# PREDICTING LOW FLOW THRESHOLDS OF HALDA-KARNAFULI CONFLUENCE IN BANGLADESH

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## ABSTRACT

Eco-hydraulic modeling for flow assessment has increased in recent years due to complex hydraulic factors that control different life stages of ecological habitat. Both the Halda and Karnafuli Rivers play a vital role in the south-eastern part of Bangladesh. In almost every dry season they experience lower inflow. In this study, a 1D eco-hydraulic model, which is representing a Physical Habitat Simulation System (PHABSIM), and a 2D eco-hydraulic model for inflow regimes (CASiMiR), are applied to selected areas. To study low and minimum flow regimes two key factors, the Weighted Usable Area (WUA) and the Habitat Suitability Index (HSI) were applied. Based on the flow during flood tide and long term flow variability, a flow series was investigated to simulate suitable environmental flow regimes. Both models predicted similar trends in incremental discharge variation during minimum inflow and average minimum inflow operating in the in a range of 25 - 30.1 m3/s. Although, difficulties arise while acquiring river bed topography data in the 2D eco-hydraulic model set up, reasonable prediction accuracy and geometry of regime could be obtained. However, insufficient bathymetric data necessitated the application of 1D eco-hydraulic simualtion which yielded reasonable performance while taking suitable eco-hydraulic factors into account.

***Keywords:*** *CASiMiR2D, Low flow, Karnafuli river, PHABSIM, Physical habitat.*

## 1. INTRODUCTION

Low flow is the minimum flow requirement to sustain the ecological habitat of a riverine ecology. Since 1980, river managers have tried to correlate habitat change with flow using the inflow habitat model that can define a minimum flow while maintaining a healthy ecology. Usually, a habitat model that is based on predefined flow of a hydraulic model can predict water velocity and depth. In terms of velocity, size and depth of a certain range might be suitable for biota (Leclerc et al., 2003, Pasternack et al., 2004, Smakhtin, 2001). A 2D or 3D hydraulic model can be sensitive to river geometry, if one considers depth, magnitude, and velocity distribution in X, Y (2D) or X, Y, Z (3D) direction. 1D models only predict mean velocities. To yield progress in modelling, the assessment of low flow regimes can be based on four major methods: a) hydrological methods (Mathews and Richter, 2007), b) hydraulic methods (Lamouroux and Capra, 2002), c) physical habitat methods (Muñoz-Mas et al., 2014), and d) holistic methods ( McClain et al., 2014). All of those methods require hydrological, hydraulic, and biological data that maybe statistically or data driven. Physical habitat methods have a wider applicability due to consideration of alternative management methods, restoration actions, and climate change effects (Yi et al., 2014). This also allows the identification of habitats, which are exposed to flow changes. Main key assumptions include and refer to river velocity, river depth, river temperature, etc. They can become limiting factors and determine the distribution of habitats, which can be considered in the model in terms of Weighted Usable Area (WUA) (Milhouse and Waddle, 2012). Based on those key assumption, model developments like PHABSIM (Nagaya et al., 2008), RHYHABSIM (Jowett, 1996), EVHA (Ginot, 1995), and Mesohabitat (Parasiewicz and Dunbar, 2001), or 2D model like Hydro2de, River 2D (Muñoz-Mas et al., 2014) were possible. However, few of these models hardly consider factors related to habitat availability and environmental factors like water quality and nutrient availability. In order to consider these factors, fuzzy logic based Computer Aided Simulation Models for inflow regimes (CASiMiR) (Yao et al., 2015) were developed to take 1D and 2D habitat modeling, environmental, and biotic and abiotic factors into account. In this study, preference curve methods used by PHABSIM and CASiMiR2D were used to assess low flow regimes and thresholds of selected areas of Karnafuli River.

## 2. MATERIAL AND METHODS

### 2.1 Study Area

The study area is situated in the downstream part of Halda River where joining Karnafuli River (Figure 1). This restoration site is located along Karnafuli River, 27 km away from the delta (Bay of Bengal). The restoration site is 3 km long. The study reach has 450~700 m width; the water depth varies from 3.28 to 7.5 m. Since 1980, researchers have started investigating ecological responses of Carp fish spawning ground at natural flow regimes, including the loss of suitable ecological factors, species and disruption of habitat for spawning fish (Tsai et al., 1981, Akter and Ali, 2012). Fish monitoring revealed that three species Catla (*Catlacatla*), Mrigala (*Cirrhinusmrigala*), and Rohi (*Labeorohita*) dominate in this area. Low flow regimes are vital for a healthy and intact spawning environment.

