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DETERMINATION OF ENVIRONMENTAL FLOWS IN RIVERS USING AN INTEGRATED HYDROLOGICAL-HYDRODYNAMIC-HABITAT MODELLING APPROACH

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ABSTRACT

We propose the novel integrated modeling procedure 3H-EMC for the determination of the environmental flow in rivers and streams; 3H-EMC combines Hydrological, Hydrodynamic and Habitat modelling with the use of the Environmental Management Classes (EMCs) that are defined by the Global Environmental Flow Calculator. We apply 3H-EMC in the Sperchios River in Central Greece, in which water abstractions for irrigation cause significant environmental impacts. Calculations of the hydrodynamic-habitat model, in which the large and the small Chub are the main fish of interest, suggest discharge values that range from 1.0 m^3/s to 4.0 m^3/s. However, hydrological modelling indicates that it is practically difficult to achieve discharges that are higher than approximately 1.0-1.5 m^3/s. Furthermore, legislation suggests significantly lower values (0.4-0.5 m^3/s) that are unacceptable from the ecological point of view. This behavior shows that a non-integrated approach, which is based only on hydrodynamic-habitat modelling does not necessarily result in realistic environmental flows and thus an integrated approach is required. We propose the value of 1.0 m^3/s as the “optimum” environmental flow for Sperchios River, because (a) it satisfies the habitat requirements, as expressed by the values of weighted useable area that are equal to 2180 and 1964 m^2 for the large and small Chub, respectively, and correspond to 82 and 95 % of their respective maximum values, (b) it is consistent with the requirements of Environmental Classes A and B, since that the corresponding percentiles are higher than 75% for discharge (77.2 %) and for habitat availability (>83.5 % for the large and >85.0 % for the small Chub), (c) it is practically achievable from the hydrological point of view, and (d) it is higher than the value proposed by the Greek legislation. The proposed modelling approach can be applied to any river or stream using the same or similar modelling tools, which should be linked via proper coupling algorithms.

Keywords: Environmental flow; Environmental Management Classes; Global Environmental Flow Calculator; Hydrodynamic-Habitat modelling; Hydrological modelling; Integrated modelling.

1 INTRODUCTION

In recent decades, over-exploitation of water resources has caused serious ecological problems worldwide (Vörösmarty et al., 1997; Saito et al., 2001; Meador et al., 2003; Paukert et al., 2011). River water abstraction is a typical case of such over-exploitation that alters flow-regime and may threaten river ecosystem (Pearce, 2012) to “artificial desiccation” (Skoulikidis et al., 2011) and fish extinction (Vörösmarty et al., 2010). Various researchers have demonstrated the important effect of flow regime alteration on the amount of habitat, distribution, abundance, and diversity of river organisms, ranging from microorganisms, algae, and aquatic plants to invertebrates, fish and other vertebrates (Bunn and Arthington, 2002; Arthington, 2012). In Mediterranean rivers, various forms of pressure, including alteration of the flow regime, resulted in the decline of fish population and in some cases in the extinction of native species (Smith and Darwall, 2006). Moreover, various characteristics of the flow regime, such as the minimum monthly flow during spawning, exerted a strong effect on the patterns of presence-absence and population densities of extended fish species, such as the Eastern Iberian Barbel (*Luciobarbus guiraonis*) (Olaya-Marín et al., 2016).

Generally, it is recognized (Poff et al. 2010; Tharme, 2003) that keeping a minimum flow along rivers to serve the aquatic organisms is crucial to sustain biodiversity and ecosystem integrity (Arthington et al., 2006). In other words, a minimum environmental flow should continue flowing along rivers to sustain biodiversity and ecosystem integrity, especially in the dry periods.

A global review of the environmental flow methodologies at the beginning of the 21st century revealed the existence of more than 207 individual methodologies that can be categorized as hydrological, hydraulic rating, habitat simulation and holistic (Tharme, 2003). One of the first widely-used hydrological methods, was the US Tennant method (Tennant, 1976), while later other similar methods were developed that analyzed the diverse hydrological components to study and apply environmental flows in the framework of an adaptive management process (Henriksen et al., 2006; Mathews and

Richter, 2007). Although some hydrological approaches were usually favored due to their simplicity, they do not consider biological requirements and interactions of aquatic organisms (Li et al., 2015). Nevertheless, the hydrological methods based on hydrological alteration have been successfully incorporated in holistic methods, such as the Building Block Methodology (BBM) by King et al. (2000) and Ecological Limits of Hydrologic Alteration (ELOHA) by Poff et al. (2010). However, the habitat simulation methods, firstly developed within the framework of the Instream Flow Incremental Method (IFIM) by Bovee (1982), are fundamental to interpret the hydrological information and to understand the ecological consequences of environmental flows on habitats and biota. Also, in holistic methodologies such as the BBM and the DRIFT, the interpretation of hydrological information with hydrodynamic models is fundamental to understanding flow–ecology relationships (Arthington et al., 2003; King and Brown, 2006). Generally, there is no explicit method or criteria to determine the actual ecological regime without considering the river water demands and availability, as well as its natural variability. Thus, the final decision upon environmental flow requirements is a multifactorial process that involves prioritization of water uses, knowledge of the replenishing water resources and risk assessment efforts.

In Europe, a Water Framework Directive Guidance Document (EC CIS, 2015) has been issued to facilitate Member States towards upgrading the status of their water bodies via the application of environmental flows, suggesting that a hydrodynamic habitat modelling approach, integrated in a holistic framework is the most comprehensive method to derive defensible environmental flow recommendations. Hydrodynamic-habitat models (HHMs) have become fundamental to apply the habitat simulation methods in the evaluation of environmental flow in the last decades (Theodoropoulos et al., 2015 and 2017; Acreman, 2016; Arthington et al., 2003; Poff et al. 2010; Tharme, 2003), because they evaluate habitat suitability for aquatic organisms, based on physical variables, such as water depth, flow velocity, substrate and shelter (Bovee, 1986).

In Greece, the current legislative framework imposes the implementation of a minimum environmental flow in rivers that is equal to a portion of the average discharge in summer months or in September (Ministry of Environment, Energy and Climate Change, 2014); such a legislation lacks the necessary ecological basis needed to protect the remarkable biodiversity of this country. However, in rivers with the presence of ichthyofauna, the environmental flow is defined as such to ensure a minimum river depth of 0.2 m at the thalweg. Apart from these basic rules, a common approach for the assessment of the environmental flow in Greek rivers and streams is the application of hydrological methodologies based on simple statistical analyses of the natural historical flow series (Papadaki et al., 2015).

