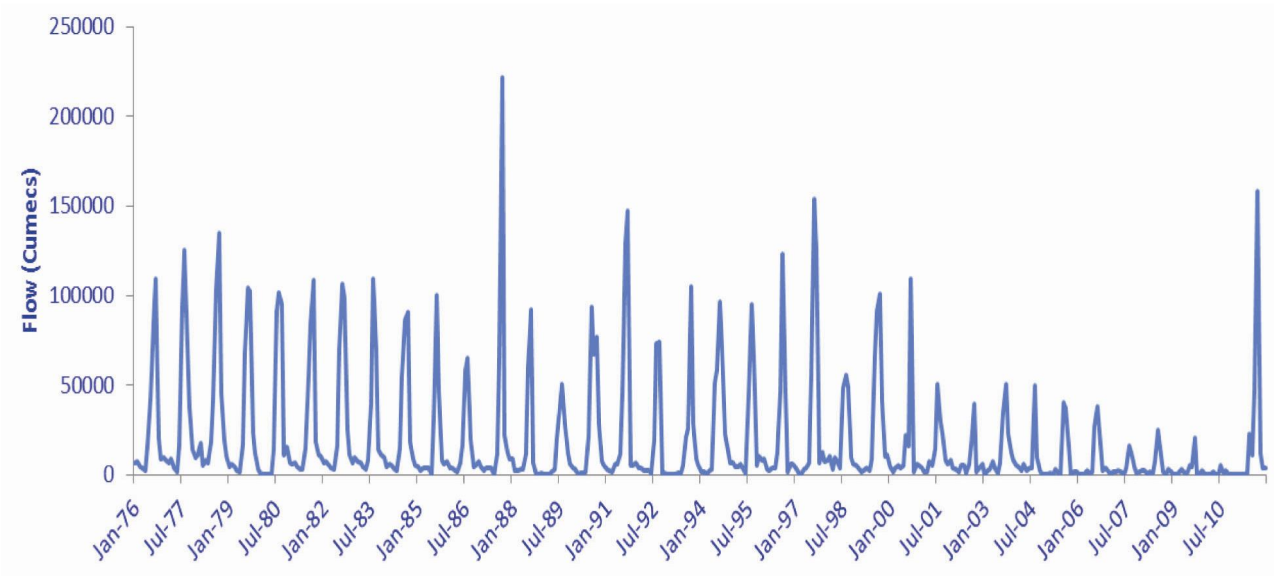

Figure 4. Monthly water discharge from Indrapuri barrage (1976-–2011).

revealed that the river received maximum discharge (>80%) during flood season. During 1976–80, discharge at the barrage was very high (366,234 $m^3 s^{-1}$ with average 30,519 $m^3 s^{-1}$), of which 82.6% was discharged during flood season (302,524 $m^3 s^{-1}$) and 17.4% (63,710 $m^3 s^{-1}$) during lean period. Till then the river was in a healthy state. After a lapse of two decades, during 1996–2000 the discharge still remained high 276,146 $m^3 s^{-1}$ (av. 23,012 $m^3 s^{-1}$), of which 83.6% was discharged during flood period and 16.4% during lean months. Later during 2006–10, the discharge showed a drastic reduction and remained only 56,363 $m^3 s^{-1}$ (av. 46,80 $m^3 s^{-1}$), of which 81% was discharged during flood and 19% during lean period. From the flow records it is clear that the river below the barrage remained ecologically balanced up to 2000 with wetted perimeter ranging between 40% and 70% of the total, but in recent years the entire riverine character had changed due to severe reduction in discharge from the barrage. The situation became critical during 2010, with practically no discharge during most parts of the year.

Unusual rainfall in 2011 augmented the river flow substantially, hence 21.78 times (683,923.6 MCM) more water was released from Indrapuri barrage. Due to massive flood condition, maximum discharge was 158,331 $m^3 s^{-1}$ in September 2011, but there was almost zero discharge during January–March 2011. The water discharge from the barrage during 2011 was considerably higher than the recommended value of 18.9% of mean annual run-off (MAR) or 114,065 MCM. The heavy monsoon rains and flood slightly improved the riverine characteristics and increased its wetted perimeter during the lean period from 2–5% to 12–15%.

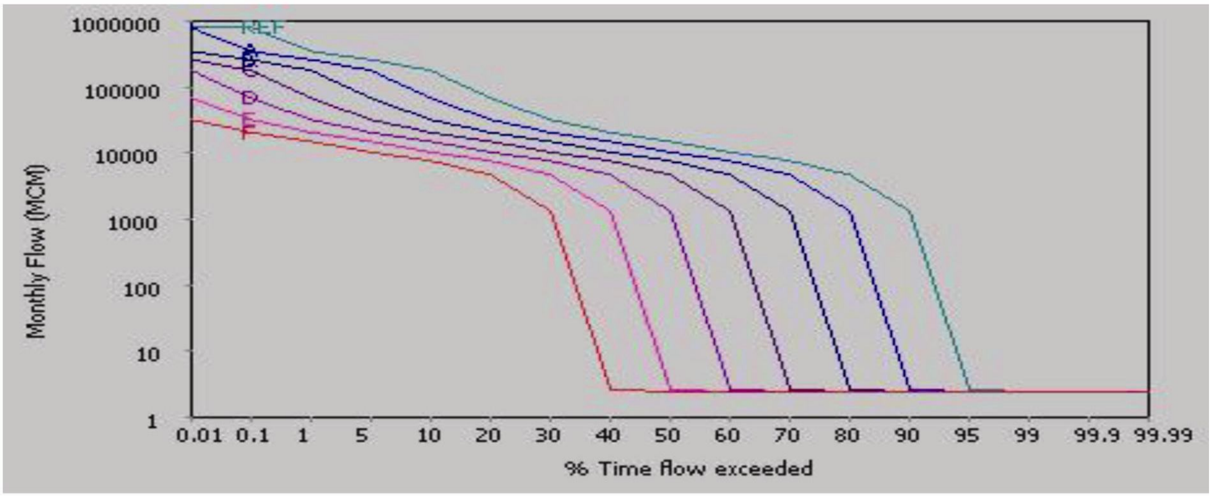

Figure 5. Flow duration curve for six environmental management classes.

