Ecological flow requirement for fishes of Godavari river: flow estimation using the PHABSIM method

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Fish habitat requirements are an essential aspect of the estimation of environmental flows. In India, a few studies have proposed environmental flows for the major rivers on the basis of qualitative observation or expert opinion. As part of a study regarding the effect of altered flow across the Godavari river on fishes, we estimated flow requirement of the fishes using a physical habitat simulation model (PHABSIM). This model uses habitat requirement of selected fish species in the form of habitat suitability curves (HSCs) against river habitat availability. We developed HSCs for five economically important fishes (*Bangana dero*, *Cirrhinus cirrhosus*, *Labeo calbasu*, *Labeo fimbriatus* and *Wallago attu*). These HSCs indicate that *B. dero* prefers high velocities (0.9–1.2 m/s) compared with the other species and that *L. fimbriatus* prefers deeper areas (1.2–1.5 m). *C. cirrhosus* uses low flows with moderate depth (0.3–0.6 m/s; 0.6–1.5 m). The HSCs were used in PHABSIM along with instream habitat data recorded from four cross-sections to predict the weighted usable areas (WUAs) of the fishes. The relationship between habitat area and discharge was used to predict the minimum acceptable flow for maintaining fish habitats. On the basis of the WUA–discharge relationship curve, 26% of the mean flow was recommended as the minimum ecological flow required below the Polavaram dam of Godavari river.

Keywords: Environmental flow, habitat suitability curves, instream flow incremental methodology, river fishes.

ESTIMATION of water flows required for sustaining the aquatic biodiversity in modified rivers due to regulated flow is a significant challenge. More than 200 flow estimation methods are available[1], and most of them are based on either qualitative data or expert knowledge and not backed up with species habitat requirements. Recent reviews of minimum flow methods suggested that the use of methods that link biologically transformed variables with hydrological data for estimation of environmental flows is more meaningful[2,3]. Therefore, habitat suitability models that predict the effects of altered or reduced flows on aquatic life are more appropriate in flow estimation[3,4].

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Among the habitat models, physical habitat simulation model (PHABSIM) is a widely used method. PHABSIM uses fish habitat requirements based on the instream flow incremental methodology[5,6]. The essential requirement of PHABSIM analysis is the habitat requirement of selected aquatic species in the form of habitat suitability curves (HSCs) against river velocity, depth and substrate. PHABSIM also calculates an index of microhabitat area known as weighted usable area (WUA), which is characterized by various combinations of weighted suitabilities for hydraulic or structural conditions[5]. This method is widely used in many developed nations for the allocation of water flow for sustainable management of fish diversity in major rivers[7–9]. PHABSIM has always focused on umbrella or flagship species because of their high value to society[7]. It can also be used to protect threatened fishes due to impediment river flows by providing the flow they require[9]. In India, environmental flow assessments are still in a nascent stage. The first information on environmental flow in major Indian rivers appeared in 2006 (ref. 10), in which flow estimation was calculated based on the environmental management class (EMC) of rivers including the Godavari. According to the EMC of River Godavari, about 24.5% mean annual run-off was suggested to maintain class 'C' status at the downstream of the river[10]. Subsequently, Kumara *et al.*[11] estimated environmental flow for River Bhadra based on biophysical and socio-economical assessment methods. In recent years, a few studies have proposed environmental flows for major rivers such as the Ganga (Upper Ganga Basin) and Sone on the basis of EMC and biodiversity value of the system[12,13]. All these methods are based on available ecological information of the river system, fish diversity as well as expert judgement.

However, no attempt has been made to assess flow requirement on the basis of fish habitat. No effort has been taken to document the HSCs of aquatic species in India. Hence, in the present study we estimate the flow requirement for selected fishes in the Godavari using site-specific HSCs of fishes such as *Bangana dero*, *Cirrhinus cirrhosus*, *Labeo calbasu*, *Labeo fimbriatus* and *Wallago attu* in the PHABSIM framework.

The Godavari is the second largest river in India. Originating from the northern Western Ghats at Triambakeshwar in Nashik district, Maharashtra, it flows east through the Deccan plateau travelling a length of about 1465 km and finally empties into the Bay of Bengal in Andhra Pradesh (Figure 1). The catchment area drained by the Godavari receives much more rainfall during the southwest (SW) monsoon (June–September) than the northeast (NE) monsoon (October–November). Consequently, most of the water flow of the river is between June and September. The area receives rainfall ranging from 889 to 1016 mm annually. This river basin has the largest number of dams in India – nearly 350 large and medium-sized dams/barrages having been constructed[14,15].

