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Habitat Simulation Technique as a Powerful Tool for Instream Flow Needs Assessment and River Ecosystem Management

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Abstract
Instream flow needs (IFN) assessment studies are performed to provide guidelines for stream water management and to assess the impacts of different water projects such as weirs, dams and stream diversions on the available fish habitat. The physical habitat simulation is one of the IFN assessment methods and also a powerful tool in management of river ecosystem that has not become a common method in many countries, yet. The main aim of the present research is representing the ability of habitat simulation technique in river ecosystem management. Delichai stream in Tehran province in Iran is selected as the case study. Based on the results habitat simulation technique has considerable ability for dynamic assessment of IFN and river habitat evaluation along the longitudinal and latitudinal cross sections and it can also present the spatial habitat suitability distribution in various months of the year dynamically. IFN assessment with habitat simulation technique has advantages related to other methods like that of the Tennant method and wetted perimeter method and creates the least discussion between river environmental managers and stakeholders. In the study stream of this research due to the variation of ecological condition for the target species, three different values for IFN in various months of the year were estimated and it was seen that the habitat near the stream bank requires more protection and restoration projects.

Keywords: Instream Flow Needs, River Ecosystem, Habitat Simulation, Delichai stream, Physical habitat

Introduction

Increase in water demand has caused contradiction between maintaining the development of river water withdrawal and protection of the aquatic ecosystem in recent years (Denisuse and Nelson, 1994). Land-use change, river impoundment, surface and groundwater abstraction profoundly alter natural flow regimes (Naiman et al., 2002; Revenga et al., 2005). River irrigation water demand has increased dramatically over the past few decades and has become the single most important factor in the reduction of stream flows in four continental river basins (Grafton et al., 2012). This has caused that researches related to IFN assessment developed rapidly in recent years (Tharme, 2003). It is predicted that the amount of surface water withdrawal will be about 70% by 2025 (Postel, 1996 & 1998). Managing ecological

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water allocations - including the quantity, timing, frequency, duration, and quality of river flows for freshwater ecosystems, herein referred to as environmental flows - are increasingly being required to sustain an agreed-upon level of ecological condition for riverine biota and provide sufficient water supply for societal needs (Newson and Large, 2006; Richter et al., 2006; Poff et al., 2010). The most important question about evaluating the river ecosystem conditions is that how much flow can maintain the ecosystem in sustainable condition and also how and how much the variation in natural flow of the river can impact the aquatic and riparian vegetation community (Richter et al., 1997). Answering to these two fundamental questions is with definition of quantity, duration and variability of flow need for sustaining biotic diversity and aquatic community in desirable condition (Poff et al., 1997).

There are different approaches for assessing the IFN. Most of the common approaches are hydrological methods that primarily rely on published hydrological data in the form of historical monthly or daily flow discharge data, for making IFN recommendations (Jowett, 1997). The most common method of hydrological approach is the Tennant (Montana) method