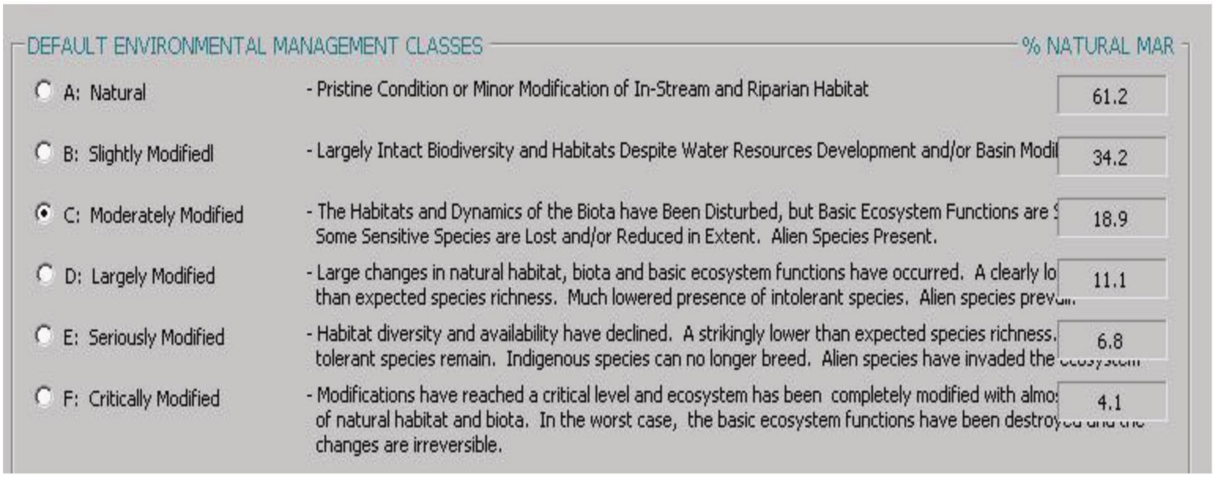

Figure 6. Water discharge estimated (%) using software for different environment management classes.

On the contrary, the discharge from the barrage during 2010 was only 31,022 MCM, therefore the river was almost in a critical stage of modification with 5.16% of MAR.

Environmental flow

The environmental flow requirement of river Sone below the barrage was estimated on the basis of FDC using GEFC (Figure 5). The method categorizes the river discharge into six EMCs spreading from natural to critically modified condition on the basis of available discharge data (Figure 6). The MAR of the river during January 1976 to December 2011 was estimated at 603,514 MCM. The calculator estimated 18.9% of MAR, i.e. 114,065 MCM discharge from the barrage to maintain the downstream stretch of the river Sone in moderate condition (management class C) and to keep basic ecosystem functions intact. The calculator further estimated 34.2% of MAR for slightly modified river (class B) and 61.2% to maintain the river in natural or pristine state (class A). On the basis of estimated discharge data, month-wise water requirement in the river Sone was also calculated for July–September, which coincides with the breeding season of important fishes (Figure 7). In a recent study conducted on river Yamuna[21], the discharge was estimated close to 50–60% of the total annual flow to maintain the health of the river, including transportation of sediment, controlling algal choking as well as pollution. Unlike Yamuna, the river Sone is free from pollution and has meagre sediment load. Hence the above estimated flow (class C) would facilitate restoration of the ecology and fisheries in the affected stretch.

Sediment and water quality

Sediment of the river was dominated with sand in the entire stretch (89.2–96.6%). Sediment was alkaline in

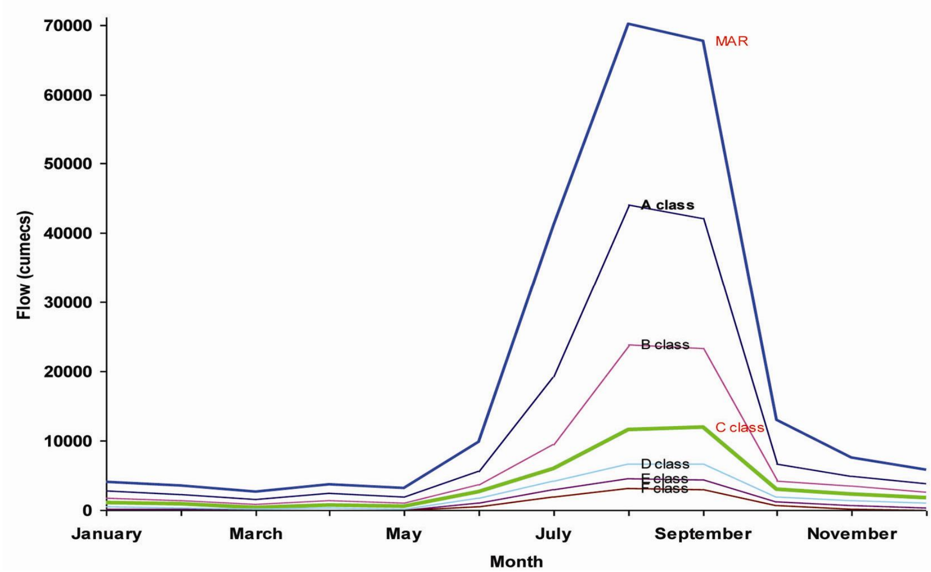

Figure 7. Estimated monthly discharge from Indrapuri barrage for different environment management classes.