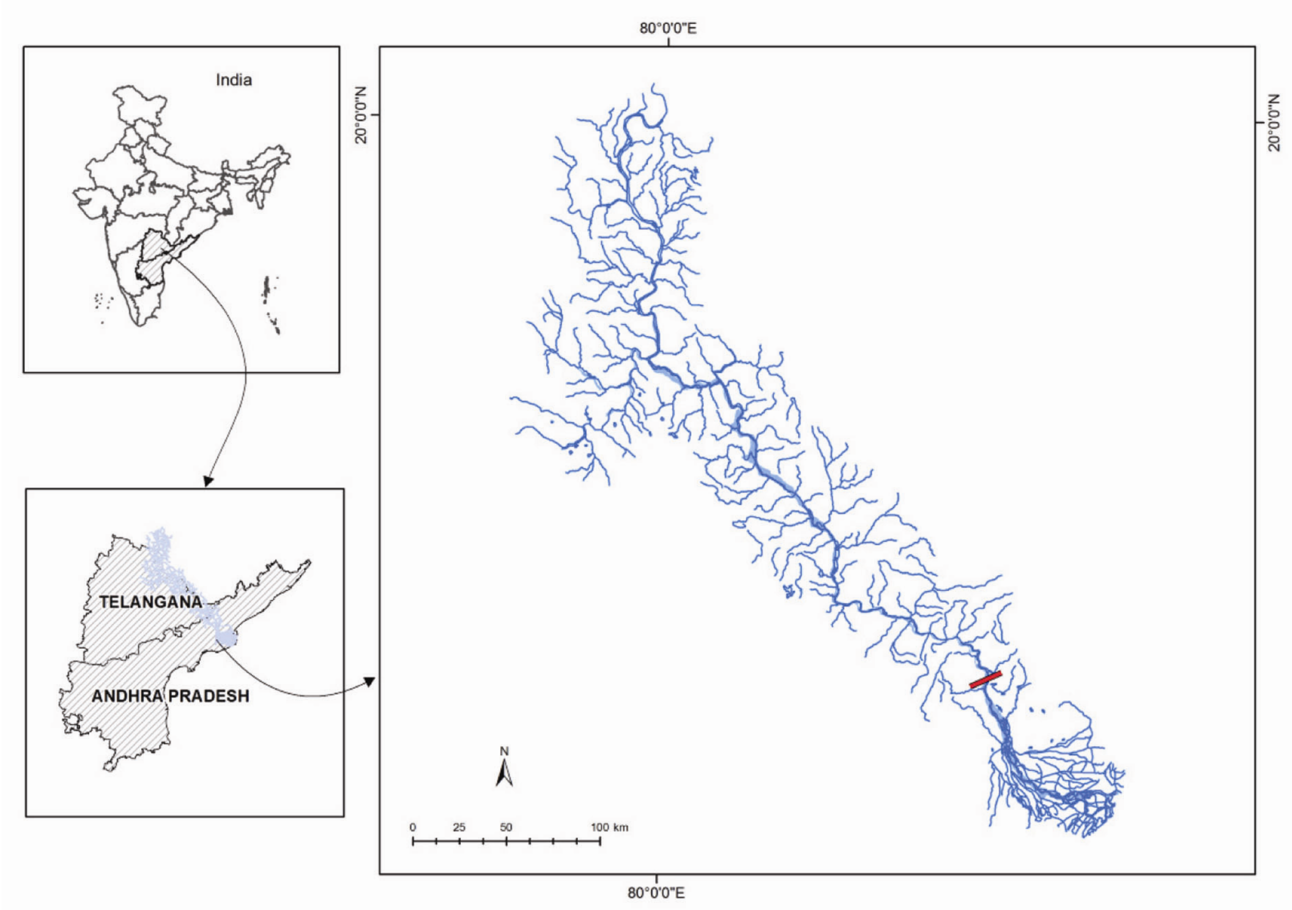

Figure 1. Location map of the study area in the Godavari river, India.

An irrigation barrage has been built on the lower stretch at Dowleswaram (about 80 km before the river meets the sea). The water level begins to rise at Dowleswaram as soon as the SW monsoon sets in at the western catchment, i.e. in Maharashtra. Although the high-flood season ends by October, there are occasional floods during the subsequent months, but these are caused by the NE monsoon.

The present study was carried out between March and May 2012 below the Polavaram dam, where a multipurpose dam is under construction (120 km above the river mouth). The width of the river at Polavaram is more than 500 m, but the wetted channel width during the lean season is 70–100 m, and the mean average discharge of the river is 2578 m^3/s (on the basis of the Central Water Commission data for the last 10 years). Four representative cross-sections were established just below the proposed dam site at 2 km intervals (Figure 1). The lower Godavari mostly consists of a shallow, open channel with no overhanging vegetation, velocity shelters or aquatic vegetation. The riverbed is uniformly sandy. The riparian vegetation on both banks is entirely altered, containing only a few scatted trees and shrubs, which provide shelter for small fishes.