In the present work, we pose the following research question: "how can we determine the environmental flow in a specific stream or river, considering all ecological, environmental, hydrological and legal factors that affect this determination?". To answer this question, we introduce the novel integrated modelling procedure 3H-EMC, which combines Hydrological, Hydrodynamic and Habitat modelling with the use of the Environmental Management Classes (EMCs) that are produced by the Global Environmental Flow Calculator (GEFC); see Smakhtin and Anputhas (2006). We apply 3H-EMC in the Sperchios River in Central Greece, in which water abstractions for irrigation cause significant environmental impacts (Mentzafou et al. 2017). The 3H-EMC permits the identification of ecologically optimal discharge ranges and the selection of the minimum acceptable discharge that satisfy ecological requirements based on habitat suitability, environmental criteria, the natural and anthropogenic hydrological water availability and legal constraints.

2 MATERIALS AND METHODS

2.1 Study area

The area of study is shown in Fig. 1; the Sperchios River originates from the Tymfristos mountain, it then flows to the east through the Village Agios Georgios, enters a wide plain and finally discharges into the Maliakos Gulf. The total length of Sperchios River is ca. 82 km, its catchment area is 1660.9 km^2, while the average and highest altitudes are 641 m and 2285 m above sea level, respectively. Approximately 32% of the entire catchment is covered by agricultural land; agriculture is the main human activity in the area, 2% by built-up areas and 66% by natural vegetation and bare land. Sperchios River is characterized by a Mediterranean climate with low discharges in summer and high discharges in late autumn, winter and spring. The most important hydromorphological alterations of the Sperchios River are water abstractions, primarily for irrigation and to a lesser extent, for industrial activities, such as small manufacturing units of agricultural products and olive oil refineries (Skoulikidis et al., 2011).

We selected a 200-m long river reach, based on its local intense upstream water abstractions for irrigation that may cause detrimental effects on river ecosystem (Mentzafou et al. 2017), but also to cover variations in channel bed and bank material, stream sizes, and stream geomorphologic characteristics. In this reach, we identified several types of hydro-morphological units (HMUs), such as pools, runs and riffles, and we measured their extent and physical attributes to obtain a quantitative description of the hydrodynamic behavior of the river. The runs represent 50% of the reach, pools 30%, while the remaining 20% are riffles. These HMUs have similar proportions to those in the Evinos river, where we collected microhabitat data; see section 2.5. The target species are the two size classes of the widespread chub *Squalius vardarensis,* which is locally common species of “Least Concern” according to the IUCN Red list; however, its geographical distribution is limited to the southern Balkans (Barbieri et al., 2015).

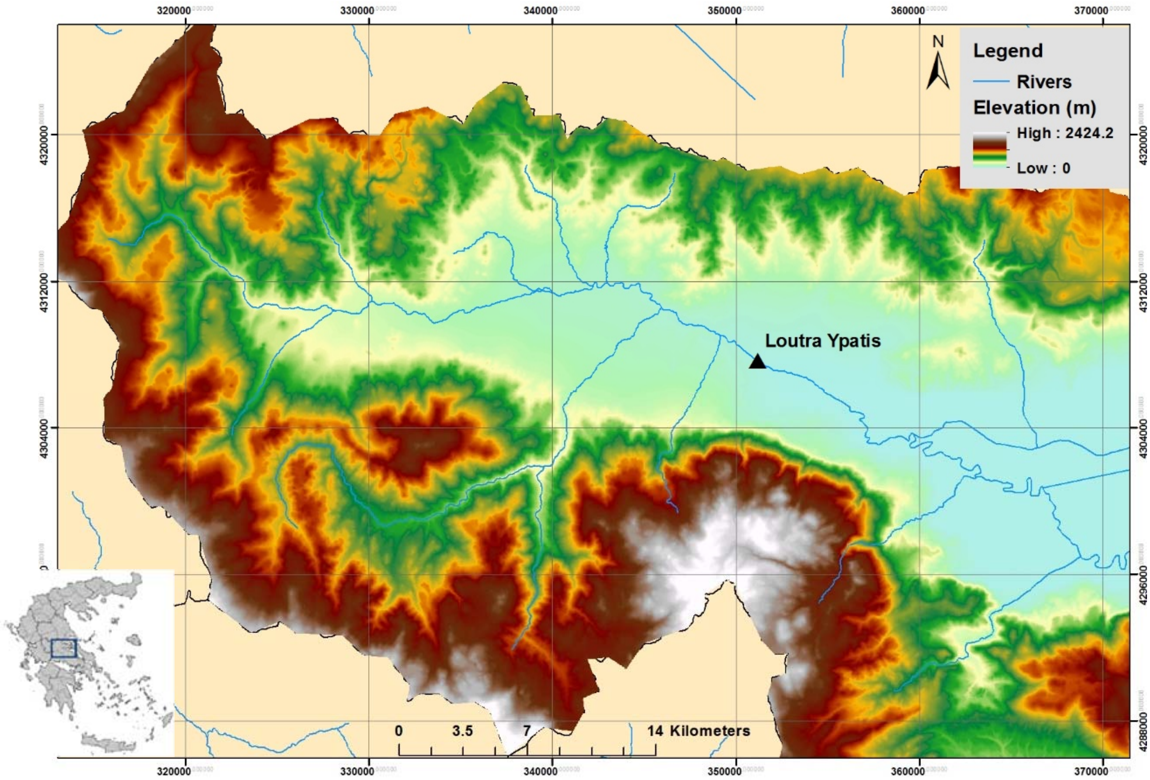


Fig.1. The area of study; the Sperchios River basin in Central Greece.

2.2 Integrated modelling procedure

The conceptual diagram of the integrated modelling procedure is shown in Fig. 2. Fig. 2 depicts that we combine three models (Hydrodynamic, Habitat and Hydrological) with the GEFC, to determine (a) possible discharges, based on habitat availability, (b) hydrologically feasible discharges and (c) environmentally acceptable discharges, which we subsequently use to determine the ecological flow, considering the legal constraints. The inputs to the three models are topographical, hydrodynamic, microhabitat and hydrological data. In the following sections, we present and apply the proposed modelling procedure in more details.