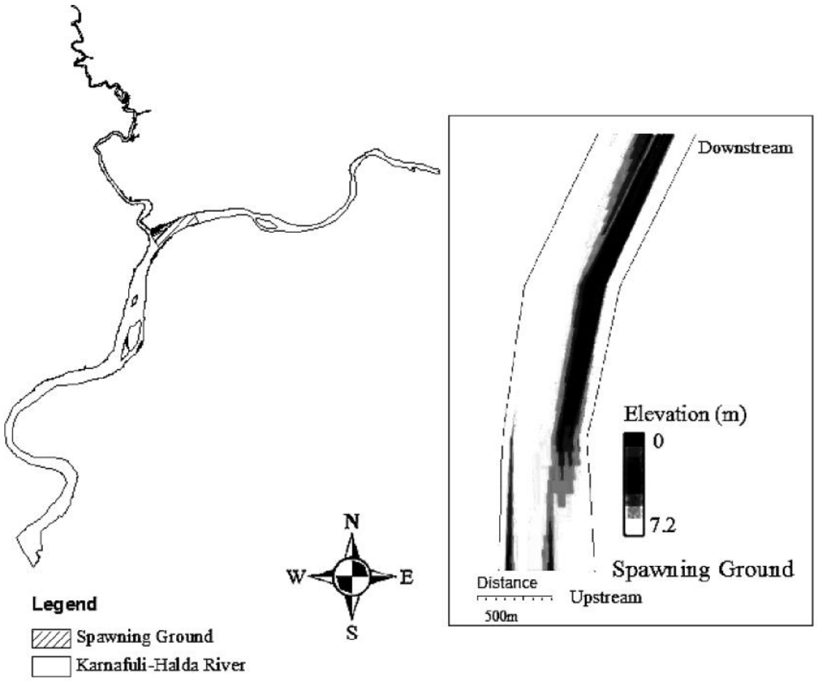


Figure 1: Study Area

## 2.2 Data Collection

The Halda-Karnafuli confluence represents a natural spawning site. Spawning duration for three native fish species ranges from April to June (Akter and Ali, 2012). During the spawning season, they migrate from upper to the lower parts of the Halda River due to suitable spawning environment. Thus, the carp fish was considered as critical ecological indicator, and establishment of minimum inflow regime was most important to sustain those ecological habitats. For the 1D PHABSIM model, a setup of total 4 cross-sections (i.e. transects obtained from Bangladesh Water Development Board in 2006 and Chittagong Port Authority in 2004 survey) were applied. Thus, acquired database was classified to establish symmetry of the CASiMiR 2D and PHABSIM model based on lateral cell boundaries. Totally, 231 surveyed points were used for the CASiMiR 2D model grid setup. Long-term flow characteristics (2010-2015) of the selected critical reach were taken from the flow pattern study of selected study sites conducted by Akter and Tanim (2017). The Habitat Suitability Curve (HSC) method was developed from comprehensive studies (Tsai et al., 1981). Microhabitat variables (depth, velocity, and substrate) were considered in this study as important factors of carp fish spawning. Different bed roughness coefficients were estimated in accordance with observations of bed material and bed form size. Substrate size was visually determined and a three-substrate type consisting of silt, sand, and vegetation type substrate was identified. The recommended channel index (Table 1) as per Schneider et al. (2010) is assigned in PHABSIM and CASiMiR 2D model.

Table 1: Channel Index code (Schneider et al., 2010)

| Code | Substrate type | Sizes (mm) | Code for model input | Substrate type | Sizes (mm) |
|---|---|---|---|---|---|
| 0 | Organic material, detritus | Visually identifiable | 5 | Large Gravel | 20-60 |
| 1 | Silt clay, loam | 0.00024~0.062 | 6 | Small stones | 60-120 |
| 2 | Sand | 0.062~2 | 7 | Large stones | 120-200 |
| 3 | Fine Gravel | 2-6 | 8 | Boulders | >200 |
| 4 | Medium Gravel | 6-20 | 9 | Rock | Visually identifiable |

