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An assessment of ecological habitat suitability in a tidal stream using River 2D model

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Abstract

Conservation and restoration of river ecology is entirely dependent on the habitat suitability. Thus, variable tidal fluctuations often face difficulties to assess this ecological indicator in a tidal stream. So, the hydraulic characteristic of a stream, i.e. the most sensitive parameter of river ecology, along with the physical habitat needs to be studied. A two dimensional finite element based eco-hydraulic model River 2D was used to assess habitat suitability in a selected reach in the Karnafuli River considering its spatial flow variability. The selected critical reach was 3 km long, 450~700 m wide with water depth of 3.28~7.5 m. In this reported study, three native species viz. Catla (Catlacatla), Mrigala (Cirrhinusmrigala) and Rohi (Labeorohita) of this stream was selected as ecological indicators. A triangular irregular network (TIN) was developed to create the surface topography and to create a hydrodynamic sub-model. This TIN was further incorporated with the boundary conditions of % of flow exceeded during flood tides in the sub-model. Then, a physical habitat simulation method was employed as ecological habitat assessment tool. Two key factors of environmental flow assessment i.e. combined suitability index and Weighted Usable Area (WUA) were evaluated to assess minimum instream flow requirement. Finally, univariate preference function of depth, velocity and substrate size was used to obtain a combined suitability index. The acquired index with spatial distribution indicates habitat suitability of corresponding discharge at different locations of studied site. As a result, the maximum WUA was obtained at a discharge of 25m3/s which showed maximum spatial habitat heterogeneity and most suitable condition for ecological habitat in this tidal reach. Thus, this assessment method is expected to contribute on quantitative flow criteria for an ecologically sound habitat and improved ecofriendly management decision to ensure river flow.

Keywords: Combined habitat suitability index, weighted usable area, river 2D modelling, ecological indicators.

1. Introduction

The lower part of Halda River is well-known as spawning ground of major Indian Carps; subsequently this is the unique Indian Carp breeding field in South Asia. Although suitable flow components that indispensible parts of all life stages of ecological habitat of a stream, the hydraulic parameter those are suitable for spawning in this regime so far remain unexplored in anypublished research work. Generally, a number of hydrologic, hydraulic and geologic factors control the environmental flow regime of an ecosystem (Shrestha et al., 2014). Since 1980s conservation of ecosystem and suitability assessment of human activities on river ecosystem as well the restoration of river ecology turn intoconcern for the river management authority. Instream flow assessments considering eco-hydraulic factors a number of methods were developed and among those habitat simulation methods got wider acceptability (Adriaenssens et al., 2006, Tharme, 2003). Based on this principle Physical Habitat Simulation (PHABSIM) model first developed using instream flow incremental methodology and became the most widely used model (Nagaya et al., 2008). Linking multivariate preference functions and correlating physical variables with habitat suitability other available 1D models are RHYHABSIM (Jowett, 1996), EVHA (Ginot, 1995) and Mesohabitat (Parasiewiczand Dunbar, 2001).

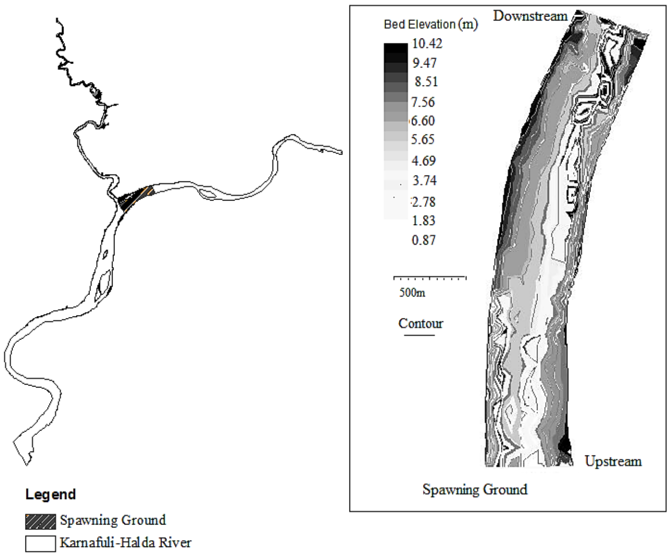

Fig. 1. Study reach i.e. spawning ground in the Karnafuli-Halda River.