We selected a site in the downstream section of a proposed dam on the Godavari river for the PHABSIM study. As the riverbed is uniformly sandy and the habitat is homogenous throughout, four cross-sections were designated to quantify the habitat availability at two pools and run habitats. Table 1 presents the habitat characteristics of each transect, such as length, width, mean depth and velocity. These were considered representative reaches containing the habitat types of the entire downstream stretch of the river. At each transect, the flow, depth and substrate type were recorded at 4 m intervals across the channel as well as along the length of the habitat. The channel depth was recorded using a graduated depth rope with a sinker. Two local fishing boats were engaged to carry out the survey. A rope of 50 m length was tied to the bank, while the other end was kept in the boat, which was anchored in the middle of the channel, and measurements were made across the channel by holding the rope. The water column velocity was recorded at 40% of the depth from the water surface (at the middle of the water column). The water velocity was measured using a water current meter (Global Water Flow Probe Meter, USA) with a digital recorder. All measurements were made by moving back and forth using the boat.

Table 1. Habitat characteristics of the PHABSIM study site during the lean flow season (April 2012). Depth and velocity are maximum values along each cross-section

Transect	Habitat type	Length (m)	Width (m)	Maximum depth (m)	Velocity (m/s)
1	Pool with sandy bed	60	140	1.33	1.10
2	Run with sandy bed	75	134	1.16	1.08
3	Run with sandy bed	66	146	1.26	1.12
4	Pool with sand bed	45	126	1.41	0.98

In the aquatic environment, the term 'instream habitat' refers to the water velocity, depth and substrate[16]. Fishes are more abundant in high quality of physical structures (depth, flow and substrate) within the channel than in poor quality of physical structures. Successful implementation of PHABSIM requires acquisition of accurate and realistic instream habitat suitability criteria for the target fishes. Therefore, the HSCs required for PHABSIM include continuous variable or univariate curves designed to encompass the expected range of suitable water depth, water velocity and substrate type. The habitat use of five fishes was utilized in this study as these are the economically important, larger fish species reported from the downstream area[17]. Field measurements relating to the habitat use of the selected fishes were conducted using an aquascope from the anchored boat during daytime in clear sunlight. For each observation, a marker stone was placed and the depth and flow measurements were recorded. In addition to direct observation, fishes, especially *W. attu*, were immobilized using bottom-set monofilamentous gill nets (20 m long × 2 m wide; three nets, mesh sizes 24, 28 and 32 mm). After 2 h of efforts at each location, the positions of the fishes were marked from their positions in the net, and the depth and flow measurements were recorded. Then the fishes were released from the net. As the substratum of the study area is uniformly sandy and open, information on substrate use was not included in the habitat suitability estimations. On the basis of the estimates, HSCs were prepared for the five target fishes according to the procedure outlined by Bovee[18] and Jowett[19]. The depth and velocity measurements were divided into different classes (depth class: 0.1, 0.3, 0.6, 1.0, 1.2, 1.5, 1.8, 2.0 m and <2.0 m; velocity class: 0.2, 0.3, 0.5, 0.6, 0.9, 1.2 m/s and <1.2 m/s). At each class, the frequencies of observed available habitat and use by fish were generated. Then the preference for each class interval of the measured variables was computed from the estimated relative frequencies of utilization and availability as

$$P_i = U_i/A_i,$$

where P_i is the relative preference value of a target species for a specific interval of the measured variable; U_i the proportion of utilization of a specific interval of the measured variables and A_i the proportion of a specific interval of the measured variables in the studied river sector at the time the fishes were sampled. The resulting ratio was normalized to a preference scale of 0 to 1 using the equation

$$P_\mathrm{n} = P_i/\max P,$$

where P_n is the normalized index of preference at each interval of the variable and max P is the maximum index of preference for the range of the variable P_i. Finally, HSCs for each species (using depth and velocity) were generated by plotting against their suitability values. These attributes were termed 'elective criteria'[18] under the assumption that species will elect to leave an area when conditions become unfavourable. These habitat suitability attributes were used to generate the WUA in PHABSIM.

In the present study, habitat modelling approach was adopted to stimulate and assess the ecological efforts of physical aquatic habitat changes due to regulated flow, and to assist decision on acceptable flow regime necessary for aquatic species. Habitat hydraulic modelling (HABTAE) in PHABSIM was used to determine the characteristics of the river in terms of depth and velocity as a function of discharge for the full range of discharge value from 7 to 170 m^3/s. In the habitat modelling process, hydraulic information of the river was integrated with the habitat suitability criteria for selected fishes to obtain the available physical habitat as a function of discharge. The general principle behind the habitat modelling programs within PHABSIM is based on the assumption that aquatic species will respond to changes in the hydraulic environment[20]. These changes are simulated for each cell in a defined reach of a river/stream. The reach simulation takes the form of a multi-dimensional matrix of the calculated surface areas of a stream having different combinations of hydraulic parameters such as depth and velocity. The depth and velocity attributes vary with the simulated changes in discharge, causing changes in the amount and quality of the available habitat. Finally, WUA of the fishes was calculated as a function of discharge and species habitat suitability using PHABSIM (Version 4.1).