### 2.3 Flow characteristics of restoration site

Tides are the major driving force in Karnafuli River, along with freshwater outflow and saline water inland flow. Tides entering from upstream (where the river joins at mouth) are gradually distorted with distance, and increasingly extinct due to channel bottom friction (Devkota and Fang, 2015). Thus, overall flow pattern prominently depends on tidal process of the river. Due to diurnal tide fluctuations, usually two tide cycles are observed in Karnafuli River and thus two directions of flow occur. During flood tide, saline water flow from the sea to the inland and direction changes in reverse order during ebb tide. Flow hydrograph and its nature changes with tide cycle and water level fluctuations. To determine low flow thresholds, the flood tide is considered and analysed as a unidirectional river. Based on the percentage of flow that exceeded the threshold during the flood tide, several incremental discharges were selected to cover the entire flow range (Table 2).

Table 2: Description of the selected discharge to assess habitat suitability

| Discharge ($m^3/s$) | Description |
|---|---|
| 15.8 | Minimum flow of flood tide in Karnafuli River during winter season(Akter and Tanim, 2017) |
| 25 | 10% of flow of annual runoff reported as per Tennant method (Tennant, 1976) |
| 30.1, 35.6 | Minimum discharge of flood tide during monsoon season(Akter and Tanim, 2017) |
| 60.7 | $Q_{95}$ reported according to $Q_{95}$ method obtained from flow duration curve (Arthington and Zalucki, 1998) |
| 75 | 30% of mean annual runoff as per Tennant method (Tennant, 1976) |
| 100, 153, 175 | Discharges were selected in incremental order based on the change of stage |
| 200, 225 | Flooding discharge (Akter and Tanim, 2017) |

### 2.4 Habitat Simulation method based on preference curve

The habitat simulation method considers physical components of river hydraulics and predicts the optimum flow regime while analysing maximum suitability of factors like depth, velocity, temperature, and substrate size. From a global perspective, among 207 methodologies of inflow assessment in 44 countries the habitat simulation method is the second most frequently applied method (Tharme, 2003). This method is employed in the habitat simulation model throughout several modules like hydraulic module, hydrologic module, and habitat module. In the hydraulic module flow, components like geometric cross sections, depth, discharge, and velocity need to be introduced in the model interface through either manual input (PHABSIM) or developing algorithm (CASiMiR 2D). The hydrologic module consists of suitable ecological factors like substrate size and habitat preference curve. Finally, the habitat module takes decision of suitable minimum inflow based on univariate preference function in terms of WUA and Habitat suitability Index (HSI).

### 2.5 Habitat Suitability Curve

Due to lack of ecological data, the generation of proper Habitat Suitability Curves (HSC) is quite challenging while conducting eco-hydraulic modeling. During the study period (i.e., 2010-2015), an expert judgement was applied to work out proper HSC. In doing so, also data from literature are assessed (Akter and Ali, 2012; Tsai et al., 1981). In the habitat simulation method, HSCs correlate the hydraulic module and the habitat module. However, HSC development usually needs comprehensive biological and environmental data collection. In Figure 2, typical habitat suitability curves are shown for carp fish species.