(Tennant, 1976) that uses a percentage of the mean annual flow (MAF) for two different six month periods to define conditions of flow regarding “instream flow regimens for fish, wildlife, recreation, and related environmental resources”. The minimum value recommended by Tennant is 10% of annual flow. Other methods which are similar to the Tennant method and are based on the defined value of mean annual flow are also used, for instance 25% of annual flow (Caissie and El-Jabi, 1995), 30% of annual flow (Annear and Conder, 1983). Some approaches are also used for assessing the IFN which are based on the relationship between hydraulic parameters and flow value. The most common method of these approaches is the wetted perimeter (Annear and Conder, 1984), which creates a relationship between the wetted perimeter and flow discharge and the breakpoint of this curve is considered as the assessment value of IFN. The main assumption of this method is that as the discharge decreases, riffles are the first locations to be impacted and exposed (Leopold and Maddock, 1953). Two methods of maximum curvature and maximum slope are used for determining the breakpoint in the wetted perimeter-discharge curve (Christopher et al., 1998). The complexity of the IFN assessment depends on the goals of assessment, level of aquatic ecosystem protection, and the importance of the project (Beecher, 1990; Annear et al., 2002). The relationship between the river flow hydrodynamic, aquatics and riparian vegetation is very intricate and therefore many of the methods that do not focus on ecology cannot evaluate an accurate value for IFN. Due to this intricate relationship, dynamically assessment of IFN is required. In fact a relationship between hydraulic, dynamic morphology and ecological processes in river must be created. Modeling freshwater fish distributions and habitat suitability seems particularly important to implement management and conservation strategies (Dauwalter and Rahel, 2008; Logez and Pont, 2011). One of the methods that tries to create a relationship between the habitat hydraulic and habitat availability is the habitat simulation technique (Bovee, 1986), that determines the physical habitat suitability for target species and their life stages and simulates the amount of physical habitat availability with discharge variations (Rosenfeld, 2003). Since their development in the 1980s, physical habitat models became an important tool for river management (Bockelmann et al., 2004). The models allow for evaluating habitat suitability for aquatic organisms, based on physical variables such as depth, flow velocity and substrate (Bovee, 1982). The influence of flow changes on biological diversity can be analysed since these variables are dependent on the flow regime. Physical habitat is the combination of two factors of physical structure of river channel and variations of river flow regime, in fact the second factor is effective on the first factor (Maddock, 1995).

One of the important parts in riverine habitat simulation is the existence of accurate habitat suitability criteria (HSC) curves for the target species. Habitat suitability curves are the biological basis of habitat methods. In general, suitability curves have been classified into three categories (Bovee et al., 1986). Category I curves are expert opinion or literature curves. Category II curves are derived directly from observation of habitat use of the target life stage and species and they are known as habitat utilization curves. And category III curves known as habitat preference curves are derived from observation data on habitat use corrected for habitat availability.

Assessment of physical habitat and its simulation can be applied as a powerful tool for environmental flow assessment and river ecosystem management, because the importance of habitat hydraulic parameters is much more than other effective parameters (Maddock, 1995). Using the physical habitat assessment as a powerful tool in management of river ecosystem has not become a common method in many countries, yet. In the present research, using the habitat simulation technique, at first the physical habitat assessment is carried out (Hajiesmaeili et al., 2014) and then doing analysis the value of IFN and also recommendations about the method of river ecosystem management is investigated. The main aim of the present research is representing the ability of habitat simulation technique in management of river ecosystem and also the method of doing analysis in this field of study. This method is investigated with studying a mountainous stream.

Material and Methods

Study area

This study was carried out on Delichai stream in Iran. Delichai stream is one of the important tributaries of Hablerood, source of this stream is the drain of Tar and Havir lakes and joins to Hablerood in Simindasht plane. Hablerood continues its way to south direction and finally enters to Garmsar region. The stream has a watershed area of approximately 340 km^2. Mean altitude of region of this stream is 2182.23 m. The average slope of the stream is 2% and is a mountainous stream. The researches have been carried out on this stream showed that currently qualitative parameters of the stream are not in a critical condition. Due to the morphological and hydraulic conditions self purification of the river is possible. Because of the special topographic condition of the region, the stream is morphologically undisturbed and protects its natural condition. Considering that the scope of this research was investigating the environmental condition of a stream under natural condition so this stream was an appropriate option.

Rainbow Trout

Rainbow trout is one of the dominant species of Delichai stream. This species is one of the most important riverine species which was remarkable in several studies and can be used as a suitable index in stream environmental studies. According to the studies carried out in Iran, rainbow trout become sexually mature during their first or second year in many regions of Iran and their spawning occur in March and beginning of spring. Spawning in certain river systems may occur in intermittent tributary streams (Everest, 1973; Price and Geary, 1979). Optimal rainbow trout riverine habitat is characterized by clear, cold water; a coarse substrate in riffle- run areas (Raleigh and Duff, 1980). Cover is recognized as one of the essential components of trout streams (Boussu, 1954). Rainbow trout remain in the gravel for about 2 weeks after hatching (Scott and Crossman, 1973) and emerge 45 to 75 days after egg fertilization, depending on water temperature (Calhoun, 1944; Lea, 1968). Fry prefer shallower water and slower velocities than do other life stages of trout (Miller, 1957; Horner and Bjornn, 1976) and velocities less than 8 cm/sec are preferred by this life stage based on field investigations (Griffith, 1972).