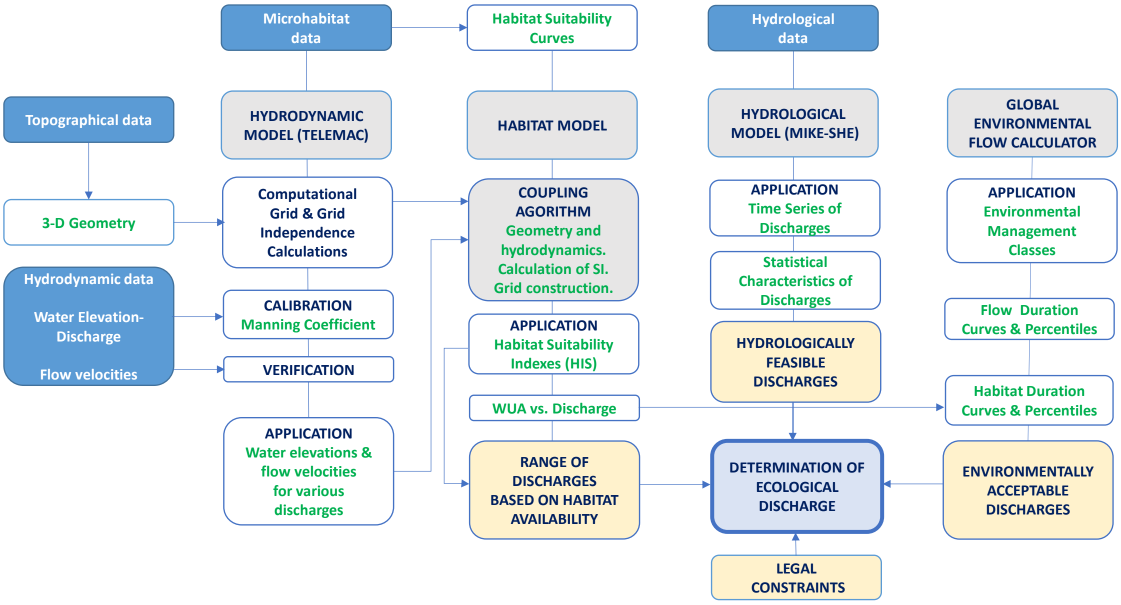


Fig. 2. The conceptual diagram of the modelling procedure.

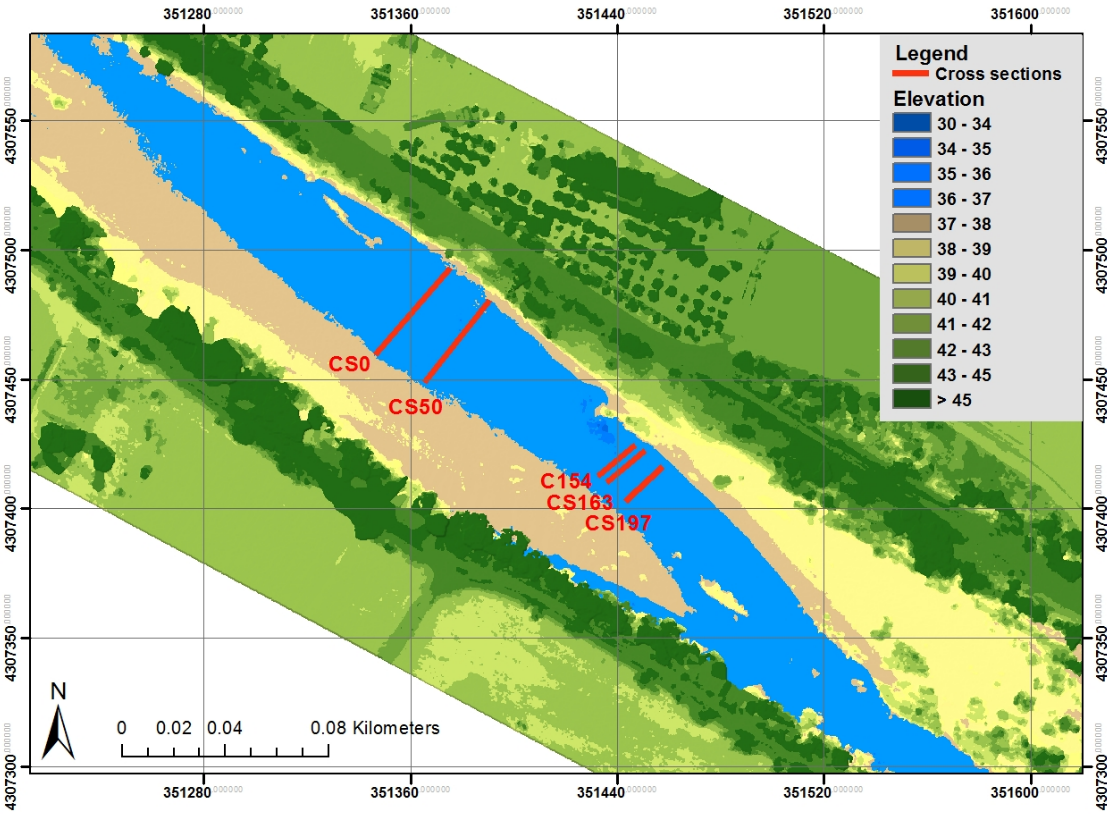


Fig.3. The reach of the river with the main cross sections; elevations are above sea level.

2.3 Topographical data

We conducted a detailed topographic survey with a GPS/GNSS Geomax-Zenith 20 to obtain the spatial coordinates and elevations from 1255 points of the river reach and the flood plain using the GGRS ’87 Greek Geodetic Reference System designated in 1987. Then, we used these data for the construction of the 3-D geometry of the reach that is an input to the hydrodynamic model; see Fig.2. We have defined five main cross-sections that are shown in Fig.3, which are placed perpendicular to the main direction of the flow, whose positions are CS0 (x=0.0 m), CS50 (x=50.0 m), CS154 (x=154.0 m), CS163 (x=163.0 m) and CS197 (x=197.0 m).

2.4 Hydrodynamic data

We measured water depths with a level staff and flow velocities with a propeller current meter (OTT®) at various sections of the river reach during 14 sampling periods; twelve in 2014, three in

2015 and one in January 2016. During these periods, the discharge ranged from 0.3 to 10.0 m3/s. In January 2016, we performed velocity measurements at the five main cross-sections that are shown in Fig. 3; we use these measurements to calibrate and validate the hydrodynamic model (Leclerc et al., 2015), as shown in Fig. 2. The spacing between velocity measurements along each cross section was equal to approximately 10% of the total width of the section and the exact points of measurement were determined in such a way to record all the major bathymetric, i.e. underwater topographic, changes along the section. The average velocity was estimated at 60% of the maximum depth, when the water column depth was smaller than 0.76 m and at 20% and 80% of the maximum depth, when it was greater than 0.76 m (Buchanan and Somers, 1976; Mosley and McKerchar, 1993). Using these measurements, we applied the velocity - area method to calculate the discharge in each cross section; this method assumes that the average velocity for the vertical column i represents the average velocity in the cross section from halfway to the preceding vertical i-1 to halfway to the next vertical i+1 (Buchanan and Somers, 1976).