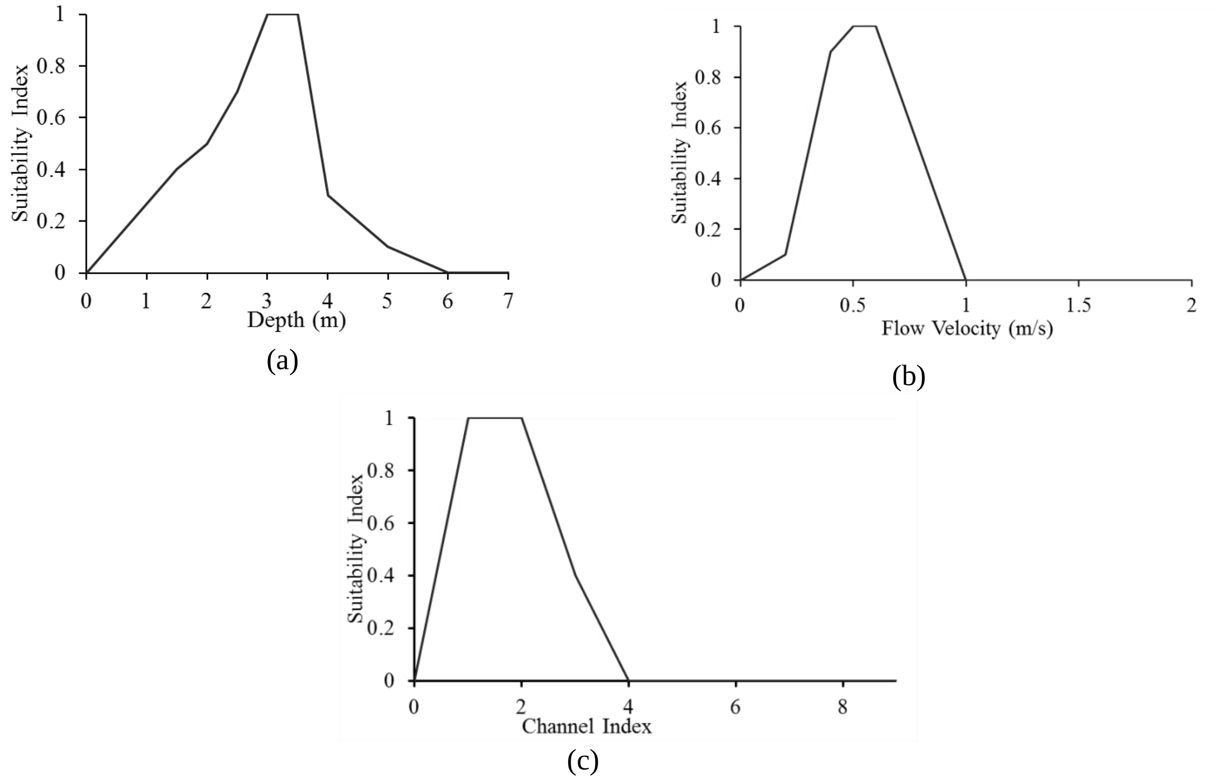


Figure 2: HSC curves of major carp fishes based on (a) depth, (b) flow velocity, and (c) channel index (Schneider et al., 2010)

## 2.6 PHABSIM model setup

To study low flow regimes in incremental discharge, the 1D eco-hydraulic model PHABSIM is the most widespread and preferred habitat model. It integrates a habitat simulation model with a biological model of habitat selection and relies on habitat suitability criteria like WUA using a discharge function (Ayllón et al., 2012). In this study, all of the 4 transects were placed along 1000 m intervals from the upstream consisting boundary conditions of defined flow and mean column velocity. Fish and other aquatic organisms can tolerate a certain range of stream velocity, water depth and bed substrate. An eco-hydraulic model like PHABSIM has key assumptions that reflect a habitat suitability of a regime based on velocity, depth, and substrate size, i.e., the Habitat Suitability Index (HSI). HSI has preference curves of targeted species on a scale of 0 to 1. The water level in the 1D eco-hydraulic model is usually predicted by three methods, whereas the Water Surface Profile (WSP) method is one of them. The WSP code uses a standard step-backwater method to determine the water surface elevations on a cross section and adjust manning's "n" (roughness coefficient for channels, closed conduits flowing partially full, and corrugated metal pipes) from the calculated discharge. Further, boundary conditions for the individual discharge can be provided. Based on predefined flow and discharge ranges, the WSP method - in this study – was modified for hydraulic modelling purposes.

The inflow is provided at upstream hydraulic section of restoration site. For 1D-HEC-RAS hydraulic simulations, the acquired water surface elevation was used as downstream boundary condition. During the HEC-RAS model setup, the average velocity ($\bar{V}$) was modified for application in each of the PHABSIM model cells. In order to minimize field survey for average velocity collection, Nikghalb et al. (2016) developed a relevant approach in the PHABSIM model. The cell velocity $(Vi)_{mod}$ obtained from the average velocity (Eq. 2) depends on the Manning's roughness coefficient (n), the hydraulic radius of each cell (HD), and the weighted discharge ($Q'$) of each cell as shown in Eq. (3).