Before the model was run, data were also subjected to water surface profiling (WSP). The WSP model is a water surface profile program used to predict how the longitudinal profile of the water surface elevation changes over a range of simulated discharges[20]. Further, velocity profiles at each cross-section were stimulated using the velocity model (VELSIM)[20]. In VELSIM, different hydraulic simulations were performed for various flows, including 5, 15, 35, 50, 70, 110 and 170 m^3/s. After the velocity was simulated, the habitat model (HABTAE) was executed with the habitat suitability criteria of *B. dero*, *C. cirrhosus*, *L. calbasu*, *L. fimbriatus* and *W. attu* for depth and velocity. Finally, the combined habitat suitability area and WUA was generated for each species at different simulated flow scenarios.

A total of 60 species of native fish were recorded from the study area over a period of three months from March to May 2012. The fish populations were dominated by Cyprinidae, which contribute about 35% of fish catch. Among the cyprinids, *B. dero*, *C. cirrhosus*, *L. calbasu* and *L. fimbriatus* were dominant in the fish catch. The catfish *W. attu* was relatively rare in the study area. Small cyprinids such as danio, barils, rasbora, barbs and loaches were found along the banks of the river channel as well as streams. The cyprinids were the dominant group, and these constituted 42% of the species assemblage structure.

On the basis of 414 measurements of depth and velocity, the habitat variables of the study sites were determined to be typically those of a riverbed with sandy bottom with a gentle flowing sector. The depth at the study area ranged from 0.1 to 3.85 m, and the most frequent depth observation (24%) was between 1.2 and 1.5 m (Figure 2). The measured water column velocity ranged between 0.0 and 2.1 m/s. In most of the available habitat (33%), the flow was moderate (between 0.9 and 1.2 m/s; Figure 2), and velocities were higher only in a small portion of the available habitat (5%).

B. dero (size ranging from 18 to 32 cm) was the species most frequently encountered during the survey. On the basis of 135 observations of depth and velocity, it was found that adult *B. dero* used a wide range of water depths, from 0.31 to 1.8 m (Table 2), although most of the observations (76%) were between 0.61 and 1.5 m. The maximum depth preference of adult *B. dero* was found to be between 1.0 and 1.2 cm, and maximum velocity preference between 0.9 and 1.2 m/s (Table 2, Figure 3 *a* and *b*). *C. cirrhosus* (size ranging from 23 to 28 cm) was the second most common species observed ($N = 121$) in the study area. Adult *C. cirrhosus* utilized depths between 0.6 and 1.2 m, and most observations were at depths ranging from 1.0 to 1.2 m (48%). Most of the adult *C. cirrhosus* (48%) were found in association with moderately deeper open-channel areas of the river. They utilized relatively low velocities, ranging from 0.15 to 0.45 m/s. The HSC of adult *C. cirrhosus* indicated that the depth preference of this species ranged from 0.6 to 1.2 m and velocity preference from 0.3 to 0.45 m/s (Table 2, Figure 3 *c* and *d*). Adult *L. calbasu* (size ranging from 27 to 45 cm) utilized the depth range between 0.6 and 1.8 m, while most of the observations were between 0.6 and 1.2 m (76%) and velocity preference ranged between 0.16 and 0.6 m/s. The optimal depth preference of this species ranged from 1.0 to 1.2 m, and velocity preference from 0.3 to 0.6 m/s (Table 2, Figure 3 *e* and *f*). *L. fimbriatus* (size ranging from 24 to 36 cm) utilized relatively greater depths, from 0.6 to 1.8 m, and most of the observations (73%) were at depths ranging from 1.0 to 1.5 m (Table 2). *L. fimbriatus* utilized a narrow range of velocities between 0.9 and 1.2 m/s. In most of the observations (80%), the velocities were high – up to 1.2 m/s. The calculated depth preference curve showed that *L. fimbriatus* prefered the depth class between 1.0 and 1.2 m and velocity preference was from 0.9 to nearly 1.2 m/s (Table 2, Figure 3 *g* and *h*). In the case of *W. attu* (size ranging from 28 to 58 cm), most of the measurements were made using bottom-set gill nets as this species swims very fast. It used a wide range of depths 0.6 to 1.5 m, and most of the observations (42%) were between 0.6 and 1.0 m. The species used water column velocities in the range 0.31–0.9 m/s. The estimated suitability curve showed that maximum depth preferred by adult *W. attu* was 1.0 m and velocity was 0.90 m/s (Table 2; Figure 3 *i* and *j*).

