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Evaluation of streamflow habitat relationships using habitat suitability curves and HEC-RAS

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Abstract: Habitat Suitability Curves (HSCs) were developed for two freshwater fish species, namely *Salmo pelagonicus* and *Barbus balcanicus,* using microhabitat data obtained at a mountainous stream, in upper Axios River, Greece, for habitat evaluation on the micro scale. Twelve riverine HSCs associating two size classes with three microhabitat parameters (water depth, velocity and substrate) were developed and used. For the hydraulic simulation of the stream, the well-known, one-dimensional HEC-RAS software was implemented. The Weighted Usable Area (WUA) was estimated by combining habitat suitability indices with the output of the hydraulic model, to evaluate the relationship between streamflow and fish habitat availability. For the calibration of the model, water depth and flow velocity measurements were performed on April 2016. In the framework of the calibration phase, an algorithm was developed, to automate this process and to implement a sophisticated optimisation method. For the upstream and the downstream boundary conditions, water velocity and depth measurements were used as well, to reduce the uncertainty propagation due to the model's parameters. The presented approach may provide a better understanding of how flow variability affects fish microhabitats, while it can contribute considerably to the sustainable water management of hydrologically altered rivers and the concomitant conservation of riverine biota.

Key words: Habitat suitability curves (HSCs), HEC-RAS software, automation, WUA

1. INTRODUCTION

The habitat requirements of freshwater fish, normally expressed as Habitat Suitability Curves (HSCs), may provide valuable information regarding the physical structure and the flow regime of a stream channel (Terrell 1984; Bovee 1986; Brown et al. 2000). Electrofishing is a common technique for fish sampling, defining at the same time fish microhabitats and consecutively collecting microhabitat use data in rivers (Copp and Garner 1995) for the development of the HSCs. However, in Greece, little relevant work has been carried out that could assist the estimation of environmental flows, as well as the identification of priority habitats for conservation and restoration purposes (Vardakas et al. 2017).

Minimum environmental flows estimated using the relationship between WUA and discharge are recommended for having a river alive and conserving its ecosystem when found in critical condition for a short time period (Nikghalb 2016). WUA estimations for habitat indexing requires estimates of depth and velocity, which can be obtained using a computational hydraulic model. One dimensional river models are far more abundant and commonly used, among others, for such hydraulic simulations. However, the spatial distribution of the habitat suitability indices (SI), require more detailed hydraulic data to determine the spatial distribution of depth and velocity throughout the reach (Bovee et al. 1998). Moreover, the geomorphology of the river is a very important factor for the output of hydrodynamic models (Boyraz and Kazezyılmaz-Alhan 2014; Benjankar et al. 2015; Greco 2015), which also influences the output of the habitat models (Papadaki et al. 2016).

The shape of the WUA curves is a function of the species/size habitat preferences and reflects the interaction between hydraulic variables and channel structure with increasing discharge. In that context, habitat simulation models for fish and other species are important tools for evaluating the present state of a river, the effects of altered morphology or altered hydrology on habitat suitability, and to predict the ecological consequences of certain restoration measures or management strategies (Alcaraz-Hernández et al. 2011). In this study, an adaptation of the Physical Habitat Simulation (PHABSIM) technique, covering the Greek conditions (Papadaki et al. 2014) for the estimation of minimum environmental flows, was used. Moreover, summer habitat use of two freshwater fish species, namely the Pelagonian trout, *Salmo pelagonicus* Karaman, 1938 and the large spot barbel, *Barbus balcanicus* Kotlík, Tsigenopoulos, Ráb and Berrebi, 2002, was examined, using microhabitat data in terms of water velocity, depth, and substrate, obtained at a mountainous stream, the Drosopigi stream located in the upper part of Axios River drainage in Greece. Differences in habitat use were explored, to obtain species-specific HSCs, and to estimate minimum environmental flows according to the habitat requirements of these two fish species.

2. MATERIALS AND METHODS

2.1 Study area

Microhabitat data were collected from the Drosopigi stream, a perennial mountainous stream located 14 km southern of the city of Florina, in northern Greece. Habitat mapping was performed in a segment of 1.5 km length to select a representative study reach of 200 m, in the beginning of August 2015, in low flow conditions. The survey involved identification of several types of hydromorphological units (i.e. pools, runs, riffles, cascades and rapids) and measurement of their physical attributes (width, mean depth). The channel and floodplain were surveyed to create a digital elevation model (DEM) of the stream. A detailed topographic survey with a GPS/GNSS Geomax - Zenith 20 was performed, using reference stations at geodetic control points for highest accuracy. In Figure 1, the location of the case study is shown.