$$(V_i)_{mod} = V_i + \frac{\Delta Q}{nA_i} \tag{1}$$

$$V_i = \overline{V} \times \left(\frac{\overline{HD}}{HD_i}\right)^{\frac{2}{3}} \tag{2}$$

$$\text{Where} HD = R = \frac{A}{P} \approx \frac{A}{b} \approx \frac{A}{T}$$

$$\Delta Q = Q' \sim Q_{actual}$$

$$Q' = \sum_{i=1}^{n} V_i \times A_i \tag{3}$$

### 2.7 CASiMiR2D model setup

CASiMiR (Schneider et al., 2010) is a fuzzy logic based eco-hydraulic model, developed by a group at the University of Stuttgart, Germany, to assess habitat suitability. The sub-model consisting of hydrodynamic parts can execute 1D, 2D and 3D hydraulic computation. It can calculate inflow values for the habitat using preference functions and fuzzy rules (Ahmadi-Nedushan et al., 2008). In this study, the CASiMiR 2D model was applied as 2D eco-hydraulic model using same univariate preference functions as for the PHABSIM model. The boundary conditions (discharge and water surface elevation) were established from HEC-RAS simulations. An algorithm in ASCII (American Standard Code for Information Interchange) languages was developed, which is based on Schneider et al. (2010). The algorithm consists of 231 numbers of X, Y, Z coordinates and channel indices to create a grid for hydraulic sub-model input. This was further interpolated in longitudinal scale (100 m) and vertical scale (0.3 m) to remove abrupt topography as well as to improve hydraulic performance of the channel. The WSP method was employed for the PHABSIM model, in which the boundary condition provides discharge throughout the water surface elevation at each sub-section. However, this boundary condition is limited between two adjacent transects. Another algorithm based on the WSP method (HEC-RAS 1D hydraulic simulation model) was developed to set the upstream and downstream boundary condition.

### 2.8 Low flow thresholds establishment

In the Habitat Simulation Method (HSM), the Weighted Usable Area (WUA) and the Habitat Suitability Index (HSI) can be used to describe the integrated habitat suitability and low flow threshold of the whole river investigated. The WUA value can be obtained by multiplying the area of each grid (CASiMiR) or cell (PHABSIM) by its HSI value. Suitable environmental flow or low flow thresholds will be achieved at maximum WUA. The WUA ($m^2$) function can be described as:

$$WUA = \sum_{i=1}^{i=n} A_i HS_i = f(Q), \tag{4}$$

where, i is the order number of cell; n is the number of all cells; $A_i$ is the area of the $i^{th}$ cell; $SI_i$is HSI value of the $i^{th}$ cell; Q is discharge ($m^3/s$).

## 3. RESULTS AND DISCUSSION

### 3.1 Habitat suitability assessment

Due to the topographic variation and sand bar formation, flow diversion occurred within the first kilometer (Figure 3). PHABSIM predicts this zone as most suitable area of carp fish spawning, due to river confluence and less turbulence. The habitat suitability criteria assumed that habitat suitability could be ascribed in a weightage scale of 0 to 1. The effect of substrate size shows less prominent effect rather than flow components (depth and velocity). The overall habitat diversity obtained was relatively low in comparison to the total area. Spawning suitability of carp fish shows more heterogeneity near the bank and around the place where flow contraction occurred. Thus, the flow velocity is relatively low and makes the velocity most dominant. The habitat simulation model was developed based on a calibrated hydraulic model HEC-RAS, and the boundary condition was incorporated from the previously applied hydraulic model. The HSI variability makes the difference in WUA computation between 1D and 2D models that influence environmental flow prediction (Figure 4). This result is expected because the hydraulic modules of both, the 1D and 2D eco-hydraulic model, have different approaches of considering transverse flow (Ayllón et al., 2012). However, the results might be influenced by optimum PHABSIM cross-section that depends on data availability. The PHABSIM hydraulic module is usually unstable in turbulent flow (Kondolf et al., 2000). However, the CASiMiR2D model was used to handle unstable turbulent flow. To maintain the required regime condition in a tidal river, the spatial flow variability is one of the common characteristics of tidal rivers.