The results generated using PHABSIM are presented in Figure 4, to provide a better understating of the minimum flow requirements of the target species. WUA was highest for *L. calbasu* at 50 m^3/s (8472.93 m^2/1000 m), followed by *B. dero* at the same discharge (6640.76 m^2/1000 m). There was a sharp reduction in WUA at a discharge of 70 m^3/s for all the target species, except for *L. fimbriatus*, where maximum WUA was observed at 70 m^3/s (6153.41 m^2/1000 m). Similarly, there was a steep decline in the quality of the habitat when the discharge was reduced below the maximum available WUA at 50 m^3/s. The WUA versus discharge relationship for the economically important fishes reveals that there is a steep increase in WUA from 30 m^3/s, reaching an optimum level of 50 m^3/s for most of the species (Figure 4). The suitable habitats of *L. calbasu*, *B. dero* and *W. attu* decline linearly with flow beyond 50 m^3/s, whereas the curves of *L. fimbriatus* and *C. cirrhosus* show a gradual decrease in suitable habitats after a discharge of 55 m^3/s (Figure 4).

The Godavari is one of the richest rivers with respect to fish diversity in peninsular India[17]. More than 90 species of fish inhabit the downstream section of this river, and about 60 fish species have been reported from the proposed dam site at Polavaram, East Godavari District, Andhra Pradesh[17]. Among these, *B. dero*, *C. cirrhosus*, *L. calbasu* and *L. fimbriatus* were the most common economically important fishes[17]. These are also the most common species in other rivers and irrigation canals of peninsular India[21,22]. They live in a broad range of flow conditions, and their abundance in the Godavari is due to the wide range of suitable habitat conditions available in this river. However, *W. attu*, which is also an economically important and large-sized fish, was less frequently encountered during the sampling period. This might be

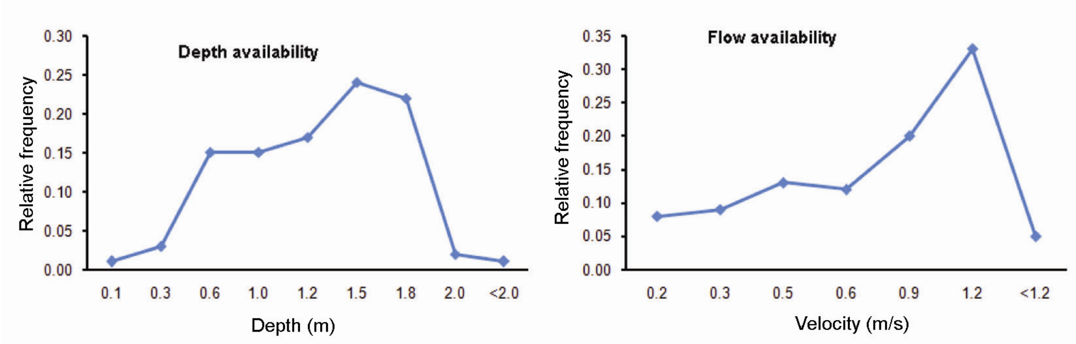

Figure 2. Relative frequency of available habitat on the basis of 414 observations of depth and velocity in the downstream of Godavari river.

Table 2. Habitat utilization (Obs) and preference (Pref) of five fishes used to develop habitat suitability curves

	Bangana dero		*Cirrhinus cirrhosus*		*Labeo calbasu*		*Labeo fimbriatus*		*Wallago attu*	
Variables	Obs	Pref	Obs	Pref	Obs	Pref	Obs	Pref	Obs	Pref
Depth (cm)										
0–0.1	–	0	–	0	–	0	–	0	–	0
0.1–0.3	–	0	–	0	–	0	–	0	–	0
0.3–0.6	5	0.2	–	0	–	0	6	0.2	16	0.5
0.6–1.0	30	1	12	0.2	34	1	14	0.5	32	1
1.0–1.2	34	1	51	1	38	1	30	1	16	0.4
1.2–1.5	39	0.8	58	1	23	0.4	43	1	13	0.25
1.5–1.8	27	0.6	–	0	–	0	20	0.5	–	0
1.8–2.0	–	0	–	0	–	0	–	0	–	0
<2.0	–	0	–	0	–	0	–	0	–	0
Velocity (m/s)										
0–0.2	–	0	–	0	–	0	–	0	–	0
0.2–0.3	–	0	50	1	26	1	–	0	–	0
0.3–0.5	7	0.2	71	1	36	1	–	0	9	0.3
0.5–0.6	14	0.5	–	0	33	1	–	0	19	0.6
0.6–0.9	43	1	–	0	–	0	23	0.4	49	1
0.9–1.2	71	1	–	0	–	0	90	1	–	0
<1.2	–	0	–	0	–	0	–	0	–	0

due to overexploitation of this species for food, as there is a great demand for it in the local market[23,24].