According to the researches habitat suitability criteria curves for three main parameters including depth, velocity and substrate are developed and are available in references (Raleigh et al., 1984; USGS, 2001; Milhouse et al., 2012).

Methods of this research

In the present research one dimensional hydraulic habitat model (PHABSIM) is used to simulate physical habitat for Rainbow trout.

In a hydraulic habitat analysis, at first the needed hydraulic model is applied to determine characteristics of the stream in terms of depth, velocity and channel index (cover or substrate) as a function of discharge for the full range of discharges to be considered for the study (Waddle, 2012). In the habitat modeling process, this information is integrated with HSC to produce a measure of available physical habitat as a function of discharge. Cell values of each of the physical parameters are combined with species preference curve information through a selected functional relationship, termed the Combined Suitability Index (CSI, which has a range of 0-1), to develop the combined habitat index, termed Weighted Usable Area (WUA). Considering the linear relationship between WUA and fish biomass the habitat simulation is carried out using a univariate model. Generally the univariate model is as follows (Ahmadi-Nedushan et al., 2006):

$$CSI = a_1 SI_1^{\,b_1} \times a_2 SI_2^{\,b_2} \times \ldots \tag{1}$$

Where *CSI* is Combined Suitability Index, a_i is the coefficient, b_i is power and SI_i is the Suitability Index of each parameter. In the present research habitat modeling is carried out considering the coefficient and power of 1 (as typical *CSI* functional relationship in habitat assessments).

WUA is expressed in units of microhabitat area per unitized distance along a stream (e.g., square feet per 1000 feet of stream or m^2 per 1000 m) and is the most commonly used output from these types of models. *WUA* is computed within the reach at a specific discharge from:

$$WUA = \left(\left(\sum_{i=1}^{n} A_i \times CSI_i \right) \Big/ L \right) * 1000 \tag{2}$$

Where A_i is the surface area of cell *i* and CSI_i is the combined suitability of cell *i* (i.e., composite of depth, velocity and channel index individual suitabilities.)

Prior to this investigation, no Iranian site-specific or regional HSCs for Rainbow trout were available and the application of habitat simulation technique was limited to the uncritical use of literature HSCs. Due to the fact that Rainbow trout is native to the rivers in North America, thus habitat suitability curves from Raleigh et al., (1984) were used for three effective factors on physical habitat including depth, velocity and substrate for fry, juvenile and adult life stages of Rainbow trout.

The hydraulic simulation of the stream was carried out by one dimensional hydraulic modeling component (Hajiesmaeili, 2014). The step-backwater computational process and relevant equations including continuity, Bernoulli and Manning's equations are used for water surface profile simulation:

$$Q = AV \tag{3}$$

$$H = Z + d + \frac{V^2}{2g} \tag{4}$$

Where Q is the flow, A: area,V: velocity, Z: elevation of channel bottom, d: depth of water and $V^2/2g$: velocity head.

$$S_{ei} = \left[\frac{Q_i * n_i}{R_i^{\frac{2}{3}} * A_i} \right]^2 \tag{5}$$

Where Q_i is discharge, n_i: roughness coefficient, A_i: Cross section area, R_i: hydraulic radius (area divided by wetted perimeter), S_{ei} is the energy slope. And subscripts refer to any cross section i.

$$H_2 = H_1 + S_{el} + (otherlosses) \tag{6}$$

Where $H_{1,2}$ is total energy at each cross section, S_{el}: energy losses over the distance L and other losses referred to losses due to expansion or contraction.

