Egyptian Journal of Aquatic Biology & Fisheries
Zoology Department, Faculty of Science,
Ain Shams University, Cairo, Egypt.
ISSN 1110 – 6131
Vol. 28(1): 209 – 221 (2024)
www.ejabf.journals.ekb.eg

Environmental Flow Estimation in Nambul River, Northeast India Through PHABSIM

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ARTICLE INFO
Article History:
Received: Nov. 22, 2023
Accepted: Dec. 15, 2023
Online: Jan. 13, 2024

Keywords:
Nambul River,
Fish habitats,
PHABSIM,
Hydrodynamic,
Habitat suitability

ABSTRACT
Freshwater fish are on the brink of extinction due to the degradation of habitat. The present research focused on the estimation of the environmental flow requirement of significant fish species in the Nambul River, Northeast India. Nambul is an important river that drains directly into Loktak Lake. Loktak Lake is an internationally important Ramsar-designated wetland. The environmental flow requirements of the significant fish, namely *Bangana dero* and *Wallago attu*, were estimated using the physical habitat simulation model (PHABSIM). The habitat suitability curves (HSCs) were employed in PHABSIM along with the instream habitat data of the cross-sections for estimating the weighted usable areas (WUAs) of the two fish species. Based on the WUA-discharge curve, an optimum environmental flow requirement of 50 cumecs of discharge is recommended for the fish habitats. The estimation of minimum environmental flow requirements can be considered as an essential step toward conservation and sustainability.

INTRODUCTION

Freshwater ecosystems can be considered one of the most endangered ecosystems in the world **(Sala *et al.*, 2000)**. The deterioration of biodiversity in a freshwater ecosystem is extremely high compared to the terrestrial ecosystem **(Sala *et al.*, 2000)**. Various anthropogenic activities, such as the construction of hydroelectric projects, river diversions, and abstraction of water for irrigation purposes, have a high impact on the freshwater ecosystem, leading to the loss of its aquatic species.

Although the freshwater available to us constitutes less than 1% of the Earth's surface, it supports about 43% of the freshwater fish species **(Nelson, 2006; Magurran *et al.*, 2011)**. Fish exhibit a high range of diversity in their behavior, morphology, and reproduction. They display tolerance to a narrow band of physico-chemical and hydraulic variables, thereby leading them to adapt to diverse habitats ranging from mountainous streams and cold water lakes to estuaries. Amongst the freshwater river system, the tropical Asian rivers and streams are the second richest in aquatic biodiversity, which supports the livelihoods of villagers in many developing countries **(Darwall *et al.*, 2008)**.

At present, the tropical river ecosystems are on the brink of deterioration due to various developmental activities and increasing needs for water and energy. Hydrological modifications, such as the construction of hydropower projects, dams, and irrigation canals led to the modification of natural hydrodynamics, leading to the disturbance of aquatic life. This led to a decrease in the threatened and native fish communities and allowed non-native fish species to grow and breed in the river systems. Furthermore, it indicates that necessary conservation actions are required to be taken in time.

The flow regime is the main critical factor for sustaining the ecological integrity of flowing river systems. The flow can be considered the master variable of the riverine systems, along with other riparian areas since it determines the biological, water quality, energy transfer, and physical habitat **(Poff *et al.*, 1997)**. The timing, duration, frequency, rate of change, and timing of the flow regime influence the primary regulators of ecological integrity. Therefore, any hydrological modifications may cause drastic changes in the ecological integrity of rivers. The seasonal variation of flows comprises low and high discharge, collectively known as the natural flow paradigm. Maintaining the natural flow regime is advantageous to native aquatic species and hinders non-native species from flourishing **(Poff *et al.*, 1997)**. The alteration in flow regime can affect aquatic biota including fish species and insects. **Poff and Zimmerman (2010)** reviewed the correlation between the flow alteration and the ecological response of biotic life. The study found that out of 165 cases studied, 152 cases have been reported to show a negative response toward changes in flow dynamics.