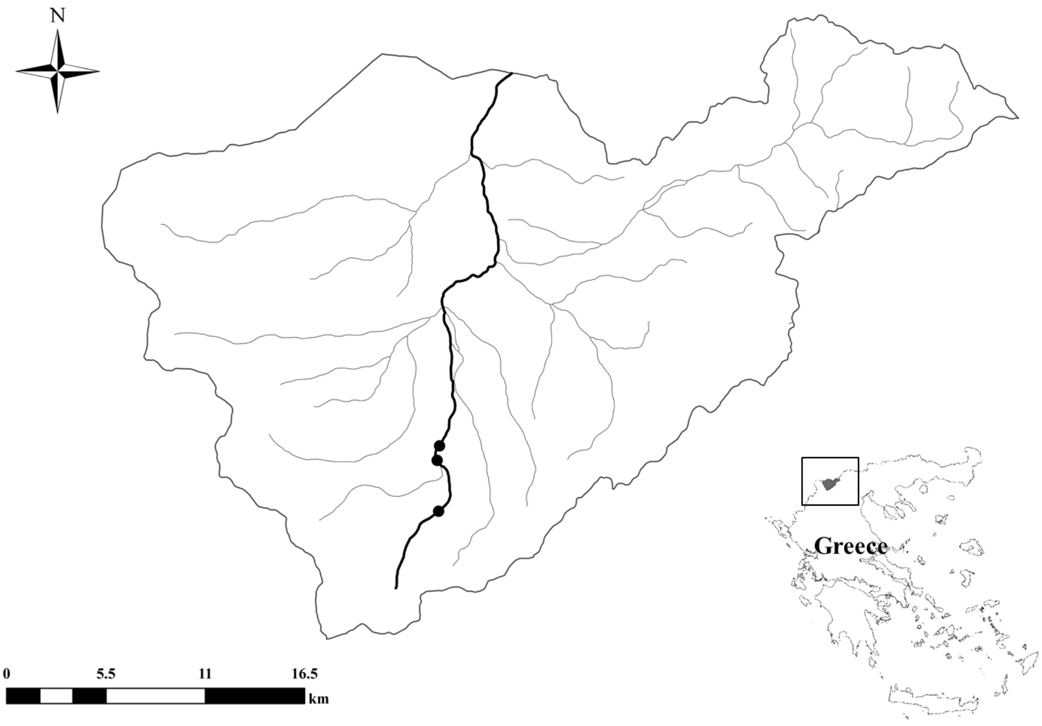

Figure 1. Drosopigi stream and its main tributaries; the location of the surveys for fish microhabitat use is marked with dots.

2.2 Fish and microhabitat data

Salmo pelagonicus and *Barbus balcanicus* are the most abundant or the only fish species, in the upper section of the Drosopigi stream where the survey took place, and for this reason, they were selected as the HSCs target species. For both species, two size-classes were recorded: small sized fish 5–15 cm, Total Length (TL) and large sized >15 cm TL. Fish data were collected using point-abundance sampling during daylight hours, using a Hans-Grassl GmbH battery-powered backpack electrofishing device (Model IG200-2, DC pulsed, 1.5 KW output power, 35-100 Hz, max. 850). Starting at the downstream point of the reach, sampling proceeded with the electrofishing crew that consisted of one operator and two netters moving in a zigzag pattern upstream, to sample all types of available fish habitats. To minimize disturbance, sampling locations were spaced about 4-5 m apart, so that the fish would not be disturbed by the previous electrofishing operation. Stunned fish were identified to species level, measured for TL and then, they were returned alive to the stream. A total of 135 observations (61 small and 74 large specimens) were recorded for *Salmo pelagonicus* and 451 observations for *Barbus balcanicus* (237 small and 214 large specimens) along the study reach. At each microhabitat, three variables were recorded: water velocity, water depth, and substrate type (Simonson 1993). Water velocity (V, m/s) and depth (D, cm) were measured using an OTT C20 flow meter. At each point the spatial coordinates and the dominant substrate type were recorded in the river channel and floodplain.