And finally using the following equation the water surface elevation at the second cross section (WSL_2) is computed:

$$WSL_2 = H_2 - \frac{V^2}{2g} \tag{7}$$

For velocity simulation, since slope, water surface and observed velocity are given as part of the calibration data, Manning's equation can be solved for n_i at each vertical:

$$n_i = \left[S_e^{1/2} \times d_i^{2/3} \right] / v_i \tag{8}$$

Where n_i is the estimated Manning's n value at vertical i, S_e: energy slope for transect, d_i: depth at vertical i and v_i: measured velocity at vertical i.

Having obtained individual Manning's n values at each vertical, individual cell velocities can be computed at any alternative discharge by solving Manning's equation for velocity and using the initial Manning's n value derived from the calibration velocity set:

$$v_i = \frac{1}{n_i} * d_i^{\frac{2}{3}} S_e^{\frac{1}{2}} \tag{9}$$

Finally the hydrological and hydraulic methods were used for IFN assessment too (Sedighkia et al., 2014), and the results of all three approaches were compared.

Results and Discussion

The flow-habitat curve for three life stages of rainbow trout is presented in Figure 1. As can be seen the value of available suitable habitat is different with changing discharge for different life stages and estimating a value as the minimum IFN will be difficult, since the living condition of different life stages is very different and a suitable condition for a life stage may create a completely unsuitable condition for other life stages. Hence the habitat time series should be considered for different life stages (Figure 2.) and combining the habitat time series curve and biological condition of the species the value of IFN must be assessed dynamically.

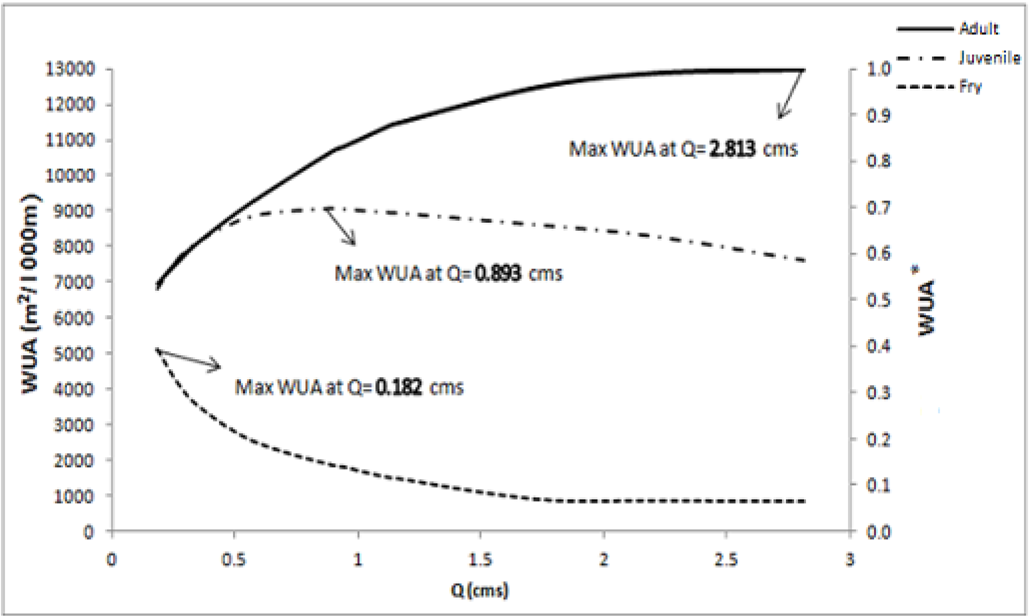

Figure 1. Flow-habitat curve for three life stages of Rainbow trout

Considering that spawning takes place in March and beginning of spring and according to the studies mentioned in previous parts fry generally emerge from the gravel in about Jun and also according to the fact that it takes about one year for fry to become adult, so period of Jun to October is a sensitive period for fry life stage.