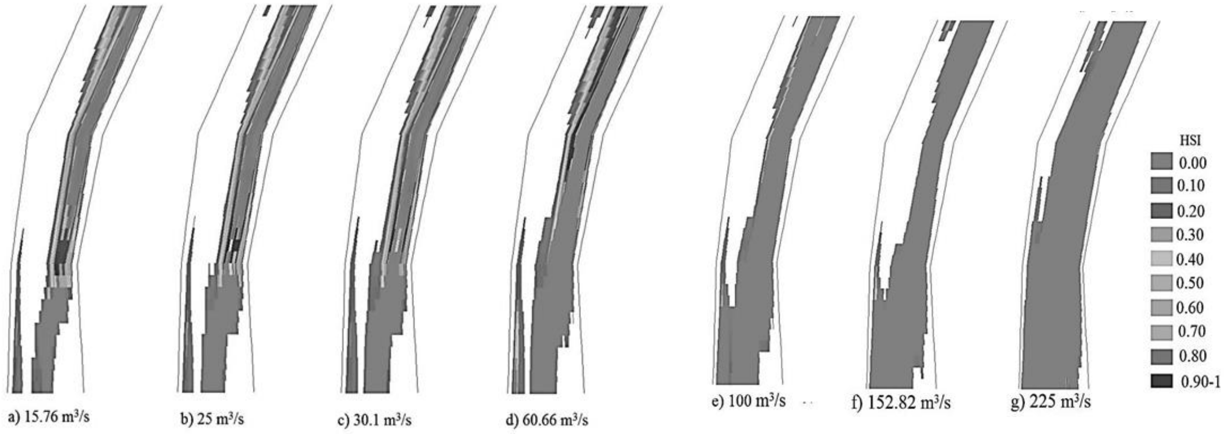


Figure 3: Habitat Suitability Index obtained from CASiMiR 2D

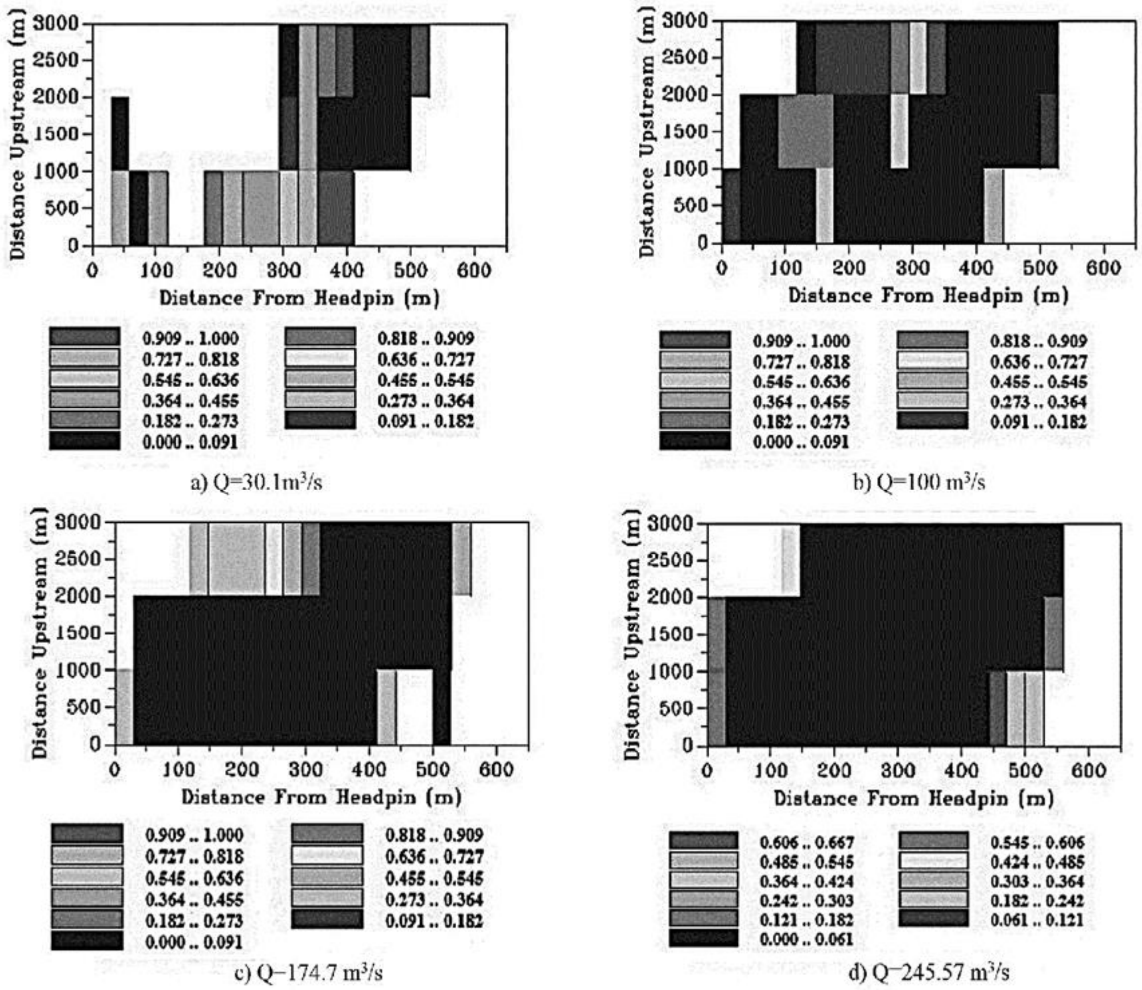


Figure 4: Habitat Suitability Index obtained from PHABSIM

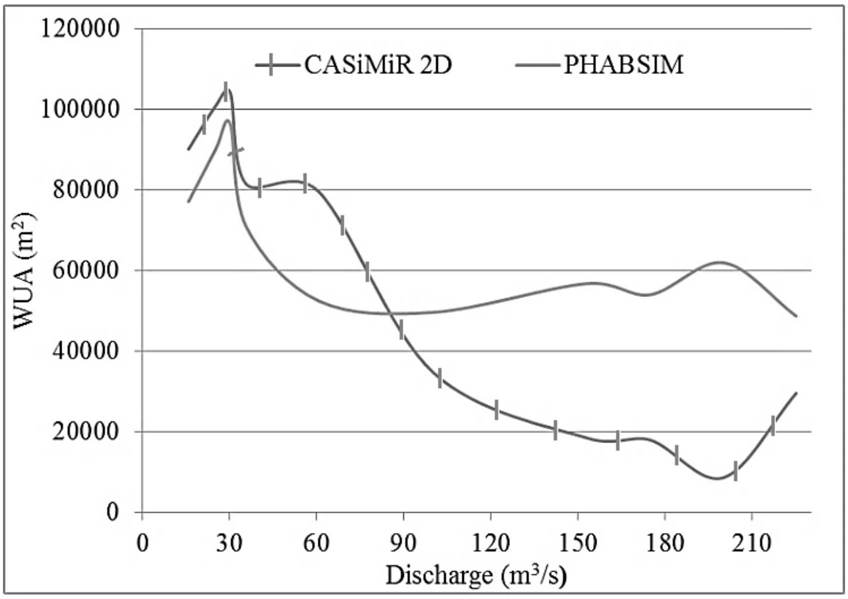


Figure 5: WUA vs. Discharge Relationship

### 3.2 Low flow thresholds

The WUA and flow relationships were obtained from model simulation (Figure 5). Both models predict that 30.1 $m^3/s$ discharge can be established as low flow threshold. WUA in view of the flow relationship shows that low flow regime is sensitive to flow influencing parameters. The CASiMiR 2D model predicts that during flood tide the habitat suitability of carp fishes can maintain sufficient discharge between 15 $m^3/s$ and 60.7 $m^3/s$. By increasing the discharge, the HSI reduces rapidly and reveals that spawning suitability is sensitive to flow parameters. In any hydraulic model, the accuracy of results relies on the topographic and hydrographical data that are influenced by river velocity and depth. Thus, related to the HIS, the variation of depth and velocity differed from 1D to 2D. This also resulted in variation of the WUA. Waddle et al. (2000) found that a 2D model can capture complex flow situations while significant transverse flow regimes are present. A significant variation of WUA in the 2D model was observed after 90 $m^3/s$ (Figure 5). This indicates that the velocity and discharge prediction significantly vary when exceeding this threshold.

## 4. CONCLUSIONS

In this study, low flow threshold was established using the WUA concept, 1D, and 2D eco-hydraulic simulations for the Karnafuli-Halda river confluence. It was found that spawning conditions for carp fish relied on flow velocity and depth. Further, climate changes (storm surges or sea level rise) will influence the tidal flow and negatively affects the spawning ground. Migration and spawning of fish might occur in upper less turbulent parts of the Halda or Karnafuli River.

With respect to the spatial variability during the habitat and flow simulation, the CASiMiR 2D model is more coherent than the 1D PHABSIM model. The 2D eco-hydraulic model is suited for rapidly varying river topographies and tidal regimes with complex flow patterns. The improved interpolation techniques of the CASiMiR 2D model allows any 3D or 2D simulation at desired scales.

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