At section CS154 (see Fig. 3), we combined measurements in all periods to develop a stage - discharge (rating) curve, which is described by equation (1), where Q (m^3/s) is the discharge, H (m) is the elevation of the free surface and Z_b = 37.57 m is the bottom elevation of section CS154.

$$Q = 71.19 \cdot (H - Z_b)^{3.40} \tag{1}$$

Based on the characteristics of the bed material in the reach that is predominantly pebbles and cobbles of uneven size (3-10 cm), we divided the reach of the river into two segments; the first segment that extends from x=0 until x=75.0 m is characterized by the presence of clay accumulated at the banks of the river, while in the second segment (x=75.0-197.0 m) the slope is steeper, silt is washed out and heavier cobbles are distributed evenly throughout the bottom of the river.

2.5 Microhabitat data

In the summer 2014, when flow conditions were low, we collected microhabitat-use data of Peloponnese chub *Squalius peloponensis* (Valenciennes, 1844) in the Evinos River in western central Greece. We used Evinos River as the “best-available” reference river for our study in Sperchios River for the following reasons. Firstly, Squalius peloponensis is morphologically very similar to the Vardar chub Squalius vardarensis (Karaman, 1928), they both presumably occupy identical niches and they are common and widespread in the mid and lower main stem river segments. Secondly, both rivers have similar stream geomorphologic characteristics and types of hydro-morphological units (HMUs); in Evinos River, the percentages of runs, pools and riffles are 42%, 39% and 19%, which are very similar to these in Sperchios river (50%, 30% and 20%, respectively). Thirdly, the two rivers have similar geometrical and hydrodynamic characteristics, i.e. width ranging from 5 to 15 m, water depth up to 0.7 m and average flow velocities up to 1.1 m/s; furthermore, both rivers belong to the same Water Framework Directive Typological class RM-2, that refers to small-medium lowland Mediterranean rivers with strongly seasonal flow regimes. Fourthly, both river sites have similar fish guild composition; they are found within the “upland cyprinid fish zone” of central Greece, where chub and two species of barbels along with some smaller cyprinids create a common general fish assemblage type (Economou et al., 2007). Both Peloponnese chub and Vardar chub are considered adequate “guiding species” as potential indicators of ecological status within biogeographically distinct fish assemblages in Greece (Economou et al., 2016). Moreover, all the Squalius species in Greece have the same ecological trait characters, which are like these of large-sized Squalius in other parts of the European Mediterranean (Ferreira et al., 2007). The chub species of central Greece are considered rheophilic omnivores, usually feeding in the water column; they undergo short to medium-range migrations, i.e. they are potamodromous during spring reproductive season and they reproduce on hard substrates in flowing waters (Economou et al., 2007).

We followed international standards for data collection by visual observation through snorkeling (Heggenes and Saltveit, 1990; Martinez-Capel et al., 2009) and measuring specific habitat use of many individual fish. We distinguished two size classes: small chub (<10 cm, 342 individuals) and large chub (>10 cm, 368 individuals). Since chub exhibits relatively strong schooling behaviour, we transformed the numbers of fish per observation by logþ1, according to similar studies (Brosse and Lek, 2000; Fukuda et al., 2011). The collected data included fish presence, i.e. number of individuals and class size, and hydrodynamic characteristics that are the average water depth (D) and the average water column velocity (V) at each occupied microhabitat. Also, we have considered the absence of species, by taking habitat measurements in areas, where no fish were observed. We performed a statistical analysis (Bovee, 1986) to develop frequency diagrams and then the Habitat Suitability Curves (HSCs). A HSC quantifies the suitability of a certain environmental condition, i.e. habitat variable, for a particular size, life stage or behaviour of the target species. Suitability is based on the frequency analysis of the number of occupied microhabitats weighted by the sum of the individuals observed and is measured for each habitat variable, such as water depth or velocity, from observations of the presence, absence or relative density of individuals in specific habitats. Typically, it is expressed as Suitability Index (SI) and measured on a scale from 0 (unsuitable) to 1 (optimal) (Waters, 1976; Jowett and Davey, 2007). In the present work, we denote SI by SID and SIV, for water depth and velocity, respectively.

2.6 Hydrodynamic Habitat Modelling

The HHM consists of the hydrodynamic model and the habitat model that are linked via a coupling algorithm (see Fig.2). The hydrodynamic model determines the 2D flow field via the solution of the continuity and momentum partial differential equations that are written as follows:

$$\frac{\partial h}{\partial t}+u\vec{\nabla}(h)+hdiv(\vec{u})=0 \tag{2}$$

$$\frac{\partial u}{\partial t}+u\vec{\nabla}(u)=-g\frac{\partial Z}{\partial x}+S_x+\frac{1}{h}div(h\nu_t\vec{\nabla}u) \tag{3}$$

$$\frac{\partial v}{\partial t}+u\vec{\nabla}(v)=-g\frac{\partial Z}{\partial y}+S_y+\frac{1}{h}div(h\nu_t\vec{\nabla}v) \tag{4}$$

where h is the depth of water, u and v are the velocity components in the directions x and y of a 2-D Cartesian coordinate system, respectively, t is the time, Z is the free surface elevation, g is the gravitational acceleration, ν_t is the eddy viscosity and S_x and S_y are source terms that represent the Coriolis force and the bottom friction in the directions x and y, respectively. For the description of turbulence, the standard k-epsilon model (Rodi, 1980) is used, which relates ν_t to the average turbulent kinetic energy per unit mass (k) and the rate of its dissipation (ε) via Eq. (5).

$$\nu_t=0.09\frac{k^2}{\varepsilon} \tag{5}$$

The distributions of k and ε are calculated by the following transport equations.

$$\frac{\partial k}{\partial t}+\vec{u}\vec{\nabla}(k)=\frac{1}{h}div(h\frac{\nu_t}{1.0}\vec{\nabla}k)+P-\varepsilon+G \tag{6}$$

$$\frac{\partial \varepsilon}{\partial t}+\vec{u}\vec{\nabla}(\varepsilon)=\frac{1}{h}div(h\frac{\nu_t}{1.3}\vec{\nabla}\varepsilon)+\frac{\varepsilon}{k}(1.44P-1.92\varepsilon)-1.44\frac{\varepsilon}{k}G \tag{7}$$

where P is the turbulent energy production term and G is a source term due to the gravitational forces; more details on the k-ε model can be found in Rodi (1980). We employed the TELEMAC Modelling System V6.2 (Hervouet, 2007) that uses the finite element technique to discretize the partial differential equations in the computational domain, and applied the method of characteristics to solve Eqs. (3), (4), (6) and (7), and the Positive Stream-wise Invariant distributive scheme that is mass-conservative for the solution of Eq. (2). A detailed description of TELEMAC can be found in Villaret et al. (2013).