Hence the mean monthly flow (MMF) during Jun to October is the most suitable value for IFN. Choosing the mean value has two advantages: firstly it protects the relative habitat suitability condition for other life stages; secondly it causes the minimum amount of possible stress for fry life stage. This value is about 450 lit/sec. In other months of the year the sensitivity of the condition is much less for fry, because fewer fry exist in the stream. In these months (especially during the period of spawning) suitable habitat condition is required for adult life stage. Due to the fact that the variation of habitat condition is approximately the same for two life stages of juvenile and adult, so these two life stages are considered together in IFN assessment. Because spawning takes place in March and April, so the river flow regime must be undisturbed in these two months. The mean discharge of 2.3 m^3/sec will create desirable condition. In other months of the year (May and October to February) creating a mean optimum condition corresponding to adult life stage can create the minimum of optimum habitat condition. This value is about 1.3 m^3/sec.

Allowable extracted value from the river for each months of the year using three methods of habitat simulation, and non-ecological methods including the Tennant method (optimum amount of flow) and wetted perimeter method (maximum curvature) are presented in Figure 3.

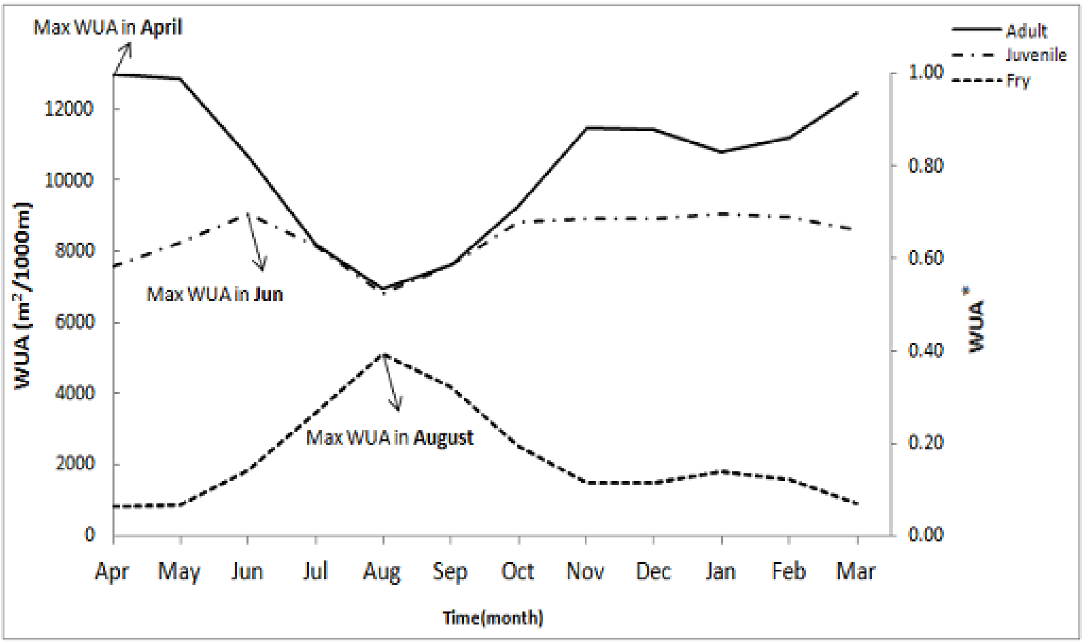