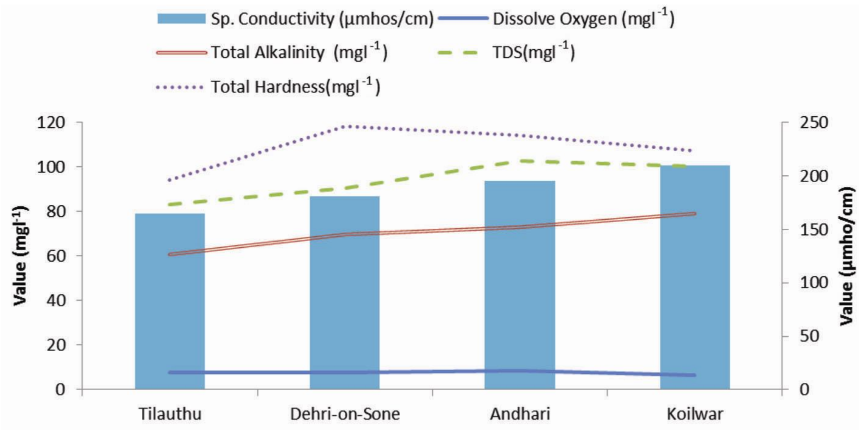

Figure 8. Changing vital water quality parameters over the location during the study period.

reaction with pH ranging from 7.5 to 7.7 throughout the river. Organic carbon, available phosphorus and available nitrogen in the upstream Tilauthu (0.272%, 4.52 mg/100 g and 4.654 mg/100 g, mean values respectively) in comparison to the downstream segments (0.117–0.231%, 2.92–4.32 mg/100 g and 2.906–3.425 mg/100 g, mean values respectively) showed significant variations.

The common water quality parameters in the river both above and below the barrage indicated rich oxygen (6.51–7.88 mg l^{-1}), alkaline pH (7.73–7.76), poor nutrients (PO_4 0.020–0.031 mg l^{-1}) and moderate dissolved organic matter (1.08–1.30 mg l^{-1}). Mean values of free carbon dioxide varied from 1.83 to 3.76 mg l^{-1}. Certain parameters such as alkalinity, conductance, dissolved solids and hardness generally showed an increasing trend from upstream Tilauthu (60.57 mg l^{-1}, 164.42 µmho, 83.28 mg l^{-1} and 94.28 mg l^{-1} respectively) to Koilwar (79.08 mg l^{-1}, 210.0 µmho, 100.42 mg l^{-1} and 107.14 mg l^{-1} respectively). The vital water quality parameters, viz. alkalinity, dissolved oxygen, total dissolved solids, specific conductance and hardness of the upstream Tilauthu and other downstream centres revealed statistically significant variations (Figure 8).

In pristine condition, sediment and water quality parameters of upstream and downstream stretches should be at almost similar levels. But variations were observed in certain sediment and water parameters of the river due to construction of barrage, which might have altered the river habitat, fish diversity and fisheries.

Macro-benthic invertebrates

A total of 20 benthic forms were recorded from 4 sampling centres on the river Sone during the study period. Among these, 9 each are bivalves and gastropods, 1

Table 1. Fish diversity in the river Sone (reported under the present and earlier studies)