The conservation of freshwater ecosystems is one of the biggest challenges we are globally facing. In order to develop conservation strategies, there is a need to determine minimum environmental flow. An environmental flow assessment (EFA) can be defined as an estimation of the amount of discharge required to retain downstream for maintaining the ecological integrity of biotic life **(Tharme & King, 1998)**. **Tharme (2003)** grouped the environmental flow methodologies into four categories, namely holistic approach, hydrological, hydraulic rating, and habitat simulation. In a holistic approach, seasonal flow variations considering low or high flows of the rivers are identified **(Tharme & King, 1998)**. The environmental flow methodologies (EFMs) based on hydrological indices with higher accuracy in capturing flow variation and ecological aspects have been evolving since the 1990s. Some of the methodologies include the Texas method **(Mathews & Bao, 1991)**, the basic flow method **(Palau & Alcazar, 1996)**, and the range of variability approach **(Richter *et al.*, 1997)**. Hydrologically-based methods use hydrological data, mostly in the form of observed monthly or daily flow discharge to predict environmental flow requirements. In the hydraulic rating method, an established empirical or well-defined hydraulic model relationship between discharge and wetted perimeter is used to estimate minimum environmental flows for fish rearing **(Tharme, 2003)**. The most commonly used habitat simulation methodology is instream flow incremental methodology (IFIM), which includes the physical habitat simulation model (PHABSIM) **(Bovee *et al.*, 1998)**. PHABSIM is suitable for assessing the flow requirements of specific sites. This model is specifically designed to predict an index of the quantity of microhabitats available for different life stages considering seasonal flow variation. The model incorporates two major components, namely stream hydraulics and habitat suitability criteria of species. This model has been employed by many researchers for preserving aquatic ecosystems and developing water resources management strategies. **Booker and Dunbar (2004)** applied PHABSIM in modified urban rivers and assessed uncertainties in PHABSIM applications. The results showed that the model has higher suitability with different flows in natural rivers as compared to an engineered channel. **Johnson *et al.* (2017)** estimated the minimum ecological flow required for fish using the PHABSIM and recommended 26% of the mean flow below the Polavarm Dam of the Godavari River in India. **Hajiesmaeili *et al.* (2018)** applied the habitat model, PHABSIM, to predict the physical habitat of rainbow trout in the Delichai Stream, Iran. Whereas, **Johnson *et al.* (2021)** studied the habitat suitability of the black-necked crane in Nyamjang Chu River in Eastern Himalaya, India, in correlation to the proposed hydropower dam, and recommended a maximum of 20 cumecs as ecological flows.

Nambul River has a high impact on the habitat and ecosystem of Loktak Lake **(Eliza *et al.*, 2019)**. Loktak Lake is a Ramsar-designated wetland located in Manipur, India. The lake is also recorded under the Montreux record due to its ecological condition. Nambul is an important river which drains directly into the Loktak Lake. **Singh *et al.* (2016)** addressed the water quality of the Nambul River, Manipur, India, and found that the water quality index is below the drinking level and recommended timely intervention for its conservation. **Singh and Gupta (2015)** studied the physicochemical parameters of the Nambul River and found that the river has high levels of inorganic and organic contaminations. **Eliza *et al.* (2020)** analyzed the habitat suitability of a fish species in relation to the water quality of rivers, including Nambul. However, there is no study regarding the environmental flow estimation of the Nambul River. The present study estimated the optimum environmental flow requirement of *Bangana dero* and *Wallago attu* fish species in the Nambul River using the PHABSIM model. The habitat suitability criteria of the two fish species and hydraulic parameters, such as depth and velocity are used as model inputs for estimating weighted usable areas (WUA) of the two fish species. The relationship between the WUA and discharge was considered to estimate the environmental flow requirements for the fish habitats.