Figure 2. Habitat time series for three life stages of Rainbow trout

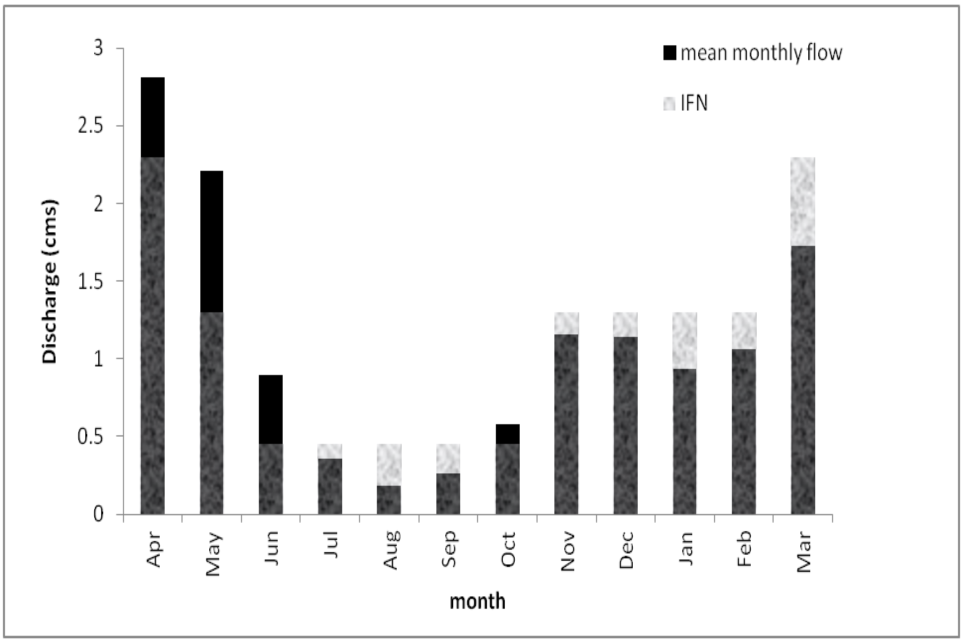

Figure 3. Monthly flow data of the stream and IFN values

A little amount of habitat stress (when IFN value is more than MMF) is accepted in some months. If negative values of extraction (lack of extraction in that month) is considered as the zero value, the mean usable value of river flow in all months of the year for wetted perimeter method will be 15 lit/sec (means lack of extraction), for the Tennant method will be about 408 lit/sec, and in the habitat simulation method will be about 70 lit/sec. Hence it can be seen that, the method like that of wetted perimeter method despite the protection of habitat suitability, makes the river exploitation very confined and methods like that of the Tennant method makes permission of river extraction less confined, but practically does not create the suitable condition for sustainability of ecosystem. But habitat simulation technique assesses the allowable value of extraction from river flow dynamically, considering the ecological condition and average intermediate values.

In the next step, habitat suitability distribution along the stream was investigated and this investigation is performed for the full range of discharges to be considered for the study. As an example, the habitat suitability distribution (CSI) at 1.11 cms discharge (mean annual flow) along the stream is shown in Figure 4.