2.3 Hydraulic modelling

For the derivation of the required water depth and flow velocity variables, HEC-RAS software was used, assuming steady inflow into the computational domain. The upstream boundary of the model was derived solving the Manning equation, using as input the value of the desired steady flow. The required parameter in this case was the energy slope. The energy slope was calculated by the following equation (Chaudhry 2008):

$$S_f = S_0 - S_L(1 - Fr^2) \tag{1}$$

where S_f is the energy slope, S_0 the bottom slope, S_L the gradient of the water surface and Fr the Froude number. Since the case study is a mountain stream, the flow was expected to be supercritical with high Froude numbers. The energy slope was calculated from field observations, for a steady flow equal to 0.02 m^3/s, using the observed data obtained in the first two upstream cross-sections. For this purpose, the bottom slope, the gradient of the water surface and the flow velocity were measured, while the Froude number was calculated. Following this approach, the energy slope was calculated equal to S_f=0.0231, whereas the bottom slope was equal to S_0=0.0426. For the downstream boundary condition, the critical depth was selected, since the downstream boundary of the computational domain was the outlet of a small pool. Therefore, the flow was considered as critical. The required parameters of the software which had to be defined, was the Manning coefficient of the computational domain.

The computational domain was classified in 10 friction zones. The classification was made depending on whether each hypothetical zone could be characterised as a small pool or a cascade. It is noticed that in real-world applications Manning coefficient values gained from the relative literature probably underestimate the energy losses, due to turbulence phenomena that often occur in a river (Jarrett 1985). Therefore, they should be calibrated (Christelis et al. 2016) if relevant measurements exist, which is the case in the present study.

For the calibration of the Manning coefficients for each friction zone, a generic algorithm was selected (Goldberg 1989). The objective function adopted was the Root Mean Square Error between the simulated water depth and flow velocity using the HEC-RAS software and observed data from five cross-sections. Since both water depth and flow velocity were measured, a normalisation process followed by transforming the simulated water depths and flow velocities in a normalised

[0,1] variable NV, with the following equation:

$$NV_i = \frac{S_{max} - S_{sim}}{S_{max} - S_{min}} \quad (2)$$

where S can be either the water depth or the flow velocity, the subscript max and min indicates the maximum or the minimum value of this variable in the i-th cross-section, whereas the subscript sim indicates the value of the variable derived by the simulation. Following the above procedure, the calibrated Manning coefficient values are provided in Table 1.

Table 1. Manning coefficient values for each friction zone

Friction zone	n ($s/m^{1/3}$)
1	0.2500
2	0.2500
3	0.2489
4	0.0204
5	0.0203
6	0.1155
7	0.2219
8	0.0203
9	0.0345
10	0.2045

2.4 Habitat suitability curves development and habitat assessment

The HSCs were developed following the relevant methodology suggested by Bovee (1986). These curves relate the hydraulic to the habitat variables with a suitability index (SI), ranging from 0 (unsuitable for the aquatic species) to 1 (excellent). Each variable (water depth, flow velocity, substrate) was divided into classes, and frequencies of each class utilization by fishes were estimated. Once the histograms for the continuous variables were developed, a smooth curve was adjusted to them by using 3rd order polynomials, in R (R Development Core Team, 2014). These individuals' suitability indices were then combined to form a composite SI for every cell of the hydraulic model, using the product mathematical operation (Vadas and Orth 2001). At the cell scale, Cell Suitability Index (CSI) indicates whether the physical parameters (depth, velocity and substrate) are within those required by individual species and particular life stages (Bovee 1978). Integration of biological data by using the HSCs, with the HEC-RAS outputs (depth, velocity and substrate maps) were made, to calculate the Weighted Usable Area (WUA). Nineteen different discharge scenarios were selected between 0.02 and 4.5 m^3/s (Figure 5) to estimate the WUA. WUA was calculated by multiplying the CSI for a given cell of the hydraulic model, by the area assigned to that specific cell and then aggregate all the values in a single figure per discharge scenario. The whole procedure was carried out in R software (R Development Core Team, 2014).