We constructed (i) the habitat model, i.e. the HSCs for the target species, and (ii) the coupling algorithm that uses as input the output of the hydrodynamic model and (both in FORTRAN language) to calculate the Weighted Usable Area (WUA, m^2) (Bovee et al. 1998); WUA is the most renowned general indicator of habitat quality and quantity and it corresponds to the sum of the areas (*i.e.* cells or pixels) weighed by the inferred suitability within the entire domain of the hydrodynamic model. The calculation procedure is as follows (see Fig.2): Firstly, we read from file SELAFIN of TELEMAC the Cartesian coordinates, the velocities u and v, the free surface elevations and the bottom elevations for all grid nodes; using these data we calculate the average water depths (D) and velocities (U) at all nodes. Secondly, we insert the HSCs for D and U and calculate the corresponding SI values, SI_D and SI_U, at every location (x,y) of the river. Thirdly, we construct the grid of the “calculation cells” of the habitat model that can be based on the numerical grid of the hydrodynamic model; to facilitate this construction, we have chosen to use structured grids with triangular cells in the hydrodynamic model, so that two neighboring triangular cells form a quadrilateral cell of the habitat model. Then, we calculate at each cell of the habitat model i the surface area (A_i), SI_D, SI_U, Habitat Suitability Index (HSI_i) by Eq. (8), and finally WUA for the whole reach of the river by Eq. (9). We determine WUA by summing up SI grid cell values only for the cells with combined SI higher than 0.5 (Papadaki et al.,2016). Like in similar studies, the effect of substrate has been neglected (Jowett and Davey, 2007, Lambert and Hanson, 1989).

$$HSI_i = \sqrt{SI_D \times SI_V} \tag{8}$$

$$WUA = \sum_{i=1}^{N} \left(A_i \times HSI_i \right) \tag{9}$$

We applied the HHM to calculate the WUA for the expected range of discharges in Sperchios River that is 0.3-10.0 m^3/s to derive the curve Weighted Useable Area vs. Discharge (WUA-Q) (Boavida et al. 2014); see section 3.1.4.

2.7 Hydrological Modelling

We used the MIKE-SHE model (DHI, 2014), which is a physically based distributed model, to simulate all hydrological domains within the land phase of the hydrological cycle in the river basin of Sperchios River. MIKE-SHE is integrated with the 1D hydrodynamic model MIKE 11, which calculates water discharges and levels, water quality and sediment transport in 1D rivers and channels. In the Sperchios River, we applied MIKE-SHE to determine its average daily discharges of its natural (near-reference) flow regime in the 4-month period June-September of the years 2009-2016.

2.8 Global Environmental Flow Calculator

The GEFC is a tool that estimates Environmental Management Classes (EMCs) by "reducing" the natural hydrologic regime in a proportional basis at specific thresholds that indicate specific degrees of ecological disturbance that are high, moderate, low or very low. Each EMC can be considered potentially an "environmental flow scenario" that deviates from the natural-unregulated flow conditions, but maintains the variation patterns and the main hydrologic features, such as frequency of floods, low flows etc. Generally, GEFC uses six default EMCs that correspond to six levels of Environmental Flows (DWAF, 1997). River ecosystems in Classes A and B represent unmodified and largely natural conditions, where no or limited modification is present or should be allowed from the management perspective. Class C represent moderately modified river ecosystems, in which modifications do not affect ecosystem's integrity. Seriously and critically modified ecosystems belong in Class D, where most of the ecosystems functions and services are lost. Class E encompasses poor and highly impacted ecosystems that very often are not acceptable from the management perspective.

In the present study, we use the hydrological data (time series of discharges) of MIKE-SHE as input to the GEFC (see Fig.2) to determine the Flow Duration Curves (FDCs) for four EMCs, which are A, B, C and E, as well as for the natural flow regime. Then, we combine the calculated FDCs with the WUA-Q curves to produce the Habitat Durations Curves (HDCc); see section 3.3.

3 RESULTS AND DISCUSSION

3.1 Hydrodynamic-habitat modelling

3.1.1 Calibration, verification and application of the hydrodynamic model

Prior to its application, we calibrated the hydrodynamic model to determine the values of the Manning coefficient (n) at the two segments of the river by comparing calculated with measured values of water elevation at four sections for Q=8.10 m^3/s, at which we performed measurements. Based on this comparison, which is summarized in Table 1, we determined the values n=0.028 and n=0.032 in the first and second segment, respectively. Then, we verified the hydrodynamic model by comparing calculated velocities with measurements; this comparison that is shown in Fig.4 indicates a satisfactory verification of the model. Finally, we applied the model for discharge values equal to 0.3, 0.5, 0.9, 1.8, 3.0, 4.0, 5.0, 6.3, 8.1 and 10.0 m^3/s. Indicative calculated flow velocities are shown in Fig.5, while the corresponding water depths are shown in Fig.6.

Table 1. Measured vs. simulated values of water elevation in meters for Q = 8.10 m^3/s.

Cross section	Measured water level	Simulated water level	Error (%)
CS0	38.92	39.02	0.26
CS50	38.91	38.90	0.03
CS154	38.10	38.11	0.03
CS163	38.05	38.07	0.05
CS197	-	37.95	-

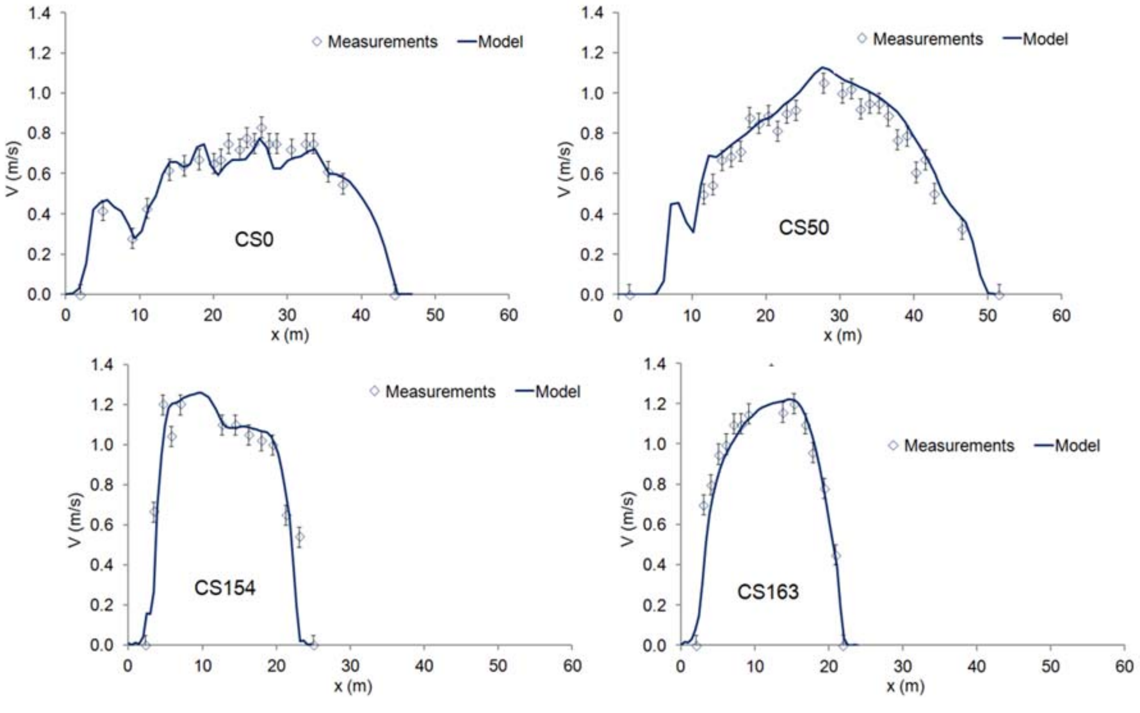


Fig.4. Calculated flow velocities vs. field measurements at different cross sections.