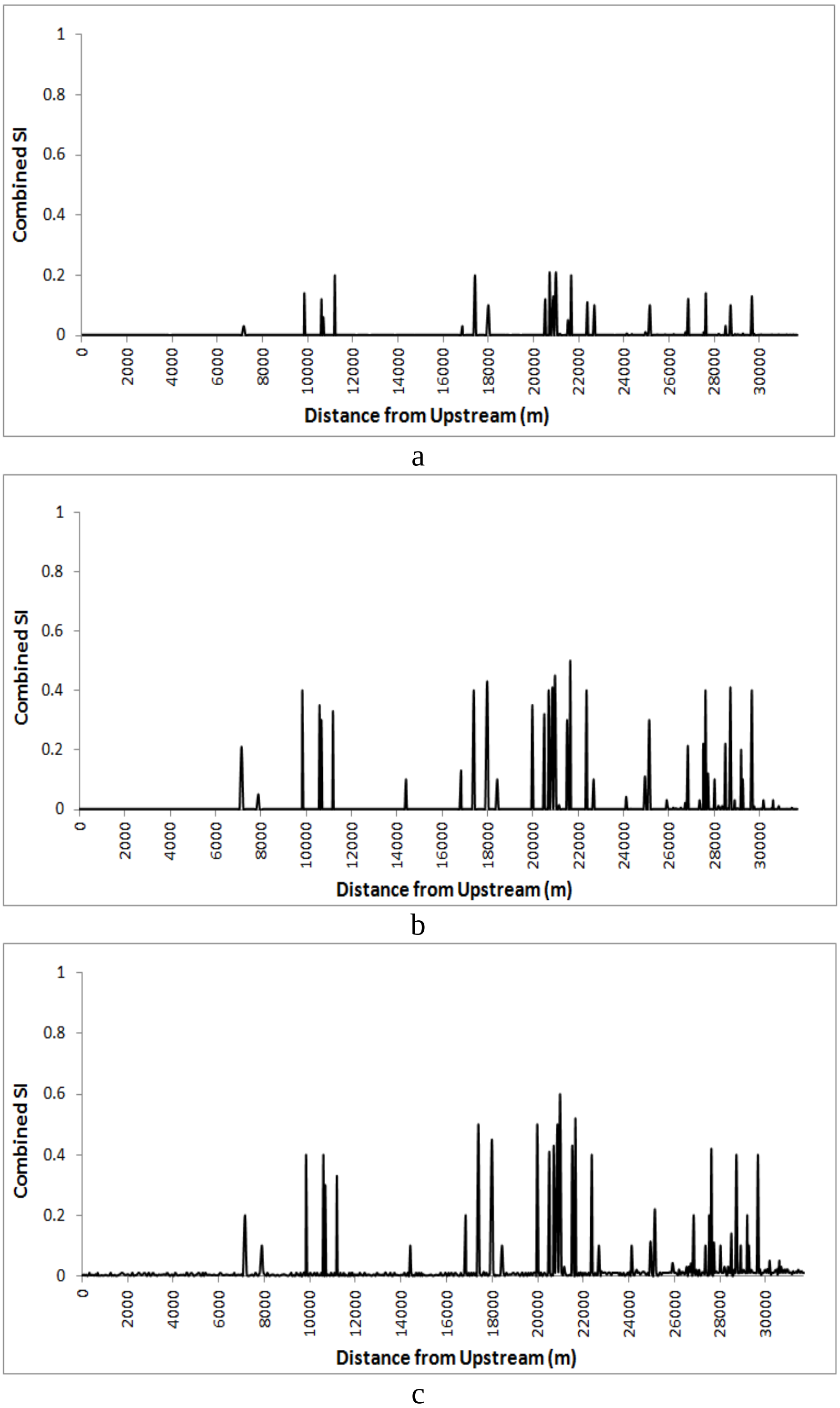

Figure 4. Habitat suitability distribution for three life stages (a- fry, b- juvenile, c- adult)

Based on the geomorphologic condition of the stream, the total stream reach is divided into three parts of upstream with the average slope of 0.03 (distance from 0 to 11000 m), middle part with the average slope of 0.02 (from 11000 to 21000 m) and downstream part with the average slope of 0.01 (from 21000 to 32000 m).

Habitat suitability distribution along the stream at different discharges showed that the upstream part of the stream (with slope of 0.03) has the poorest habitat condition and moving towards the downstream parts the habitat suitability condition will be improved. In other words, if the fish moves towards the upstream parts physical tensions on fish will be increased and consequently damages to rainbow trout fish communities will increase, too. Available field data about the frequency and distribution of rainbow trout at different stations of this stream also verify this fact (Figure 5). As can be seen in Figure 5 from station 1 to 7 (from upstream to downstream part) the number of target species is increasing.

Habitat suitability distribution along the width of the stream cross sections is presented in Figure 6.