The HSCs generated for the five species indicate that all except *L. fimbriatus*, used similar depth ranges (0.9–1.5 m/s). *L. fimbriatus* used deeper habitats (0.9–2.1 m/s), but the range of optimal suitability was close to that of the other species. The calculated velocity curves also indicate that *B. dero* and *L. fimbriatus* had high flow preference (>0.9 m/s) compared to *C. cirrhosus*, which preferred low-velocity habitats (<0.3 m/s). Therefore, it can be concluded that *L. fimbriatus* prefers the fast-flowing but deeper sections of the river, whereas *B. dero* prefers fast to moderate flows with shallow regions of the river. The depth preference of *B. dero* were shallow habitats associated with the open channel and areas near the river banks. The channel bottom in the area examined was either uniformly sandy, or a combination of sand and silt. Hence, the substrate suitability curves of these fishes were not evaluated.

Based on the results of WUA, the estimated minimum ecological flow required for economically important fishes of the Godavari river was 26% of the mean flow observed during the lean season. From this it can be inferred that a flow less than 50 m^3/s would have considerable impact on the available suitable habitats for these economically important fishes. The discharge of 50 m^3/s was estimated as the point of inflection of the suitable habitats of *L. calbasu*, *L. fimbriatus* and *W. attu*. Any reduction in discharge below this inflection point was observed to be detrimental to these species as their suitable habitat availability reduced sharply. Further, any increase in the discharge above 50 m^3/s was of little benefit to most of these species. Hence, the optimum flow requirement of the selected fish species was estimated at 50 m^3/s, which is approximately 26% of the mean flow (192.51 m^3/s) during the lean flow season (i.e. April) of the Godavari river.

This flow estimation is based on the habitat requirements of economically important larger fishes found in the proposed dam site. It is assumed that in a large river like the Godavari, the minimum ecological flow set for the larger fishes will be adequate to maintain native fish