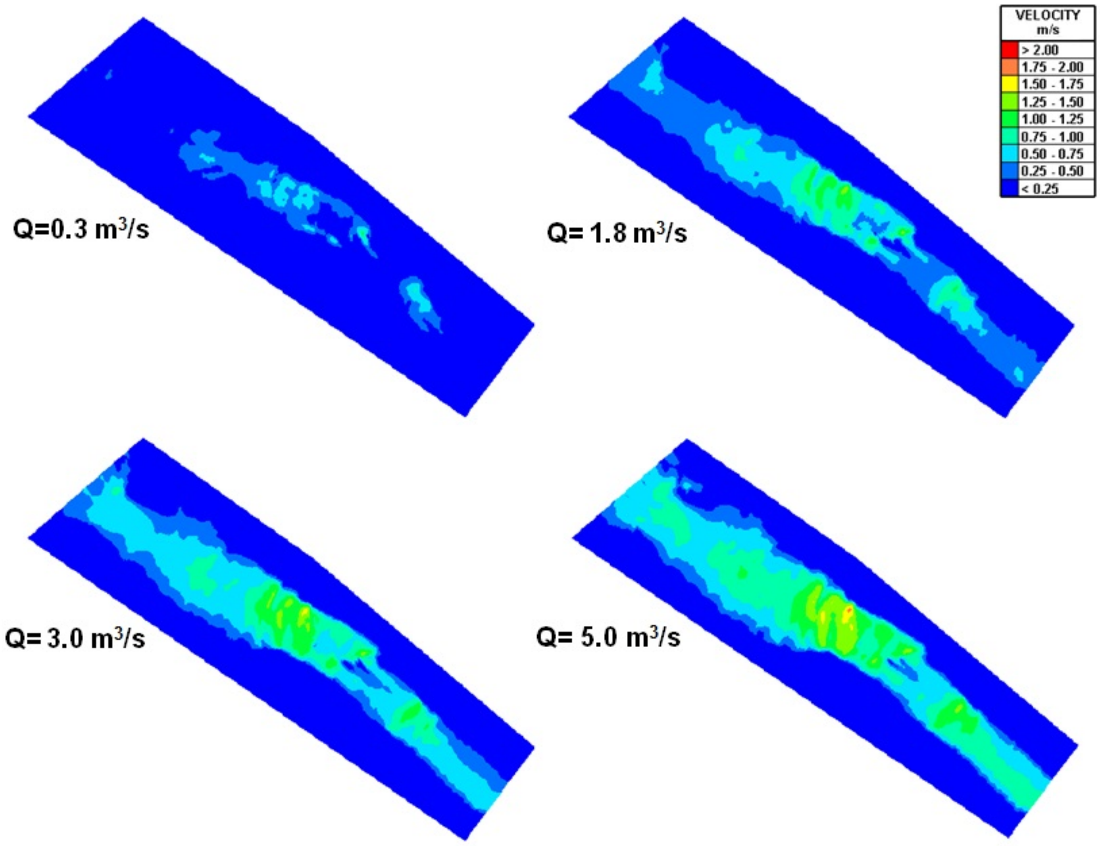


Fig.5. Calculated flow velocities for various discharges Q=0.3, 1.8, 5.0 and 10.0 m^3/s

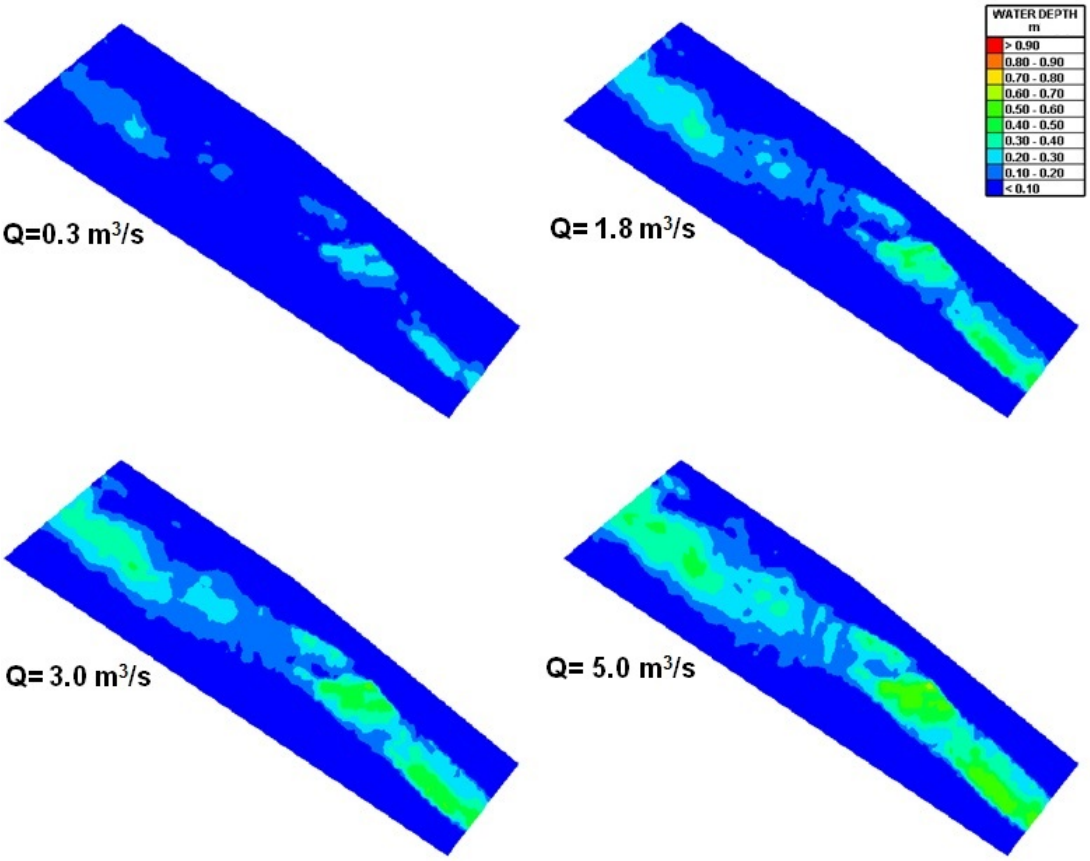


Fig.6. Calculated water depths for various discharges Q=0.3, 1.8, 5.0 and 10.0 m^3/s