MATERIALS AND METHODS

1. Study area

The present study area is Nambul River, located in Manipur, Northeast India (Fig. 1). A river stretch of about 2,910m extending from Hiyanthang to upstream was considered for field sampling and modeling purposes. Fig (1) also displays the location of five cross sections, which are about 500m apart. The Nambul River originates from Litan Waiphei, located at the Kangchup hill range. The Nambul River, with a length of about 23km, passes through the Bishnupur and Imphal West districts. The river flows through a heavily populated area where there is very poor management of solid waste, as observed during the field survey. Solid waste is mainly comprised of domestic and small-scale textile industries. Villagers are using the water from the river, mostly for bathing and washing purposes. The Nambul sub-catchment covers about 196km^2, with elevation ranging from about 767 to 2,329m above mean sea level (MSL). The area of the sub-catchment and elevation were obtained from DEM after extracting the area of interest. The source of DEM is Earth Resources Observation and Science (EROS), United States Geological Survey (USGS). The clayey, loamy, clay-skeletal types of soil are found in the Nambul sub-catchment. The digital soil map was obtained from the National Bureau of Soil Survey and Land Use Planning (NBSS and LUP), Government of India. In the Nambul sub-catchment, various types of land used are identified, including agriculture (91km^2), dense forest (47km^2), Jhum (10km^2), degraded forest (15km^2), settlement (20km^2), Phumdis (6km^2), and water (3km^2). This information is obtained from the State Forest Department, Government of Manipur. Jhum cultivation, also called the slash-and-burn method of cultivation, involves cutting down forests and burning plant remains. Phumdis are masses of floating vegetation found in Loktak Lake, located in Manipur, India.

Some of the fish species which were observed during the field sampling include *Glossogobius giuris*, commonly known as ngamu, and *Lepidocephalichthys guntea* (Ngakijou), *Mystus bleekeri* (Ngasep), *Mystus cavasius* (Ngasep), *Wallago attu* (Sareng), *Bangana dero* (Ngaton), *Puntius chola* (Phabounga). *Glossogobius giuris*, *Lepidocephalichthys guntea*, *Mystus bleekeri*, *Mystus cavasius*, *Bangana dero*, and *Puntius chola* that were all observed throughout the year, while *Wallago attu* was observed during the rainy season only. Among these species, *Wallago attu* and *Bangana dero* were considered based on their importance and data availability. *Wallago attu* is found across India, Sri Lanka, Pakistan, Bangladesh and Nepal. This fish species is listed as a vulnerable species in the International Union for Conservation of Nature (IUCN) Red List of Threatened Species. *Bangana dero* is distributed throughout the Himalayan foothills in India, Nepal, China, and Bangladesh. The species has also been introduced in Sri Lanka and peninsular India. The species has also been listed under the least concern species in the IUCN Red List of threatened species.