Species	Reported by Motwani and David[26]	Recorded in the present study
Order – Anguilliformes		
Anguilla bengalensis (Gray, 1831)	+	+
Order – Clupeiformes		
Family – Clupeidae		
Gudusia chapra (Hamilton, 1822)	+	+
Tenualosa ilisha (Hamilton, 1822)*	+	–
Gonialosa manmina (Hamilton, 1822)	+	+
Family – Engraulidae		
Setipinna phasa (Hamilton, 1822)**	–	+
Order – Cypriniformes		
Family – Cyprinidae		
Catla catla (Hamilton, 1822)	+	+
Cyprinus carpio Linnaeus, 1758**	–	+
Cirrhinus mrigala (Hamilton, 1822)	+	+
Cirrhinus reba (Hamilton, 1822)	+	+
Chagunius chagunio (Hamilton, 1822)	+	+
Osteobrama cotio cotio (Hamilton, 1822)	+	+
Crossocheilus latius latius (Hamilton, 1822)	+	+
Labeo rohita (Hamilton, 1822)	+	+
Labeo calbasu (Hamilton, 1822)	+	+
Labeo gonius (Hamilton, 1822)	+	+
Labeo angra (Hamilton, 1822)**	–	+
Labeo boga (Hamilton, 1822)	+	+
Labeo boggut (Sykes, 1839)	+	+
Labeo pangusia (Hamilton, 1822)	+	+
Labeo bata (Hamilton, 1822)	+	+
Labeo fimbriatus(Bloch, 1795)*	+	–
Bangana dero (Hamilton, 1822)	+	+
Tor tor (Hamilton, 1822)*	+	–
Tor khudree (Sykes, 1839)*	+	–
Garra mullya (Sykes, 1839)	+	+
Garra gotyla gotyla (Gray, 1830)*	+	–
Hypophthalmichthys molitrix (Valenciennes, 1844)**	–	+
Subfamily – Barbinae		
Genus – *Puntius*		
Puntius sophore (Hamilton, 1822)	+	+
Puntius conchonius (Hamilton, 1822)	+	+
Puntius ticto (Hamilton, 1822)	+	+
Puntius chola (Hamilton, 1822)	+	+
Puntius sarana sarana (Hamilton, 1822)	+	+
Puntius amphibius (Valenciennes, 1842)*	+	–
Salmophasia bacaila (Hamilton, 1822)	+	+
Salmophasia boopis (Day, 1874)	+	+
Salmophasia clupeoides (Bloch, 1795)*	+	–
Chela cachius (Hamilton, 1822)*	+	–
*Amblypharyngodon mola (*Hamilton, 1822)	+	+
Aspidoparia morar (Hamilton, 1822)	+	+
Parluciosoma daniconius (Hamilton, 1822)	+	+
Esomus danricus (Hamilton, 1822)	+	+
Danio rerio (Hamilton, 1822)*	+	–
Laubuca laubuca (Hamilton, 1822)	+	+
Raiamas bola (Hamilton, 1822)	+	+
Barilius barila (Hamilton, 1822)	+	+
Barilius bendelisis (Hamilton, 1807)	+	+
Barilius barna (Hamilton, 1822)	+	+
Barilius shacra (Hamilton, 1822)	+	+
Barilius vagra (Hamilton, 1822)*	+	–
Securicula gora (Hamilton, 1822)	+	+
Family – Psylorhynchidae		
Psylorhynchus balitora (Hamilton, 1822)**	–	+
Family – Cobitidae		
*Lepodocephalichthys guntea (*Hamilton, 1822)	+	+
Subfamily – Botiinae		
Genus – *Botia*		
Pangio pangia (Hamilton, 1822)*	+	–
Botia lohachata Chaudhuri, 1912**	–	+
Family – Balitoridae		
Acanthocobitis botia (Hamilton, 1822)	+	+
Nemachelius scaturigina McClelland, 1839	+	+
Nemacheilus denisoni Day, 1867*	+	–
Schistura dayi (Hora, 1935)*	+	–
Order – Osteoglossiformes		
Family – Notopteridae		
Notopterus notopterus (Pallas, 1769)	+	+
Chitala chitala (Hamilton, 1822)	+	+
Order – Siluriformes		
Family – Sisoridae		
Bagarius bagarius (Hamilton, 1822)	+	+
Gogangra viridescens (Hamilton, 1822)	+	+
Gagata cenia (Hamilton, 1822)	+	+
Sisor rabdophorus Hamilton, 1822	+	+
Glyptothorax stolickae (Steindachner, 1867)**	–	+
Glyptothorax annandalei Hora, 1923*	+	–
Glyptothorax telchitta (Hamilton, 1822)*	+	–
Glyptothorax indicus Talwar, 1991*	+	–
Family – Erethistidae		
Erethistoides montana Hora, 1950*	+	–
Pseudolaguvia ribeiroi (Hora, 1921)*	+	–
Family – Siluridae		
Wallago attu (Bloch & Schneider, 1801)	+	+
Ompok bimaculatus (Bloch, 1794)	+	+
Ompok pabda (Hamilton, 1822)**	–	+
Family – Bagridae		
Sperata aor (Sykes, 1839)	+	+
Sperata seenghala (Hamilton, 1822)	+	+
Mystus cavasius (Hamilton, 1822)	+	+
*Mystus bleekeri (*Day, 1877*)***	–	+
*Mystus vittatus (*Bloch, 1794*)*	+	+
Mystus tengara (Hamilton, 1822)**	–	+
Rita rita (Hamilton, 1822)	+	+
Family – Claridae		
Clarias batrachus (Linnaeus, 1758)	+	+
Clarias gariepinus (Burchell, 1822)**	–	+
Family – *Heteropneustidae*		
Heteropneustes fossilis (Bloch, 1794)	+	+
Family – Schilbeidae		
Ailia coila (Hamilton, 1822)	+	+
Clupisoma garua (Hamilton, 1822)	+	+
Clupisoma montana Hora, 1937*	+	–
Eutropiichthys vacha (Hamilton, 1822)	+	+
Eutropiichthys murius (Hamilton, 1822)	+	+
Neotropius atherinoides (Bloch, 1794)**	–	+
Silonia silondia (Hamilton, 1822)	+	+
Family – Pangasiidae		
Pangasius pangasius (Hamilton, 1822)	+	+
Family – Amblyceptidae		
Amblyceps mangois (Hamilton, 1822)*	+	–

(*Contd*)

Table-1. (Contd)

Species	Reported by Motwani and David[26]	Recorded in the present study
Order – Mugiliformes		
Family – Mugilidae		
Rhinomugil corsula (Hamilton, 1822)	+	+
Sicamugil cascasia (Hamilton, 1822)	+	+
Order – Beloniformes		
Family – Belonidae		
Xenentodon cancila (Hamilton, 1822)	+	+
Order – Perciformes		
Family – Ambassidae		
Chanda nama Hamilton, 1822	+	+
Genus – *Parambassis*		
Parambassis ranga (Hamilton, 1822)	+	+
Family – Sciaenidae		
Genus – Johnius		
Johnius coitor (Hamilton, 1822)	+	+
Family – Cichlidae		
Oreochromis niloticus (Linnaeus, 1758)**	–	+
Family – Osphronemidae		
Colisa fasciata Bloch & Schneider, 1801	+	+
Family – Channidae		
Channa marulius (Hamilton, 1822)	+	+
Channa striatus (Bloch, 1793)	+	+
Channa punctatus (Bloch, 1793)	+	+
Channa orientalis (Hamilton, 1822)	+	+
Family – Gobiidae		
Glossogobius giuris (Hamilton, 1822)	+	+
Order – Tetraodontiformes		
Suborder – Tetraodontidae		
Genus – *Tetraodon*		
Tetraodon cutcutia Hamilton, 1822**	–	+
Order – Synbranchiformes		
Family – Mastacembelidae		
Mastacembelus armatus (Lacepede, 1800)	+	+
Macrognathus pancalus Hamilton, 1822	+	+
Macrognathus aral (Bloch & Schneider,1801)	+	+