2.5 Minimum environmental flow assessment

Optimisation matrices were developed depicting nineteen flows relative to summer conditions for two size classes (small sized: 5–15 cm and large sized: >15 cm) of the *Salmo pelagonicus* and the *Barbus balcanicus*, according to the optimization criterion of Bovee (1982). These flow values were arrayed across the top of the matrix and the WUA values for the aforementioned species were recorded accordingly (Table 2). Then, the minimum WUA value was identified for each flow. Finally, the minimum environmental flow was estimated based on the flow with the highest WUA value among all size classes and species (Bovee et al. 1998). This value corresponds to the flow that maximizes the habitat area for the particular fish species during the dry period in the study site.

3. RESULTS

For the calibration phase of the hydraulic model, constraints for the range of the Manning coefficient values were adopted. Specifically, the Manning coefficient values were ranging from 0.02 to 0.25 s/m$^{1/3}$. In Figure 2 the simulated water surface elevation and the flow velocities against the corresponding observed data are shown, for five cross-sections. The performance of the model was quite better for the water depths than for the flow velocities. This was expected, since it is generally accepted that flow velocity is more difficult to be simulated than the water depths (Guinot and Cappelaere 2009).

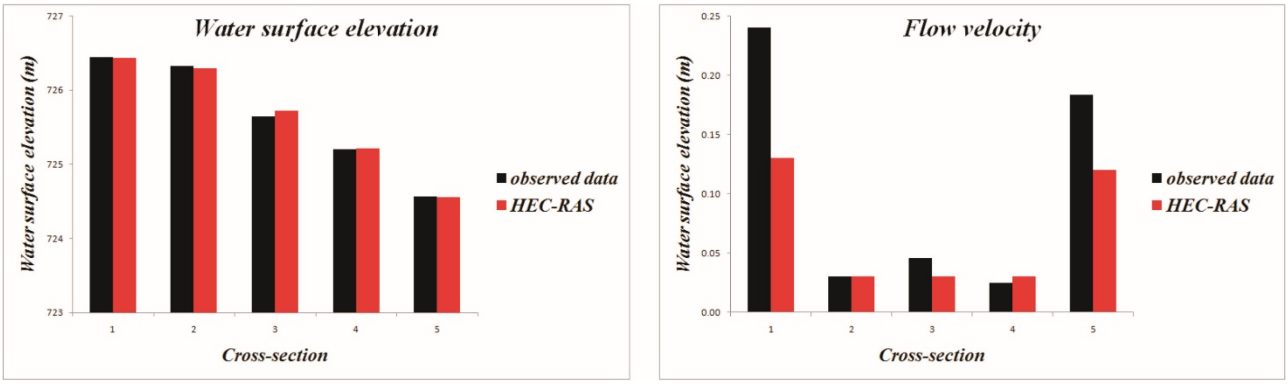

Figure 2. Performance of HEC-RAS model against observed data in five cross-sections

Water depth and current velocity ranged from 0 to 1.2 m and from 0 to 1.4 m/sec, respectively, in the study reach (Figure 3a, b). Substrate resulted to be mainly composed of boulders (>264 mm) and cobbles (64–264 mm). Regarding size differences in depth use (Figure 3a), depths most frequently used by both size classes of *Salmo pelagonicus* were between 0.4 to 0.9 m. *Barbus balcanicus* individuals smaller than 15 cm in TL occurred at depths between 0.1 m and 0.6 m, while the larger sized individuals of the same species were mostly found at depths ranging from 0.3 to 0.8 m. Water velocity HSCs (Figure 3b) calculated for the small sized *Salmo pelagonicus* showed optimum velocity values at 0.25 m/s. As expected, the large sized trout individuals occupied positions with higher velocities (0.45 m/sec). Regarding *Barbus balcanicus*, small sized fish were found in positions with relatively lower velocities (0.05 to 0.6 m/sec) than the large sized ones (0.2 to 0.8 m/sec).