Considering sensitivity and spatial variability of physical variables and hydraulic variables two dimensional eco-hydraulic models get attention for more reliable prediction. Based on fuzzy sets and rules the Computer Aided Simulation Model for instream flow Requirements (CASiMiR) 2D, developed at the University of Stuttgart's Institute for Hydraulic Engineering. CASiMiR, a surface water habitat model, usually used to investigate fish habitats (Mouton et al., 2007). Then, finite element based hydrodynamic 2D depth averaged River 2D model was developed to incorporate hydrodynamic function with habitat simulation (Fukuda et al., 2015). In this study, to determine suitable eco-factors for spawning suitability of major Indian Carps River 2D model was applied using preference curve method, based on which spawning suitability of selected reach was evaluated.

2. Methodology

A brief overview on hydrodynamic model set up including channel morphology and ecological habitat data incorporation with River 2D are described in this section.

2.1 Study area

Tide is a dominant stream driver of the studied spawning ground of Karnafuli-Halda confluence (Figure 1) and so it is considered as a strategically important reach to assess the habitat suitability under present flow circumstances. The selected critical reach was 3km long, 450~700m width with water depth varying 3.28~ 7.5m. Significant number of stakeholder of Chittagong district depend on Karnafuli-Halda River that dominates a major south-eastern part of Bangladesh, whenever it flows 270 km along the catchment and finally disposed to the Bay of Bengal. This restoration site is well recognised with the unique carp fish. This indigenous carp fish viz.Catla *(Catlacatla),* Mrigala *(Cirrhinusmrigala) and* Rohi *(Labeorohita)* as ecological indicator always play a vital role to maintain a healthy ecology of this regime (Tsai et al 1981). The naturally occurring low tide can influence habitat connectivity as well as flooding discharge can disrupt the habitat suitability. Thus an assessment tool must have such versatility to consider the effect of tidal phenomena on those ecological habitats.

2.2 Hydraulic modelling

In a tidal river tide progress from sea (upstream) to inland and decays by channel bottom friction with the increasing distance from mouth of sea. Also the tidally influenced river experiences with the hydrodynamic process controlled by ocean with the periodic circulation of tide. To perform better simulation, the selected numerical model must be capable to deal with the complex channel geometry, dynamics between different lateral and vertical boundary layers. But the effect of channel bottom friction pose difficulty in tidal flow modelling and low flow habitat modelling. Ali and Steffler (2012) suggests River 2D model to overcome such problems as this model uses Characteristic Dissipative Galerkin (CDG) method in shock capturing scheme where mesh refinement can reduce those effect significantly. In this reported study, considering those pragmatic circumstances River 2D model was used to assess ecological habitat suitability. The data preparation section describes the stepwise hydraulic model set up in River 2D.

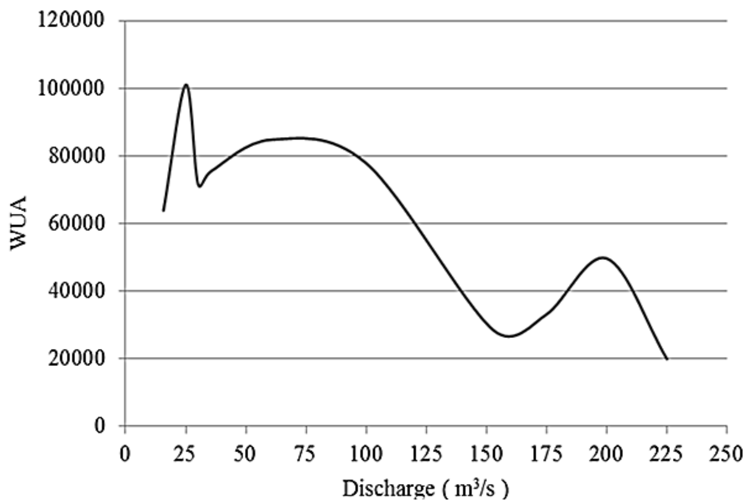

Fig. 2. WUA vs. Discharge relationship.