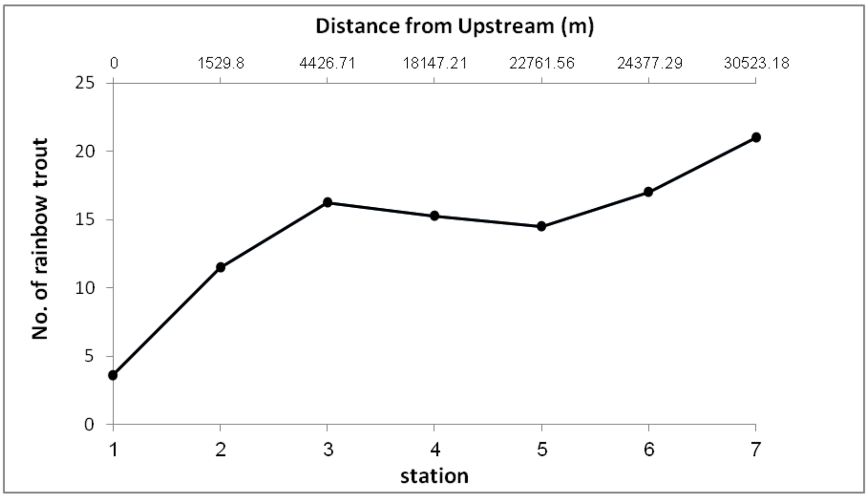

Figure 5. Rainbow trout distribution along the stream

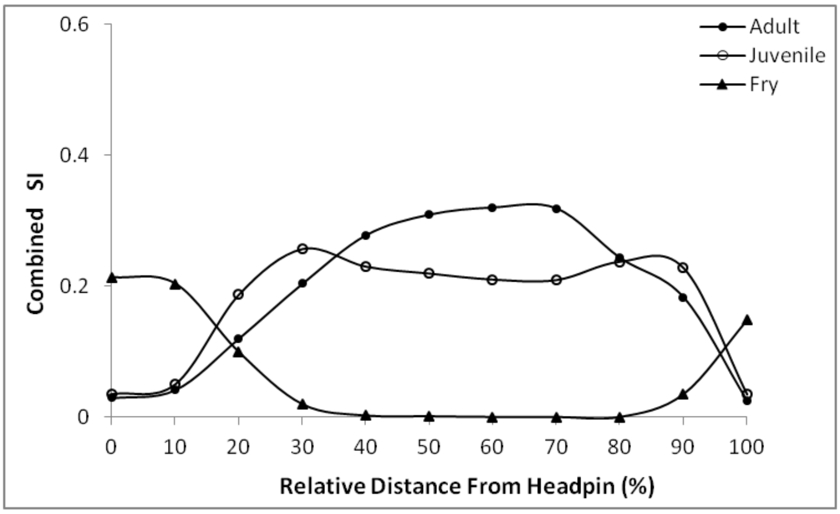

Figure 6. Habitat suitability distribution along the stream cross section

According to the cross sectional distribution of habitat suitability it can be seen that for fry life stage the stream banks have more suitable condition, while for adult and juvenile life stages the middle part of the stream cross section has suitable condition. Hence protection of river banks (due to the flow deficiency) is very important, since lack of the existence of these habitats extreme tensions and many losses will be created for the fish in its initial life stages. Hence it should be considered that protecting the habitat suitability in banks of the study river ecosystem is necessary, and based on the results of the present research habitat simulation technique is a powerful tool for IFN assessment and habitat evaluation.

Conclusion

In the present research the ability of habitat simulation technique for IFN assessment and evaluating the river habitat condition is investigated and is compared with the results of non-ecological methods in IFN assessment. Delichai stream is selected as the case study. Based on the results of the present research habitat simulation technique has considerable ability for dynamic assessment of IFN and river habitat evaluation along the longitudinal and latitudinal cross sections and it can also present the spatial habitat suitability distribution in various months of the year dynamically. IFN assessment with habitat simulation technique presents the intermediate values of water extraction from river, and has advantages related to other methods like that of the Tennant method and wetted perimeter method and creates the least discussion between river environmental managers and stakeholders. IFN value estimated from the Tennant method creates ecological problems and its value from wetted perimeter method causes very confined value of extraction from river. The habitat simulation technique also has the ability of river habitat prioritization in light of protection and restoration requirements. In the study stream of this research due to the variation of ecological condition for the target species, three different values for IFN in various months of the year were estimated and it was seen that the habitat near the stream bank requires more protection and restoration projects.

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