3.1.2 Development of Habitat Suitability Curves

The HSCs for the water depth (with SI > 0.8 e optimum values; see Bovee, 1986) that are shown in Fig. 7 indicate that both sizes of chub actively selected shallow areas with water depths ranging from 0.28 to 0.55 m, whereas the large chub occupied slightly deeper microhabitats than the small chub. In this case, a residual suitability of 0.4 was assigned to the tail of the HSC for water depth, assuming that the reduction on the number of observations was caused by the low number of deep microhabitats available rather than by the unsuitability of these microhabitats. Nonetheless, previous studies on the genus indicated that water depths close to or exceeding 1.5 m may be equally suitable than shallower ones (Martinez-Capel et. al., 2009; Muñoz-Mas et al., 2017b). In the HSC for the average water velocity we assigned the highest suitability, which is equal to 1, to low velocities ranging from zero to 0.3 m/s, by considering the behaviour of the genus that has been observed in the studies by Santos and Ferreira (2008), Martinez-Capel et. al. (2009) and Muñoz-Mas et al. (2017b). For velocities between 0.3 to approximately 1.0 m/s, the suitability index decreased linearly. For higher velocity values, the suitability index remained constant at a low level, according to the criteria of Martinez-Capel et al. (2009), which accounts for the natural limitations that water velocity exerts on fish swimming.

Generally, previously published HSCs for the European chub (Squalius cephalus L. 1758) indicated optimum water depths between 0.5 and 2.0 m (Cowx and Welcomme, 1998), showing a partial coincidence with our results for the small and the large chub. Regarding Mediterranean species of chub, some studies in the Iberian Peninsula obtained similar values for the optimum depth, which ranged from 0.26 to 1.40 m for the Southern Iberian chub (Squalius pyrenaicus Günther, 1868) (Martinez-Capel et al., 2009) and the Eastern Iberian chub (Squalius valentinus Doadrio & Carmona, 2006) (Muñoz-Mas et al., 2017b). However, other studies indicated smaller optimal depths. For instance, the optimal depth for the Northern Iberian chub (Squalius carolitertii Doadrio, 1988) during the summer periods was determined to be in the range 0.54-0.60 m (Santos et al., 2004), whereas the optimal depth for the Arade chub (Squalius aradensis Coelho, Bogutskaya, Rodrigues & Collares-Pereira, 1998) was around 0.4 m (Santos and Ferreira, 2008). Regarding water velocity, in the Iberian Peninsula, these studies coincided indicating an optimal average velocity ranging between 0.0 and 0.5 m/s, although the optimal range was below 0.25 m/s in the majority of these studies (Martinez-Capel et. al., 2009; Muñoz-Mas et al., 2017b; Santos and Ferreira, 2008; Santos et al., 2004). Nevertheless, these differences in the optimal ranges could be caused by differences in the available microhabitats. For example, the Arade chubwas studied in a river segment dominated by shallow and moderate-to-fast flowing riffles and runs, which may displace the habitat use towards these habitats (Santos and Ferreira, 2008). However, other sources of uncertainty exist, such as the sampling approach (Brosse et al., 2001); for example, Alcaraz et al. (2014) using electrofishing concluded that the Jucar nase (Parachondrostoma arrigonis Steindachner, 1866) was a rheophilic species, while Muñoz-Mas et al. (2017a), who employed snorkeling determined that it was rather limnophilic. Therefore, although snorkeling has been suggested to be more accurate than electrofishing (Brosse et al., 2001), flexible microhabitat-use strategies are common among fish inhabiting Mediterranean streams due to the long-term adaptations to irregular flow regimes (Martelo et al., 2014). In accordance, any comparison with other species or studies should be made cautiously, as similarities may be due to particularities, either spatial or temporal (Muñoz-Mas et al., 2017b).

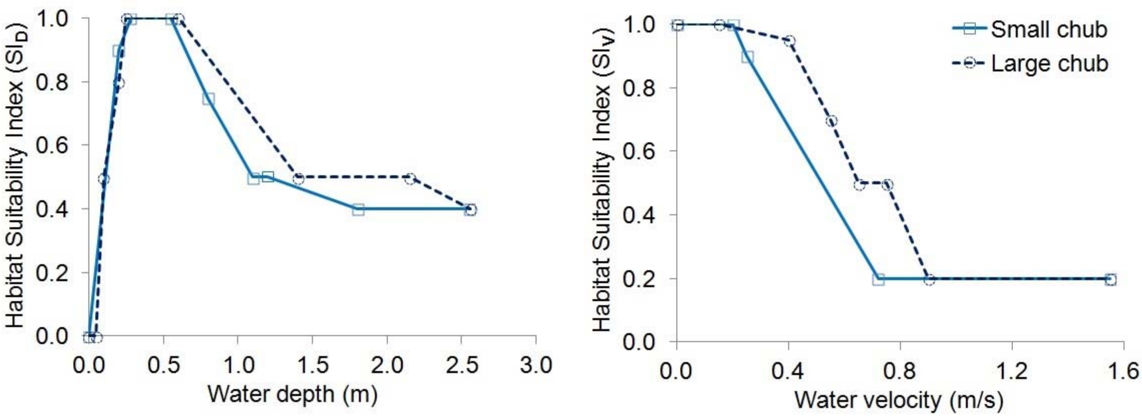


Fig.7. Habitat Suitability Curves for water depth and average water column velocity.

3.1.3 Calculation of the distributions of Habitat Suitability Index

The distributions of calculated Habitat Suitability Index (HSI) are shown in Fig.8 and Fig. 9, for the small and large Chub, respectively. For comparison purposes, we used four ranges of HSI values: 0.00-0.25, 0.25-0.50, 0.50-0.75, and 0.75-1.00. Fig.8 depicts that the highest availability of appropriate habitats (HSI>0.5) for the small Chub is observed for Q=0.9 and 1.8 m^3/s; then, with increasing discharge, HSI also increases significantly. For the large Chub, the image is slightly different; Fig. 9 shows that the best discharge values that ensure highest availability of appropriate habitats are 1.8 and 3.0 m^3/s; Q=5.0 m^3/s provides also a relatively good result in terms of suitable habitat availability, while for discharge values lower than 0.9 or higher than 5.0 m^3/s the areas of suitable habitats decrease significantly.