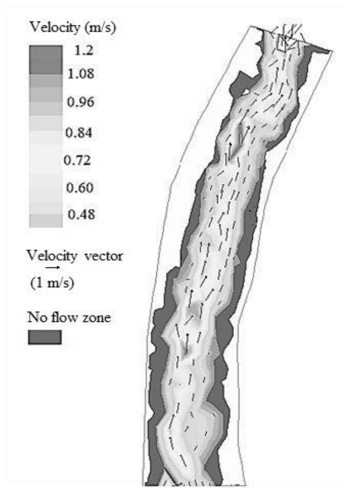

Fig. 3. Simulated velocity at discharge Q= 225 m^3/s.

2.1.1 Data preparation

Bed topography and 4 cross sections of the studied channel were obtained from Bangladesh Water Development Board and Chittagong Port Authority for the survey periods 2006 and 2004 respectively. For this study, additional survey points were interpolated to capture detailed bed topography. Thus, total 231 surveyed points were obtained for bed topography to engaged mesh generation in River 2D. Long term flow characteristics i.e. velocity, discharge and stage data were obtained from the research study by Akter and Tanim (2016). Substrate size was visually determined and three substrate type silt, sand and vegetation type substrate were identified. Channel Index 1, 2 and 10 assigned respectively for silt, sand and overbank vegetation. A triangular irregular network (TIN) algorithm was prepared as bed topography of the selected study area. Each observed location was coded as topographic feature and substrate category.

2.1.2 Modelling in River 2D

The River 2D is a two-dimensional, depth averaged hydrodynamic and habitat simulation model, widely used to assess human intervention on river ecology (Im et al. 2011, Yi et al. 2014). This model has also applicability to predict river morphology analyes in sedimentation process and bed shear stress (Vietz et al. 2012).The hydrodynamic module is a finite element model which is based on a conservative Petrov–Galerkin up winding formulation. The fish habitat module is based on the PHABSIM weighted usable area approach, adapted for a triangular irregular network geometrical description (Steffler and Blackburn, 2002). Similar to the available two-dimensional models, it solves for the mass conservation equation (Equation 1) and two horizontal components of momentum conservation (Eq. 2 and 3), the model output consists of two velocity components with depth consideration at each node.

$$\frac{\partial H}{\partial t} + \frac{\partial q_x}{\partial t} + \frac{\partial q_y}{\partial t} = 0 \tag{1}$$

$$\frac{\partial q_x}{\partial t} + \frac{d}{dx}(Uq_x) + \frac{\partial}{\partial y}(Vq_y) + \frac{g}{2}\frac{\partial}{\partial x}H^2 = gH(S_{0x} - S_{fx}) + \frac{1}{\rho}\left[\frac{\partial}{\partial x}(H\tau_{XX})\right] + \frac{\partial}{\partial y}(H\tau_{xy}) \tag{2}$$

$$\frac{\partial q_y}{\partial t} + \frac{d}{dx}(Uq_y) + \frac{\partial}{\partial y}(Vq_x) + \frac{g}{2}\frac{\partial}{\partial y}H^2 = gH(S_{0y} - S_{fy}) + \frac{1}{\rho}\left[\frac{\partial}{\partial x}(H\tau_{XX})\right] + \frac{\partial}{\partial y}(H\tau_{yy}) \tag{3}$$

Where, H is average depth; U and V average speed along x and y axes; S_{0x} and S_{0y} are the frictional slope values; S_{fx} and S_{fy} are the frictional resistance values; q_x and q_y are the discharge components in the respective direction and τ_{xx} ,τ_{xy} , τ_{yx} , τ_{yy} represent horizontal shear stress in different directions.