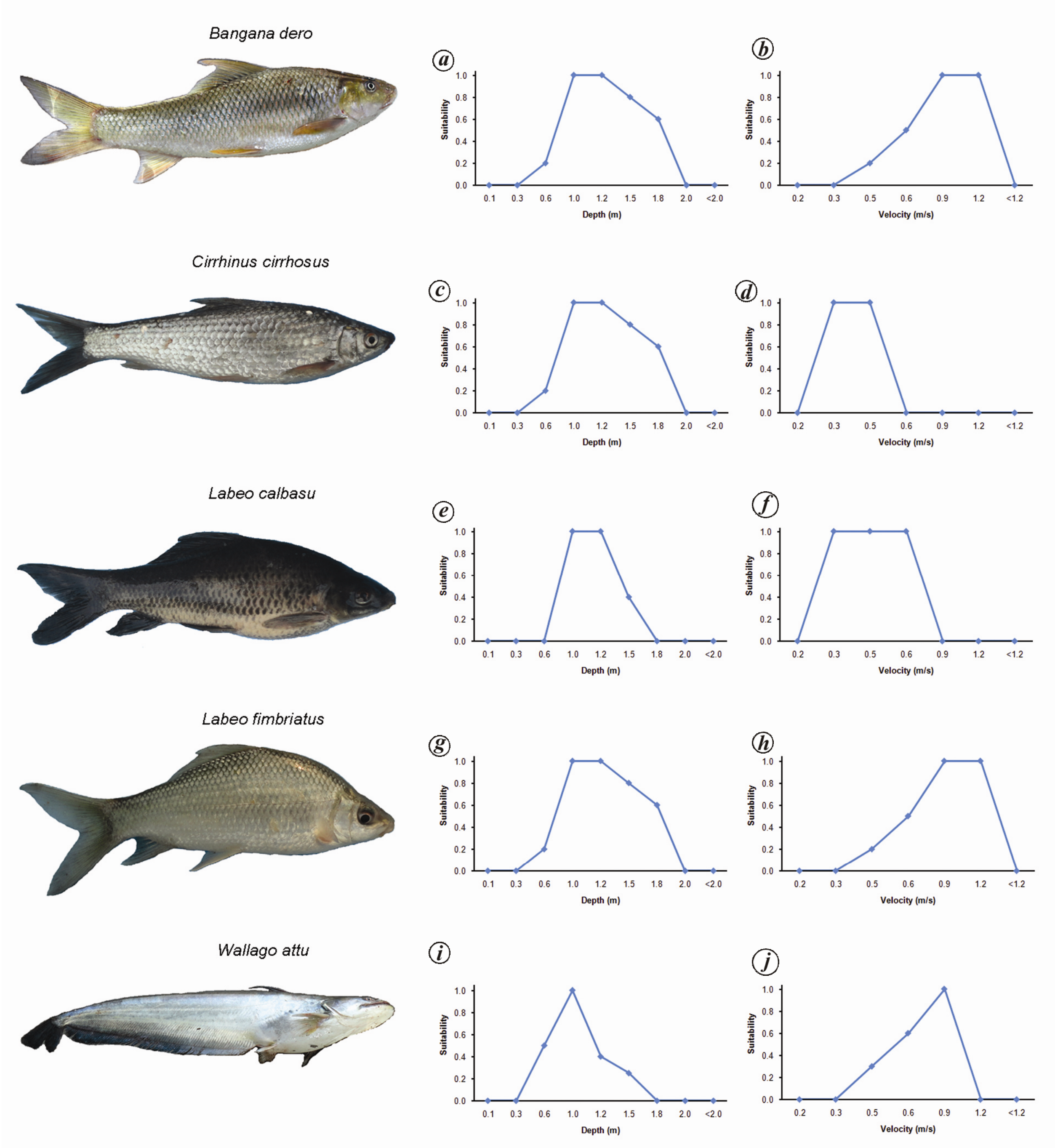

Figure 3. Habitat suitability curves of economically important fishes of the Godavari river.

populations. The rationale behind this is that the larger fishes require greater depths and velocities compared to the coexisting species. Many small cyprinids (e.g. danio, barils, rasboras, barbs) are abundant in streams or shallow regions of the river[17]. Therefore, the optimal habitats of these species have low flows. The river margin always provides some refuge for these small fishes, where the flow is high as required by the larger fishes (pers. obs). Earlier, flow estimation studies in Indian rivers were mainly based on EMC and expert opinion. Rajvanshi *et al.*[12] determined the environmental flow to be 14.5% of the mean seasonal flow for the no-fish zone and 21.5% of the mean seasonal flow for the mahseer zone of the upper Ganga basin. Another study conducted in the River Sone, in the lower Ganga basin, concluded that a minimum of 18.9% of the mean annual flow is required to maintain the basic ecosystem functions[13]. However, in this study the minimum environmental flow has been estimated for a modified river using PHABSIM, which requires details of the habitat requirements of fishes. We estimated

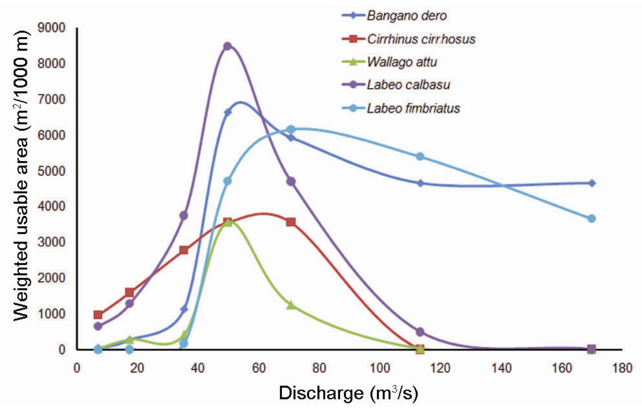

Figure 4. Habitat–flow relations of five species derived from PHABSIM analysis. Curve peaks indicate the optimum suitable habitats for a given discharge.

50 m^3/s to be the minimum environmental flow for the downstream of the Godavari, which is approximately 26% of the mean flow observed during the lean flow season, i.e. April. This estimated volume is similar to the flow suggested on the basis of EMC of the Godavari[10].