*Species (20) recorded by Motwani and David[26] were not observed in the present study.
**Species (14) observed in the present study were not recorded by Motwani and David[26].

chironomid and 1 annelid. Benthic maro-invertebrates comprised of *Bellamya bengalensis*, *Lymnaea accuminata*, *Melanoides tuberculata*, *Brotia costula*, *Tarebia lineata*, *Gyraulus convexiusculus*, *Thiara scabra*, *Physa acuta*, *Pila globosa* among gastropods; *Parreysia andersoniana*, *Parreysia corrugata*, *Parreysia caerulea*, *Parreysia favidens*, *Corbicula striatella*, *Lamellidens corrianus*, *Lamellidans marginalis*, *Scabies crispate* among bivalves; *Tubifex* spp. among annelids and *Chironomus* spp. among dipterans. Species richness at Tilathu, Dehri-on-Sone, Andhari and Koilwar was 18, 16, 9 and 13 respectively. Least abundance at Andhari, situated below the barrage may be attributed to the low discharge and fragmentation of the river into pools and pockets during major span of the year. The population ranged from 228 to 582 m^{-2}, being maximum during winter and minimum during monsoon. Gastropods dominated the entire downstream stretch possibly due to almost negligible discharge during most parts of the year. No significant differences were observed in the distribution and abundance of the biota along the river.

Fish diversity and fishery

The river has torrential flow at its up and midstream segments and passes through gorges in this section. The substratum in the upstream and midstream segments generally consists of bedrocks and boulders, while gravels, sand, silt and clay dominate the downstream. Due to variations in the substratum and habitat, the river holds rich fish diversity. A total of 89 fish species belonging to 63 genera, 25 families and 10 orders have been collected from the river (Table 1) during the study. Species richness at Tilauthu, Dehri-on-Sone, Andhari and Koilwar stretches was 80, 77, 77 and 76 respectively. The family Cyprinidae showed its versatile presence (Figure 9), represented by 36 species belonging to 20 genera, followed by Bagridae (7 species and 3 genera) and Schilbeidae (6 species and 5 genera). Fish fauna of the river in general is Gangetic in character with admixture of Himalayan and peninsular elements, hence important from the zoogeographical point of view. The peninsular forms are represented by *Labeo boggut* and *Salmophasia boopis* and recorded from Tilauthu only. About 70% of the total species recorded was common at all centres showing their long-range distribution pattern. According to the IUCN Red List, of the total 89 species recorded from the river, 8 are listed as 'Threatened' in which 7 are 'Near Threatened' and 1 'Vulnerable'[33].

The present fish diversity in the river Sone witnessed drastic changes in comparison to earlier studies[26,27]. The impaired river habitat resulted in alterations of fish diversity and composition in the river in general and downstream to the barrage in particular. A total of 95 species belonging to 20 families were observed from the river in a study conducted during 1950s, while 89 species have been recorded in the present study. Though the present study recorded loss of 6 species in comparison to the earlier study, analysis of the diversity structure indicates disappearance of a total of 20 species recorded earlier[26,27]. *Tenualosa ilisha*, *Chela cachius*, *Barilius vagra*, *Danio rerio*, *Garra gotyla gotyla*, *Labeo*