Table 1
Description of the selected discharge to assess habitat suitability

Discharge (m^3/s)	Description
15.76	Minimum flow of flood tide in Karnafuli River during winter season (Akter and Tanim, 2016)
25	10% of flow of annual runoff reported as per Tennant (1976)
30.1,35.6	Minimum discharge of flood tide during monsoon season (Akter and Tanim, 2016)
60.66	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
100, 152.82, 174.7	Discharge selected in incremental order based on change of stage
200, 225	Flooding discharge (Akter and Tanim, 2016)

The merged survey data was converted into Triangular Irregular Network (TIN) to create finite element mesh model in River 2D. Mesh sizes was initially set at 5-10m from acquired data which further refined in case of riffle adding floating node providing elevation from model interpolation. In this study, 1D HEC-RAS model was employed to establish upstream and downstream boundary condition and water surface elevation as input in River 2D. This objective determination approach combining 1D and 2D model investigated in other hydro-ecological studies shows a reasonable performance for overcoming hydraulic complexity

(Reinfelds et al. 2010).To assess the ecological habitat suitability the flood tide is considered and analyzed as unidirectional flow in River 2D. Based on the % of flow exceeded during flood tide several incremental discharges were selected to cover entire flow range of selected critical reach (Table 1).

2.2 *Habitat suitability modelling*

Spawning suitability in a river of ecological habitat for example fish depends on a number of factors, and those are: velocity, depth and substrate size of the stream. Preference curve method of habitat simulation correlates hydraulic components with these factors based on Habitat Suitability Index (HSI) or Combined Suitability Index (C_i) on a scale 0 to 1. Three species of the Indian major carps, Catla (*Catlacatla*), Mrigala (*Cirrhinusmrigala*) and Rohi (*Labeorohita*), spawn in this region and reported as important ecological indicator. During the spawning season (April to June)the Carp fish migrates from upper part to lower part of Halda. Preference curve of factors viz. velocity, depth and substrate size were obtained from hydrological suitability study of Major Indian Carps described in Tsai et al., (1981). Two key factors of habitat suitability assessment is Weighted Usable Area (WUA) and C_i were determined to assess spawning suitability (Steffler and Blackburn, 2002).

$$\mathrm{WUA} = \sum_{i=1}^{n} A_i \times C_i \tag{4}$$

Where A_i is an area covered by node i and C_i is combined HSI of node i.
The combined C_i is a suitability criterion with a combination of HSI of depth, velocity and substrate size. The combined C_i is determined as follows:

$$C_i = \gamma(v_i) \times \gamma(d_i) \times \gamma(c_i) \tag{5}$$

Where, v_i is HSI of i regarding velocity, d_i is HSI of node i regarding depth of flow and c_i is HSI of node i regarding substrate size.

3. Results

River 2D model simulated the selected discharge and then two of habitat assessment criteria (WUA and C_i) were evaluated to predict habitat suitability of carp fish. Initially, the WUA increases with discharge and while the maximum discharge of 25m^3/s obtained this implies the suitable in stream flow to maintain healthy ecology (Figure 2). With the increasing discharge of WUA gradually decreases except discharges of 75m^3/s and 200m^3/s. The velocity of those discharges reduces the turbulence which in turn increases HSI of velocity. The 2D velocity distribution apparently influences from channel topography (Figure 3). The velocity obstructed from sand bar formation consequently increases the velocity nearby adjacent sandbar. Observing the velocity vector it can be predicted the carp fish prefer the less turbulence nearby bank area (Figure 3). That area become most prominent habitat area when C_i was determined (Figure 4).The C_i at different discharge reveals the formation of different sizes riffle make this spawning ground more suitable during low discharge (Figure 4a, 4b, 4c). Due to less variation in substrate size, there influence on the suitability index remains negligible compare to depth and velocity influence on the HSI. Thus, it can be concluded that the carp fish may prefer a less turbulence place. Due to tidal influence of this river the low flow condition (25 m^3/s) can be achieved for small duration. In such case, the carp fish may migrate to upper parts of Halda to select a less turbulence uninterrupted place to spawn. But, the channel bottom with weeds or bushes might reduce the vertical velocity distribution as well as flow turbulence, this can be determined by using a 3D model for instance FLOW-3D (Kolden et al. 2016) which is under consideration of the ongoing research study and not explaining in this paper.