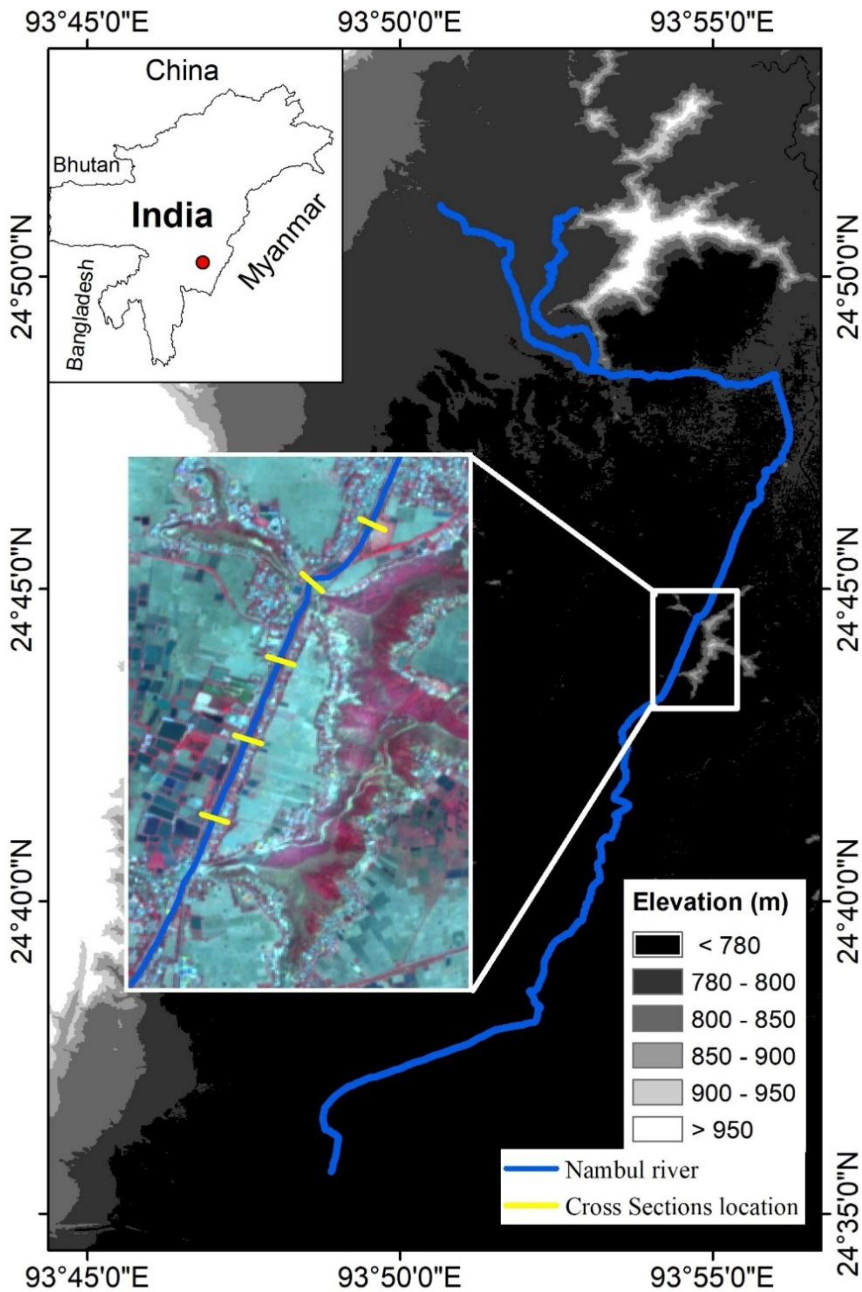

Fig. 1. Location map of study area in Nambul River, Manipur, Northeast India

2. PHABSIM

PHABSIM is integral to a conceptual and systematic framework designed to address various issues of stream flow management called the instream flow incremental methodology (IFIM) **(Stalnaker *et al.*, 1995)**. IFIM delivers an outline for solving various problems related to rivers and streams. PHABSIM and IFIM were developed to provide aid in solving water resources-related issues. PHABSIM estimates variation in physical microhabitats associated with flow changes. It employs various types of simulation tools that describe the microhabitat conditions of rivers and streams and defines the habitat characteristics, which are dependent on flow, in correlation to the biological response of selected species and their life stages. The PHABSIM model has an assumption that the physical habitat characteristics, which are dependent on flow, are beneficial in determining the carrying capacity of rivers and streams and, thereby, related to the impacts of flow on aquatic life and fish. Additionally, it assumes that the productivity of fish is limited by the physical microhabitat availability.

The term microhabitat used in PHABSIM can be defined as the localized, small areas inside a mesohabitat unit used by fish or aquatic life for their breeding period. Mesohabitat can be defined as a longitudinal portion of the river or stream within which chemical or physical properties impact the suitability of the entire river stretch for fish or aquatic life. Mesohabitat are usually portions of rivers or streams with similar physical features, such as depth, width, slope, and substrate availability. At the same time, microhabitat is usually characterized by aggregation of hydraulic or physical characteristics, such as depth, width, slope, cover, and substrate availability at a spatial scale of a few meters to near zero.

PHABSIM considers flow-dependent variables of the ecosystem and predicts the quantity and quality of microhabitats for aquatic species. The variation in flows across different seasons is taken into account to estimate the relationship between physical variables (velocity, depth, cover, and substrate) and habitat suitability of selected species, including their life stages. The identification of target species and their life stages can be considered a crucial step in the PHABSIM modeling. Habitat suitability curves (HSC) are also known as suitability criteria, suitability indices, suitability curves, preference curves, and preference indices. The simulation of hydraulic programs in PHABSIM assumes that the structure of the river or stream remains constant with the seasonal variation of discharge. The simulated hydraulic parameters include depth (water surface elevations) and velocities. The habitat modeling employs data on channel shape, velocities, simulated water surface elevation, and HSCs into an index of quality and quantity of available use, also referred to as weighted usable area (WUA). The total WUA of a specific site is calculated using the following equation (1):

$$WUA = \sum_{i=1}^{n} A_i * C_i \quad (1)$$

Where, WUA = Total weighted usable area
A_i = Vertical view area of cell i (Bed area or volume)
C_i = Composite suitability for cell i