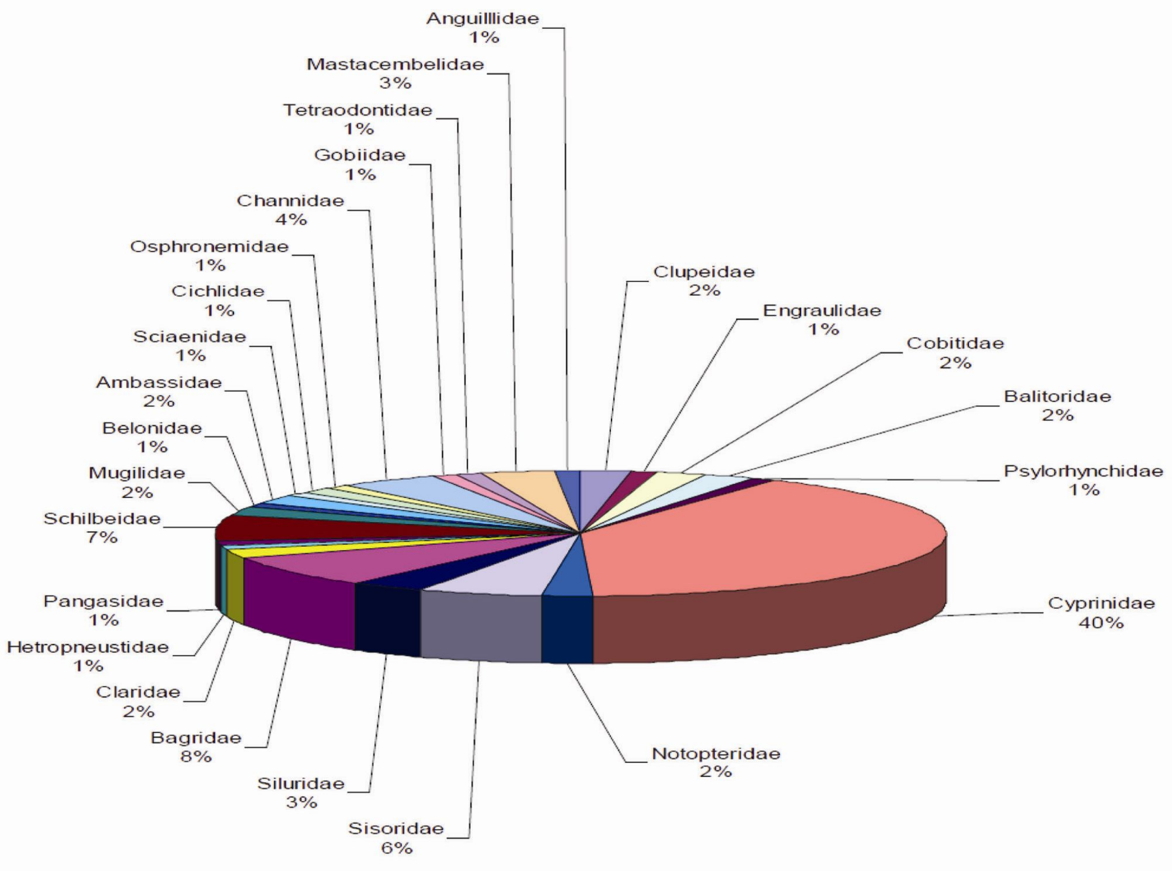

Figure 9. Percentage distribution of fish species in different families of the river Sone.

fimbriatus, *Tor tor*, *Tor khudree*, *Puntius amphibius*, *Salmophasia clupeoides*, *Pangio pangia*, *Nemacheilus denisoni*, *Schistura dayi*, *Clupisoma montana*, *Amblyceps mangois*, *Glyptothorax annandalei*, *Erethistoides montana*, *Glyptothorax indicus*, *Glyptothorax telchitta* and *Pseudolaguvia ribeiroi* were not recorded during the study period.

Disappearance of the above species and drastic depletion in Indian major carps (IMC) in the affected river stretch could be mainly attributed to severe reduction in downstream discharge coupled with cumulative effect of obstruction, narrowed wetted perimeter and decrease in average depth. Reduction in discharge also affected distribution of rheophilic fishes like *Garra*, *Glyptothorax* and *Erethistoides*, as the river reduced to pools and pockets with feeble current. Owing to distinct morphological features and popularity, presence or absence of ornamental fishes like *Danio rerio*, *Botia lohachata* and *Lepidocephalichthys guntea* may be perceived as a strong indicator of river habitats. Of these, *L. guntea* was recorded in both the studies; *D. rerio* reported earlier[26] was not encountered in the present study, while *B. lohachata* was encountered in the present study only.

Decline in fish catches and disappearance of individual species due to increasing use of water for agriculture, hydropower generation and supplies for domestic and industrial purpose from river systems have also been recorded elsewhere[34–36]. In river Ganga, disruption of habitat connectivity in the lower stretch by the construction of the Farrakka barrage in 1975 has adversely affected the migratory run of the anadromous Indian Shad *Tenualosa ilisha* upstream[37]. Depletion of migratory fishes like *Tenualosa ilisha, Pangasius pangasius*, *Anguilla bengalensis*, *Tor tor* and *Bagarius bagarius* in the river Sone may be due to cumulative effect of the multiple stressors.

Moreover, 14 fish species – *Hypophthalmichthys molitrix*, *Cyprinus carpio*, *Clarias gariepinus*, *Oreochromis niloticus*, *Labeo angra*, *Botia lohachata*, *Mystus tengara*, *Mystus bleekeri*, *Setipinna phasa*, *Psilorhynchus balitora*, *Neotropius atherinoides*, *Glyptothorax stolickae*, *Tetraodon cutcutia* and *Ompok pabda* not evidently reported from the system in earlier studies were now observed from the downstream stretch. Among these *Clarias gariepinus*, *H. molitrix*, *Cyprinus carpio* and *O. niloticus* were exotic. The altered river habitat favoured establishment of resilient native and exotic fishes. The reduced flow and depth of the river Ganga, particularly in the middle stretch, also provided an optimum habitat for the exotic fish species *Cyprinus carpio* and *O. niloticus*, which were recorded in sizeable numbers[37]. Similarly, increase of non-indigenous fish species was observed in some other large rivers due to reduced flow regime and altered macro and micro habitats[38,39]. Occurrence of some native species, viz. *L. angra*, *B. lohachata*, *M. tengara*, *M. bleekeri*, *S. phasa*, *P. balitora*, *N. atherinoides*, *G. stolickae* and *O. pabda* in river Sone may be attributed to local movement of the species from the confluence zone of the river with river Ganga, particularly during flood periods.

Downstream water discharge from the barrage reveals substantial decrease during different months over the period (Figure 10). The average monthly discharge values recorded as 48,394.66, 80,529.97 and 77,443.46 MCM respectively, during 1976–2011 for monsoon months, i.e. July, August and September reduced to 38,899.88, 42,954.53 and 42,107.09 MCM respectively, during 2001–2010. Since the monsoon flood is essential for spawning of IMC, reduction in downstream discharge during monsoon severely affected its breeding and resultant seed availability. Populations of commercially important major carp species, viz. *Catla catla*, *Labeo rohita*, *Cirrhinus mrigala* and *Labeo calbasu* were also adversely affected due to failure in recruitment process. Annual landing of these fishes recorded in tonnes during 1980s has been reduced to minimum and replaced by the residential fishes. The river Sone remained a source of quality fish spawn to the thousands of the fishermen along its course. The past records of 1960s and 1970s showed collection and transportation of average 4787 hundis (earthen pots with red soil) from the river at and around Koilwar. Spawn availability has been reduced to a mere 10–15% in 2011–12 in comparison to values in 1965, a pre-dam baseline. Index of spawn quality also decreased from 80% to just 3.5% over the same period[40]. Similar depleting spawn availability trend was also observed in river Ganga due to drastic reduction in downstream water flows. The fish spawn availability index of IMC in river Ganga declined drastically from 2984 ml in 1960s to 568 ml during 2005–2009 (refs 41 and 42).