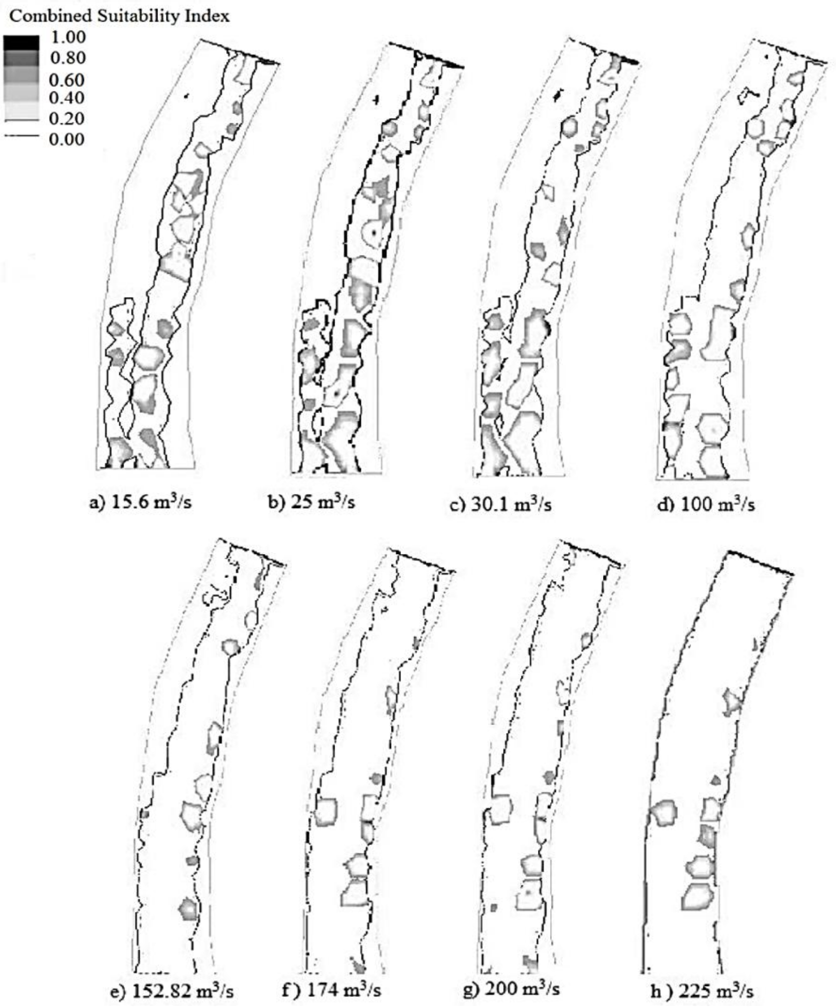

Fig. 4. The Spawning suitability of Carp fish at incremental discharge.

4. Conclusion

In this study habitat suitability of a tidal stream was assessed using habitat simulation method. The probability of minimum low flow thresholds i.e. 25 m^3/s depends on the upstream tide pattern. But, the flooding discharge can disrupts the habitat suitability at regular interval during flood tide. So, in a tidal river the low flow duration should consider while environmental flow assessment. The validation of model outcomes needs to monitor with daily counts of fish movements using a fixed device in a long term basis. Since, those counting device of fish still not available this is a matter of intensive field study to validate and update flow hydraulics. However, an improved modelling framework for developing country was outlined to take reasonable decisions under constraint ecological and hydraulic database. Data driven modelling approach like fuzzy logic based habitat simulation, artificial neural network, generalised additive method etc. can provide more improved study under such hydrologic data constraints which needs to be included in future study.

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