3. Data input and modeling

The selection of the study site and cross-section were based on references from the PHABSIM manual **(USGS, 2001)**. The model was developed for the longitudinal portion extending about 2,910m in Nambul River (Fig. 1) using PHABSIM. Five cross-sections with a distance of about 500m were specified in the model. Hydraulic and habitat simulations were performed. For hydraulic simulation, depth and velocities at every 2m were specified in the model, which were observed during the field sampling. The model inputs and data sources are exhibited in Table (1). Manning's coefficient was specified to be 0.04 on the basis of the available substrate observed during the field sampling and the literature **(Chow, 1959; Eliza *et al.*, 2018)**. For calibration purposes, observed discharge and corresponding water surface level were specified in the model. The water surface level (WSL) was set to run using the STGQ model. The STGQ model employs a rating curve (stage-discharge) for estimating the WSL for all cross-sections. In the stage-discharge relationship, the WSL for each cross-section is simulated independently of all other cross-sections. The basic computation is performed on the basis of a log-lag regression between stage-discharge relations at each cross-section. The regression equation obtained is then employed to estimate WSL for the remaining cross-sections. The WSL was simulated for different discharge covering from lean to rainy season. The amount of daily discharge throughout the year was stipulated from the observed discharge obtained from the Loktak Development Authority (LDA), Government of India (Fig. 2). Fig. (2) displays that the highest observed discharge was 98.53 cumecs on October 2, 2000, while the lowest, 0.05 cumecs, occurred on March 21, 2001, within the specified period from June 1, 1999 to May 31, 2003. The velocity was also simulated for the different discharges in each cross-section. The model assumes that the WSL is constant for a single cross-section, while depth varies since it is estimated by subtracting the bed elevation from the WSL. Additionally, the velocity varies from cell to cell across any cross-section.

For habitat simulation, the habitat suitability of target fish species was specified in the model in the form of habitat suitability curves (HSCs). Considering the complexity of finding the exact location of target fish species, the HSCs were obtained from the literature **(Johnson *et al.*, 2017)**. The HSCs curves for *Bangana dero* and *Wallago attu* fish species at adult stages are shown in Figs. (3, 4), respectively. Irrespective of the method employed to collect the data, suitability curves will establish some specificity to the stream in which the models are developed. With the high cost of developing stream-specific suitability curves and the availability of limited resources, transfer of HSC developed for other streams is common **(USGS, 2001)**. The model assumes that the aquatic species will respond to the changing hydraulic environment **(USGS, 2001)**. The varying depth and velocities will affect the available habitat for the target fish species. Figs. (3, 4) show that *B. dero* species prefers depth ranging from 0.6 to 1.5m, while *W. attu* species uses a narrower range varying from 0.6 to 1m. Moreover, Figs. (3, 4) indicate that the optimal range of velocity for *B. dero* varies from 0.6 to 1.2m/ s, while *W. attu* prefers a velocity ranging from 0.6 to 0.9m/ s. Thus, it can be implied that *B. dero* and *W. attu* fish species have a preference for shallow depth and higher velocity. In the model, habitat was set to run to simulate the uses of target fish species. The WUA for each species was obtained as output from the habitat model. WUA indicates the availabity of suitable habitat units in square meters per km.

Table 1: Data input and source

Data	Source
Geographical location	Field sampling
Elevation	Field sampling
Velocity and width	Field sampling
Substrate available	Field sampling
Manning’s n	Substrate and literature (Chow, 1959; *Eliza et al.*, 2018)
Observed discharge for calibration	Field sampling
Observed discharge throughout the year	Loktak Development Authority, Government of India
Suitability indices	Literature (Johnson *et al.*, 2017)

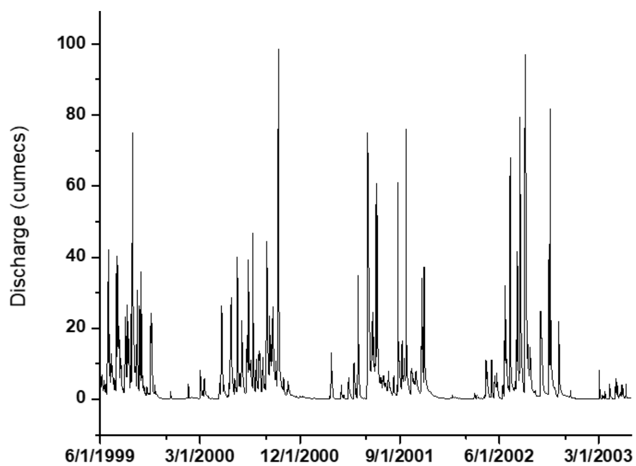

Fig. 2. Observed discharge of Nambul River (Source: Loktak Development Authority)