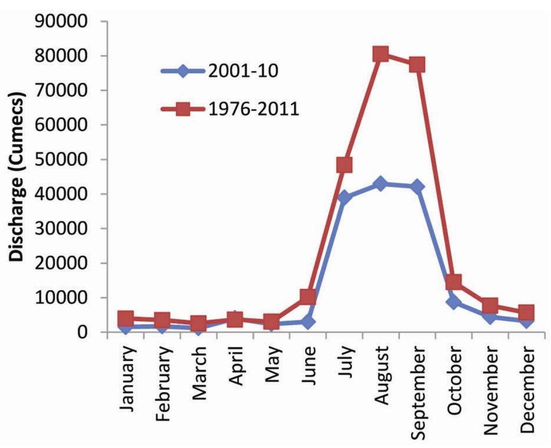

Figure 10. Average monthly discharge from the barrage during 1976–2011 and 2001–2010.

Besides IMC, some catfishes breed in river Sone during summer season and need sufficient width, depth and deep pools for nest preparation. But, estimated monthly discharge from Indrapuri barrage (Figure 7) showed negligible discharge in the downstream stretch during summers as a result the catfish population also registered considerable depletion.

The present study attempted to categorically estimate environmental flow requirements of a river downstream to a commissioned barrage. It is a preliminary study done using hydrological data with the help of GEFC, software developed for desktop rapid assessment of environmental flows. Environmental flow estimation studies are still in nascent stage in our country and the required database on ecological and fishery aspects is lacking. Hence, the present study would be a valuable baseline in the field of much required environmental flow estimation for the rivers under modification. Further studies in this multidisciplinary direction are required to estimate the environmental flow using latest versions of holistic approaches with provision to meet the specific requirements of riverine ecology, biota, fish species and other stakeholder.

Conclusions

On analysis of 36 years water discharge data of the river Sone at Indrapuri barrage using GEFC, the river is observed in critically modified (class F) condition with discharge of mere 5.16% of MAR and resultant 2–5% wetted perimeter. Hence, the estimated 18.9% of MAR would be helpful in restoration of the river from almost critically modified (5.12%) to moderately modified class (class C). Further, to maintain the river in slightly modified class (class B), 34.2% of MAR will be required. Besides, EF estimation, the present study also revealed loss of fish diversity, fisheries and invasion of exotic species owing to decreased flow. In case of damming a pristine river stretch, the environmental flow should be maintained optimally to sustain the downstream ecosystems and the rights of other stakeholders. The above recommended discharges estimated as MAR, must be released in a manner to mimic the natural seasonal flow, including flood pulses. Though this is a preliminary e-flow study done using hydrological data, the findings will be helpful in planning and development of hydro-electric and irrigation projects.

1. Vass, K. K., Tyagi, R. K., Singh, H. P. and Pathak, V., Ecology, changes in fisheries, and energy estimates in the middle stretch of the River Ganges. *Aquat. Ecosyst. Health Manage.*, 2010, **13**(4), 374–384.
2. Richter, B. D., Baumgartner, J. V., Wigington, R. and Braun, D. P., How much water does a river need? *Freshwater Biol.*, 1997, **37**, 231–249.
3. Richter, B. D., Braun, D. P., Mendelson, M. A. and Master, L. L., Threats to imperilled freshwater fauna. *Conserv. Biol.*, 1997, **11**, 1081–1093.