1. 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; doi:10.1002/rra.736.
2. Gore, J. A., Layzer, J. B. and Mead, J., Macroinvertebrate instream flow studies after 20 years: a role in stream management and restoration. *Regul. Rivers: Res. Manage*., 2001, **17**, 527–542; doi:10.1002/rrr.650.
3. Vishmara, R., Azzellinno, A., Bosi, R., Grosa, G. and Gentili, G., Habitat suitability curves for brown trout (*Salmo trutta fario* L.) in the river Adda, northern Italy: comparing univariate and multivariate approaches. *Regul. Rivers: Res. Manage.*, 2001, **17**, 37–50; doi:10.1002/1099-1646(200101/02)17:1<37::AID-RRR606>3.0.CO;2-Q.
4. Jowett, I. G., Hayes, J. W. and Duncan, M. J., *A Guide to Instream Habitat Survey Methods and Analysis*, NIWA Science and Technology Series No. 5, New Zealand, 2008, p. 121.
5. Bovee, K. D., Lamb, B. L., Bartholow, J. M., Stalnaker, C. B., Taylor, J. and Henriksen, J., Stream habitat analysis using the instream flow incremental methodology. Biological Resources Division Information and Technology Report USGS/BRD-1998-0004, US Geological Survey, Washington, DC, USA, 1998, p. 159.
6. Annear, T. *et al.*, *Instream Flows for Riverine Resource Stewardship*, Instream Flow Council, Cheyenne, WY, USA, 2004.
7. Conklin Jr, D. J., Canton, S. P., Chadwick, J. W. and Miller, W. J., Habitat suitability curves for selected fish species in the central Platte river, Nebraska. *Rivers*, 1996, **5**(4), 250–266.
8. Reiser, D. W., Wesche, T. A. and Estes, C., Status of instream flow legislation and practices in North American fisheries. *Fisheries*, 1989, **14**(2), 22–29.
9. Rosenfeld, J. S. and Plotemy, R., Modelling available habitat versus available energy flux: do PHABSIM applications that neglect prey abundance underestimate optional flows for juvenile salmonids? *Can. J. Fish. Aquat. Sci*., 2012, **69**, 1920–1934; doi:10.1139/f2012-115.
10. Smakhtin, V. and Anputhas, M., An assessment of environmental flow requirements of Indian river basins. International Water Management Institute, Colombo, Sri Lanka, IWMI Research Report 107, 2006, p. 42.
11. Kumara, B. K. H., Srikantaswamy, S. and Bai, S., Environmental flows in Bhadra River, Karnataka, India. *Int. J. Water Res. Environ. Eng.*, 2010, **2**(7), 164–173.
12. Rajvanshi, A. *et al.*, Assessment of cumulative impacts of hydroelectric projects on aquatic and terrestrial biodiversity in Alaknanda and Bhagirathi basins, Uttarakhand. Technical Report, Wildlife Institute of India, Dehradun, 2012.
13. Joshi, K. D., Jha, D. N., Alam, A., Srivastava, S. K., Vijay Kumar and Sharma, A. P., Environmental flow requirements of river Sone: impacts of low discharge on fisheries. *Curr. Sci*., 2014, **107**(3), 478–488.
14. CWC, National register of dams in India. Central Water Commission, New Delhi, 2014; www.cwc.nic.in (accessed on 31 December 2014).
15. WRIS, Dams and barrages location map in India. Water Resource Information System of India, New Delhi, 2014; www.india-wris.nrsc.gov.in (accessed on 31 December 2014).
16. Bovee, K. D., A guide to stream habitat analysis using the instream flow incremental methodology. Instream Flow Information Paper 12, FWS/OBS-82/26, US Fish and Wildlife Service, Washington DC, USA, 1982, p. 248.
17. Sivakumar, K., Johnson, J. A., Gokulakkannan, N., Ray, P., Katlam, G. and Bagaria, P., Assessment of ecological settings and biodiversity values of Papikonda National Park and Indira Sagar (Polavaram) Multipurpose Project Impact Zone in Andhra Pradesh for development of mitigatory measures. Wildlife Institute of India, Dehradun, 2014, p. 159.
18. Bovee, K. D., Development and evaluation of habitat suitability criteria for use in the instream flow incremental methodology. Instream Flow Information No. 21, US Fish and Wildlife Service (Biological Report 87[7]), Washington, DC, USA, 1986, p. 231.
19. Jowett, I. G., Native fish and minimum flows in the Kakanui river. Conservation Advisory Science Notes No. 88, Department of Conservation, New Zealand, 1994, p. 288.
20. PHABSIM, Physical Habitat Stimulation Model for Windows. User's Manual and Exercises, Midcontinent Ecological Science Center, US Geological Survey, Washington DC, USA, 2001.
21. Talwar, P. K. and Jhingran, A. G., *Inland Fishes of India and Adjacent Countries*, Oxford-IBH Publishing Co Pvt Ltd, New Delhi, 1991.
22. Jayaram, K. C. and Dhas, J. J., Revision of the genus *Labeo* from Indian region with a discussion on its phylogeny and zoogeography. ZSI, Occasional Paper No. 183, Zoological Survey of India, Kolkata, 2000.
23. Mishra, S. S., Acherjee, S. K. and Chakraborty, S. K., Development of tools for assessing conservation categories of siluroid fishes of fresh water and brackish water wetlands of south West Bengal, India. *Environ. Biol. Fish*, 2009, **84**(4), 395–407; doi:10.1007/s10641-009-9448-9.
24. Ng, H. H., *Wallago attu*. The IUCN Red List of Threatened Species. Version 2014.3, 2010, www.iucnredlist.org (accessed on 15 December 2014).

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