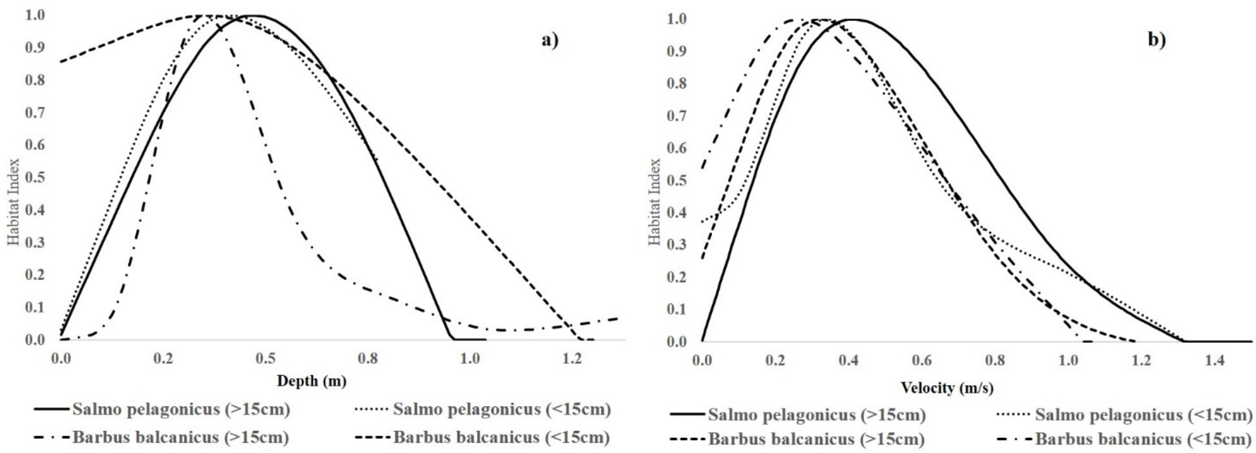

Figure 3. Habitat use curves for depth (a) and velocity (b) for two size classes of Salmo pelagonicus and Barbus balcanicus.

Typical habitat types are mainly riffles, runs and small pools. Substrate types are mainly cobbles, boulders and gravel. Substrate data are shown in Figure 4. Both fish species displayed a strong association to boulders and bedrocks, which are coarse enough to provide shelter.

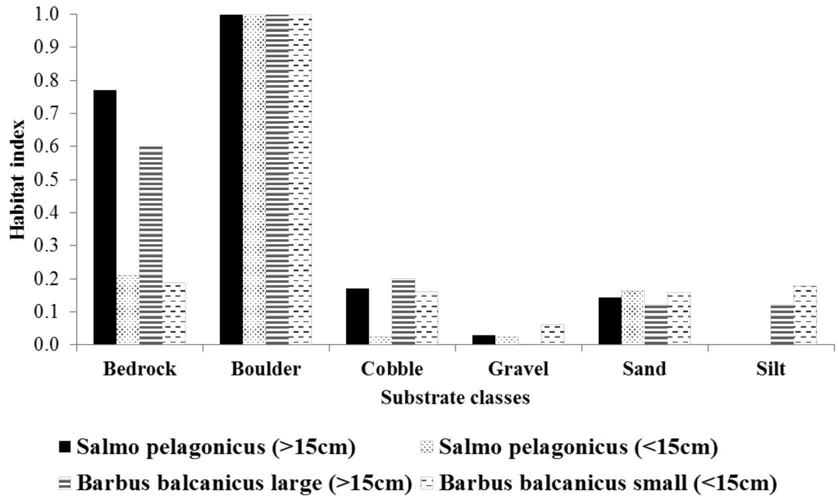

Figure 4. Small and large sized Salmo pelagonicus and Barbus balcanicus habitat index for substrate.

Discharge values ranging from 0.2 to 1.9 m^3/sec provided the most suitable habitat for both species and both size classes. WUA increases rapidly over a specific point (0.4 m^3/sec, threshold), and slowly becomes moderate, especially for the small sized fish. This variation shows that a small decrement in discharge, results to a noticeable decrement in the WUA also, which will affect the suitable habitat for the selected species. In Table 2 the habitat assessment results are expressed as WUA values.