4. Poff, N. L., A hydrography of unregulated streams in the United States and an examination of scale-dependence in some hydrological descriptors. *Freshwater Biol.*, 1996, **36**, 101–121.
5. Poff, N. L. *et al.*, The natural flow regime a paradigm for river conservation and restoration. *BioScience*, 1997, **47**, 769–784.
6. Naiman, R. J., Bunn, S. E., Nilsson, C., Petts, G. E., Pinay, G. and Thompson, L. C., Legitimizing fluvial ecosystems as users of water: an overview. *Environ. Manage.*, 2002, **30**, 455–467.
7. Sparks, R. E., Need for ecosystem management of large rivers and their floodplains. *BioScience*, 1995, **45**, 168–182.
8. Baron, J. S. *et al.*, Meeting ecological and societal needs for freshwater. *Ecol. Appl.*, 2002, **12**, 1247–1260.
9. Postel, S. and Richter, B. D., *Rivers for Life: Managing Water for People and Nature*, Island Press, Washington, DC, USA, 2003.
10. Ricciardi, A. and Rasmussen, J. B., Extinction rates of North American freshwater fauna. *Conserv. Biol.*, 1998, **13**(5), 1220–1222.
11. Sinha, M., Khan, M. A. and Jha, B. C., *Ecology, Fisheries and Fish Stock Assessment of Indian Rivers*, Central Inland Fisheries Research Institute Publication, Barrackpore, 1999, p. 325.
12. Vass, K. K., Biomonitoring an effective tool in EIA studies. In *Ecology, Fisheries and Fish Stock Assessment in Indian Rivers* (eds Sinha, M., Khan, M. A. and Jha, B. C.), Central Inland Fisheries Research Institute Publication, Barrackpore, 1999, pp. 63–73.
13. Sarkar, U. K. *et al.*, Freshwater fish biodiversity in the River Ganga (India): changing pattern, threats and conservation perspectives. *Rev. Fish Biol. Fish.*, 2011; DOI:10.1007/s11160-011-9218-6.
14. Postel, S. and Carpenter, S. R., Freshwater ecosystem services. In *Nature's Services* (ed. Daily, G.), Island Press, Washington, DC, USA, 1997, pp. 195–214.
15. Revenga, C. and Cassar, A., Ecosystem management of water resources in Africa, World Wide Fund for Nature Global Network, World Wildlife Fund, 2002.
16. Knights, P., Environmental flows: lessons from an Australian experience. In Proceedings of International Conference: Dialog on Water, Food and Environment, Hanoi, Vietnam, 2002, p. 18.
17. Smakhtin, V. U., Revenga, C. and Döll, P., Taking into account environmental water requirements in global-scale water resources assessments. Research Report of the CGIAR comprehensive assessment programme of water use in agriculture. International Water Management Institute, Colombo, Sri Lanka, 2004, p. 24.
18. Smakhtin, V., Revenga, C. and Döll, P., A pilot global assessment of environmental water requirements and scarcity. *Water Int.*, 2004, **29**, 307–317.
19. Tharme, R. E., A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. *River Res. Appl.*, 2003, **19**, 397–441.
20. Gopal, B., Environmental flows: the South Asian experience. In *Environmental Flow – An Introduction for Water Resource Managers*, National Institute of Ecology, New Delhi, 2013, pp. 183–195.
21. Soni, V., Shekhar, S. and Singh, D., Environmental flow for the Yamuna river in Delhi as an example of monsoon rivers in India. *Curr. Sci.*, 2013, **106**(4), 558–564.
22. Jha, R., Sharma, K. D. and Singh, V. P., Critical appraisal of methods for the assessment of environmental flows and their application in two river systems of India. *KSCE J. Civ. Eng.*, 2008, **12**(3), 213–219; DOI:10.1007/s12205-008-0213-y.
23. Gopal, B., *Environmental Flow – An Introduction for Water Resource Managers*, National Institute of Ecology, New Delhi, 2013, p. 248.
24. Nitin, K. and Babu, S., Environmental flows assessment in India: the Ganga experience. In *Environmental Flow – An Introduction for Water Resource Managers*, National Institute of Ecology, New Delhi, 2013, pp. 207–226.
25. Lenin Babu, K. and Harish Kumara, B. K., Environmental flows in river basins: a case study of River Bhadra. *Curr. Sci.*, 2009, **96**(4), 475–479.
26. Motwani, M. P. and David, A., Fishes of the river Sone with observations on the zoogeographical significance. *J. Zool. Society India*, 1957, **9**(1), 9–15.
27. Hora, S. L., The fish fauna of the Rihand river and its zoogeographical significance. *J. Zool. Soc. India*, 1949, **1**, 1–7.
28. Smakhtin, V. U. and Eriyagama, N., Developing a software package for global desktop assessment of environmental flows. *Environ. Model. Software*, 2008, **23**, 1396–1406.
29. Talwar, P. K. and Jhingran, A. G., *Inland Fishes of India and Adjacent Countries*, Oxford and IBH Publishing Co. Pvt Ltd, New Delhi, 1991, vols 1 and 2, p. 1158.
30. Nelson, J. S., *Fishes of the World*, Wiley, New York, 2006, 4th edn.
31. Knight, J. D. M. and Devi, K. R., Species persistence: a re-look at the freshwater fish fauna of Chennai, India. *J. Threat. Taxa*, 2010, **2**(12), 1334–1337.
32. Froese, R. and Pauly, D. (eds), *FishBase*, 2010 (version 10/2011); http://www.fishbase.org
33. IUCN, The IUCN Red List of Threatened Species, version 2013.1; http://www.iucnredlist.org (accessed on 2 July 2013).
34. Dudgeon, D. *et al.*, Freshwater biodiversity: importance, status, and conservation challenges. *Biol. Rev.*, 2007, **81**, 163–182.
35. Welcomme, R. L., *River Fisheries*, Food and Agriculture Organization, Fisheries Technical Paper 262, 1985, p. 330.
36. Welcomme, R. L., Bene, C., Brown, C. A., Arthington, A., Dugan, P., King, J. M. and Sugunan, V., Predicting the water requirements of river fisheries. In *Wetlands and Natural Resource Management* (eds Verhoeven, J. T. A. *et al.*), Ecological Studies, Springer-Verlag, Berlin, 2006, vol. 190, pp. 123–154.
37. Das, M. K., Sharma, A. P., Vass, K. K., Tyagi, R. K., Suresh, V. R., Naskar, M. and Akolkar, A. B., Fish diversity, community structure and ecological integrity of the tropical River Ganges, India. *Aquat. Ecosyst. Health Manage.*, 2013, **16**(4), 395–407.
38. Kolar, C. S. and Lodge, D. M., Ecological predictions and risk assessment for alien fishes in North America. *Science*, 2002, **298**, 1233–1236; DOI:10.1126/science.1075753.
39. Aarts, B. G. W. and Nienhuis, P. H., Fish zonation and guilds as the basis for the assessment of ecological integrity of large rivers. *Hydrobiologia*, 2003, **500**, 157–178.
40. Anon., Annual Report, Central Inland Fisheries Research Institute (ICAR), Barrackpore, 1965, p. 18.
41. Das, M. K., Environment and fish health: a holistic assessment of inland fisheries in India. In *Natural and Anthropogenic Hazards on Fish and Fisheries* (ed. Goswami, U. C.), Narendra Publishing House, Delhi, 2007, pp. 137–151.
42. Anon., Annual Reports, Central Inland Fisheries Research Institute, Barrackpore, 1994–2011.

ACKNOWLEDGEMENTS. We thank late Dr V. Pathak (formerly at Allahabad Regional Centre of CIFRI), who was associated with the initiation, planning and execution of this work. We also thank the Superintending Engineer, Irrigation Department, Indrapuri Barrage, Bihar, for providing the discharge data and for help during the course of the study; Dr V. U. Smakhtin and Mr N. Eriyagama (International Water Management Institute, Colombo, Sri Lanka) for providing the software and the reviewers for their critical comments that helped improve the manuscript.

Received 20 July 2013; revised accepted 27 June 2014