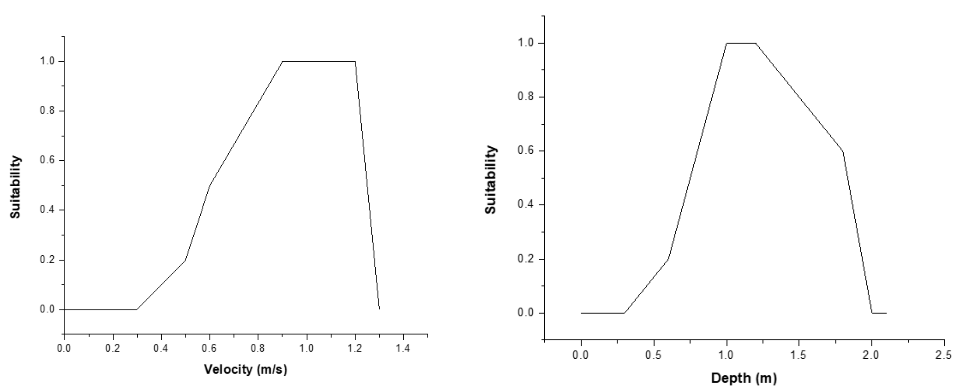

Fig. 3. Habitat suitability curves for *Bangana dero* (mature)

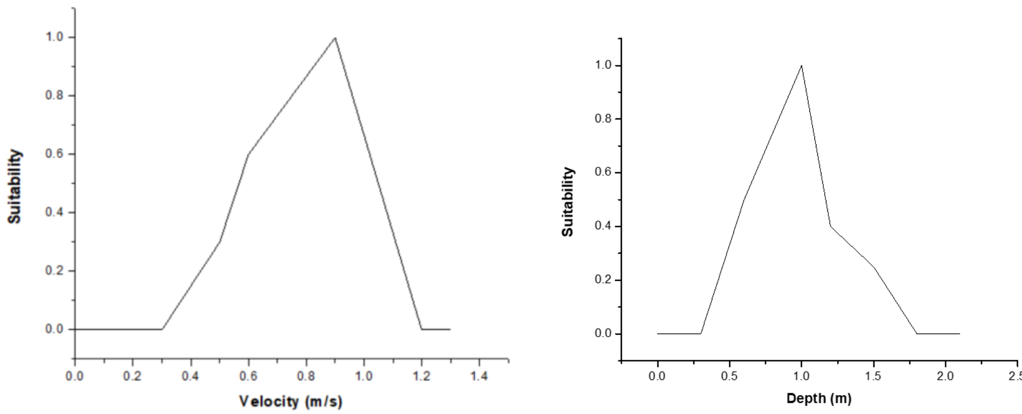

Fig. 4. Habitat suitability curves for *Wallago attu* (mature)

RESULTS AND DISCUSSION

The PHABSIM model simulates WSL for the different discharges at each cross-section. The model also simulates velocity at every 2m for each cross-section, considering varying discharge. The WUA for the two target species, *Bangana dero* and *Wallago attu*, were obtained considering the seasonal variation throughout the year, as shown in Fig. (5). The highest WUA for *Bangana dero* in Nambul River is estimated to be 4,891.56 sq m/ 1,000m at 50 cumecs. At the same time, *Wallago attu* shows 2,274.69 sq m/ 1,000m at 50 cumecs. The results show that the WUA of *Wallago attu* is smaller as compared to the WUA of *Bangana dero*. However, both fish species show the highest suitability at 50 cumecs of discharge in the Nambul River. Both *B. dero* and *W. attu* species show a steep increase of WUA from 38 to 50 cumecs. Consequently, the two species show a decline when the discharge is higher than 50 cumecs. *B. dero* shows WUA of 2,845.69 sq m/ 1,000m at 60 cumecs, while *W. attu* shows suitability of 2,255.23 sq m/ 1,000m at 60 cumecs. Thus, the results show that the suitability decreases when the discharge is more than 50 cumecs. Additionally, it shows that any increase in the discharge of 50 cumecs is not beneficial for the target fish species. The WUA versus discharge relationship for *B. dero* shows a broader range of depths and velocities as compared to *W. attu* species. The wider range of depths and velocities of *B. dero* may be attributed to the wide range of suitable habitat conditions available in the Nambul River. On the other hand, *W. attu* is an economically important species, and its availability is comparatively lesser during field sampling. This might be attributed to over exploitation for commercial and food purposes.