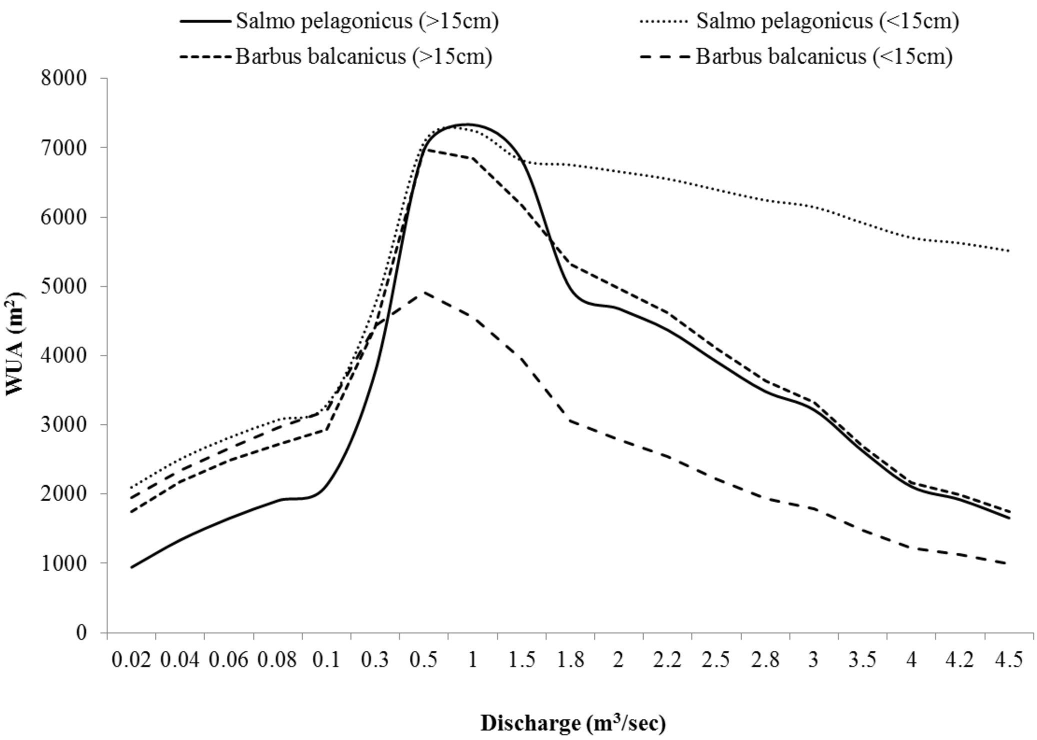

Figure 5. WUA-discharge relationship

The minimum environmental flow that minimise habitat losses for dry period conditions, was estimated according to Table 2 (0.5 m^3/sec).

Table 2. WUA values for two size classes of Salmo pelagonicus and Barbus balcanicus over a range of possible flows under summer conditions for the specific study site.

	Discharge (m^3/sec)																		
WUA	**0.02**	**0.04**	**0.06**	**0.08**	**0.1**	**0.3**	**0.5**	**1**	**1.5**	**1.8**	**2**	**2.2**	**2.5**	**2.8**	**3**	**3.5**	**4**	**4.2**	**4.5**
Salmo pelagonicus (>15cm)	945	1340	1651	1907	2130	3779	**6976**	7334	6825	4968	4677	4369	3914	3483	3217	2622	2110	1920	1657
Salmo pelagonicus (<15cm)	1746	2182	2486	2721	2931	4416	**6980**	6849	6171	5320	4973	4620	4112	3629	3332	2693	2173	1990	1744
Barbus balcanicus (>15cm)	2095	2503	2812	3069	3285	4749	**7082**	7248	6820	6755	6657	6550	6395	6243	6145	5913	5700	5624	5513
Barbus balcanicus (<15cm)	1955	2341	2663	2960	3207	4428	**4923**	4553	3950	3061	2793	2548	2221	1943	1787	1474	1224	1128	992
minimun WUA	945	1340	1651	1907	2130	3779	**4923**	4553	3950	3061	2793	2548	2221	1943	1787	1474	1224	1128	992

4. CONCLUSIONS

The present study indicated that the two investigated fish species have different habitat preferences, i.e. large sized *Salmo pelagonicus* abundances peaked at higher velocities and water depths than the small sized. The small sized *Barbus balcanicus* were spatially and temporally more dynamic, occupying habitats within relatively wider ranges of depth conditions than the large ones.

Fish habitat simulation methods can set operational benchmarks for flow and water level conditions during the most stressful seasonal period in Mediterranean Mountain Rivers. In this study, a minimum flow criterion could be set based on a threshold point, which in this case is the discharge value of 0.5 m^3/sec, under which the WUA decreases rapidly. Nevertheless, aquatic species have variable preferences at their life stages, and to set a constant minimum environmental flow for the whole year may lead to degradation of their habitats. Therefore minimum environmental flows should be used in conjunction with other techniques, which together produce a recommended environmental flow regime.

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