The PHABSIM model simulated 50 cumecs as the optimum flow requirement for the Nambul River. However, the amount of discharge in the river is comparatively very low during the lean season. The river flows through the settlement area, which leads to high pollution from domestic waste and small-scale textile industries. At the same time, the amount of discharge is higher during monsoon season. The PHABSIM predicts the changes in physical habitat as a function of discharge considering seasonal variation but does not consider other factors in the river or stream system, such as energy inputs and water quality parameters. The drawback in the present study can be the non-consideration of other parameters, such as water quality, for defining the habitat suitability of target fish species. Essentially, in most situations, physical habitat is necessary, but water quality parameters may add to define the production and survival of aquatic life. Thus, the PHABSIM results can be considered as an indicator of potential habitat conditions that need to be maintained for the survival and production of the target fish species.

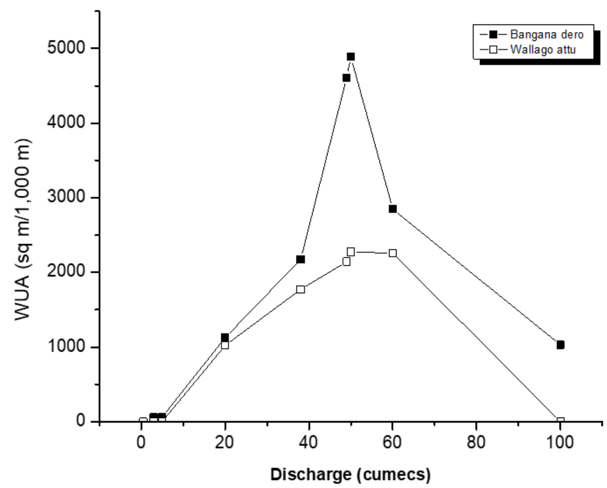

Fig. 5. Weighted usable area (WUA) versus discharge for *Bangana dero* and *Wallago attu* fish species in Nambul River

CONCLUSION

The present study presents the estimation of the minimum environmental flow requirement for the two selected fish species, *Bangana dero* and *Wallago attu*, in the Nambul River. Nambul is an important river that drains directly into Loktak Lake and has a high impact on the habitat and ecosystem of Loktak Lake **(Eliza *et al*., 2019)**.

The PHABSIM model was developed for the river stretch of about 2,910m extending from Hiyanthang (Nambul River) towards upstream. The field sampling was conducted for the five cross-sections. Hydraulic and habitat simulations were performed using the PHABSIM model. The water surface level (WSL) was simulated for different discharge covering from the lean to the rainy season. The velocity was also simulated for the different discharges in each cross-section. Moreover, the PHABSIM model estimates the WUA for the two target species. The relationship between WUA and discharge estimates that 50 cumecs of discharge is required for maintaining optimum environmental flow. The highest WUA for *Bangana dero* and *Wallago attu* are estimated to be 4,891.56 and

2,274.69m^2/ 1,000m at 50 cumecs, respectively. Both of the species show a steep increase of WUA from 38 to 50 cumecs. The two species show a decline in suitability when the amount of discharge is higher than 50 cumecs. *B. dero* and *W. attu* show WUA of 2,845.69 and 2,255.23m^2/ 1,000m at 60 cumecs, respectively. The study concluded that discharge higher than 60 cumecs is not beneficial for the target species. However, the amount of discharge is comparatively much lesser during the lean season. The PHABSIM predicts the changes in physical habitat as a function of discharge considering seasonal variation. The estimation of recommended environmental flows can be considered an essential step toward framing conservation and management strategies.

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