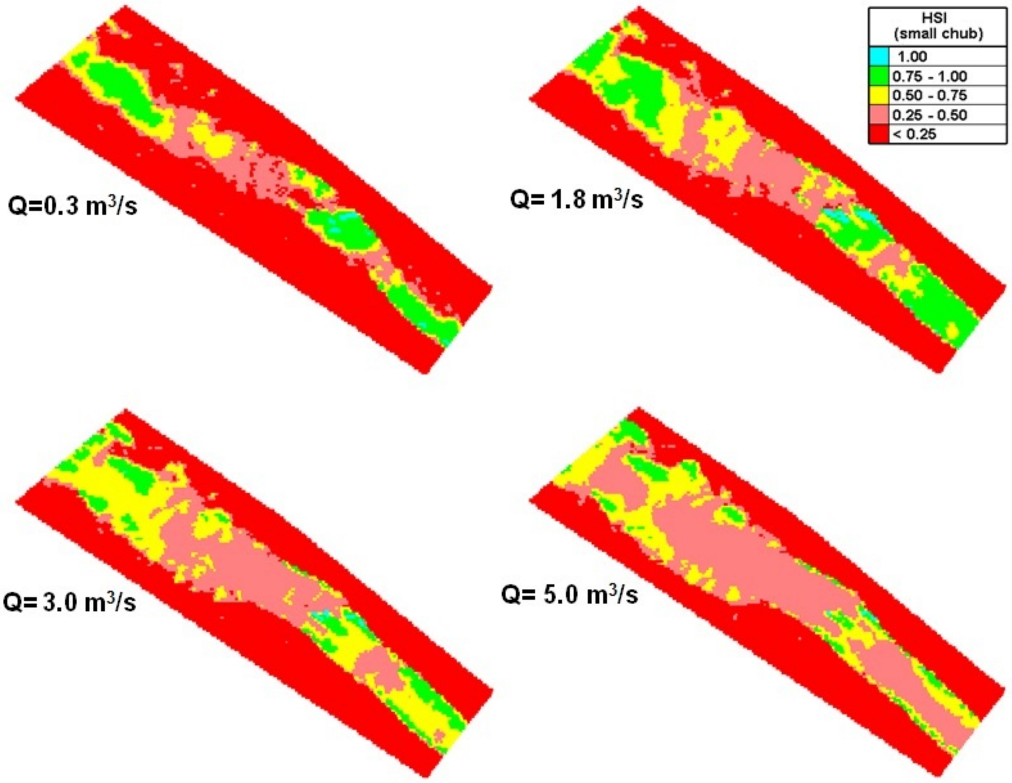


Fig.8. Calculated Habitat Suitability Index (HSI) for the small chub for various discharges Q=0.3, 1.8, 3.0 and 5.0 m^3/s.

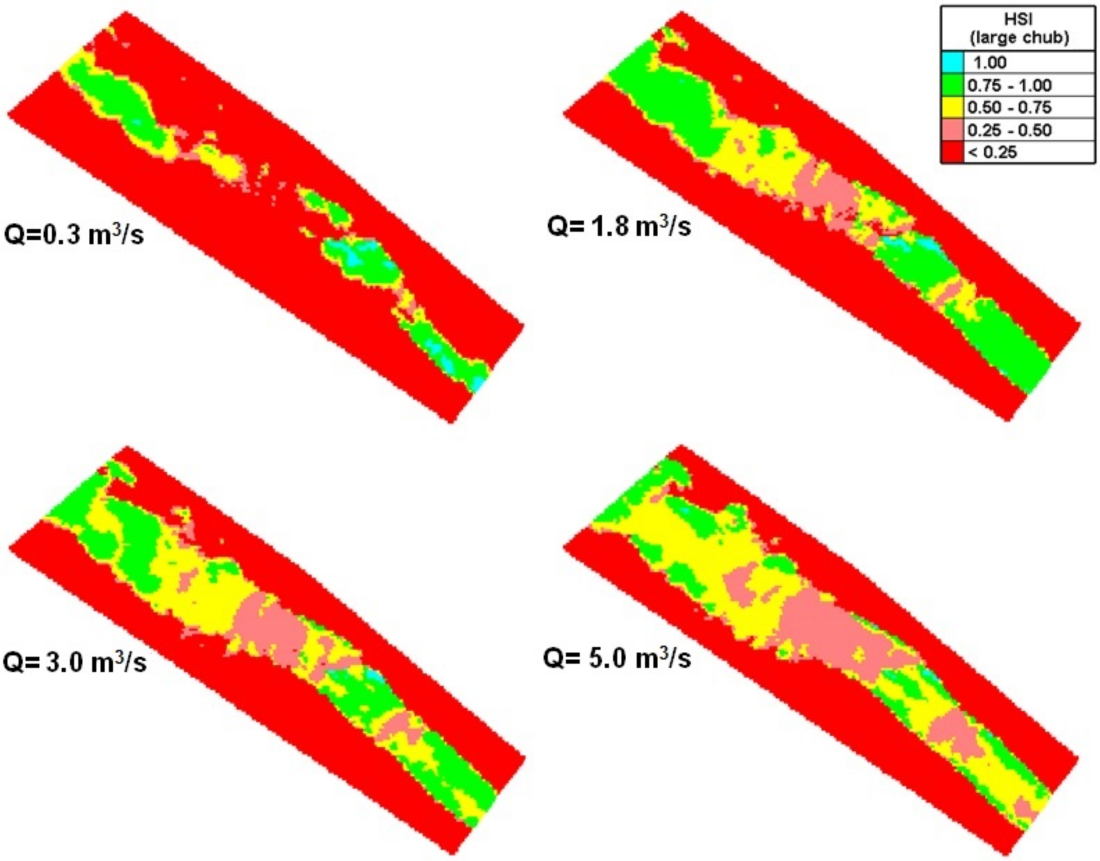


Fig.9. Calculated Habitat Suitability Index (HSI) for the large chub for various discharges Q=0.3, 1.8, 3.0 and 5.0 m^3/s.

3.1.4 Determination of the Weighted Useable Area -Discharge curve

In Fig. 10, the variation of the Weighted Useable Area (WUA) is shown, expressed in m^2 (left) and m^2/1000 m length of river (right) as a function of discharge (Q). Fig.10 indicates that the optimum range of discharge that satisfies most of the hydrodynamic requirements and provides the highest habitat availability is 2.0-4.0 m^3/s for the large Chub and 1.0-3.0 m^3/s for the small Chub. Higher or lower discharge values seem to have a negative impact on suitable habitat availability, while values above 10.0 m^3/s were not considered, since they are out of the usual discharge range in Sperchios River.

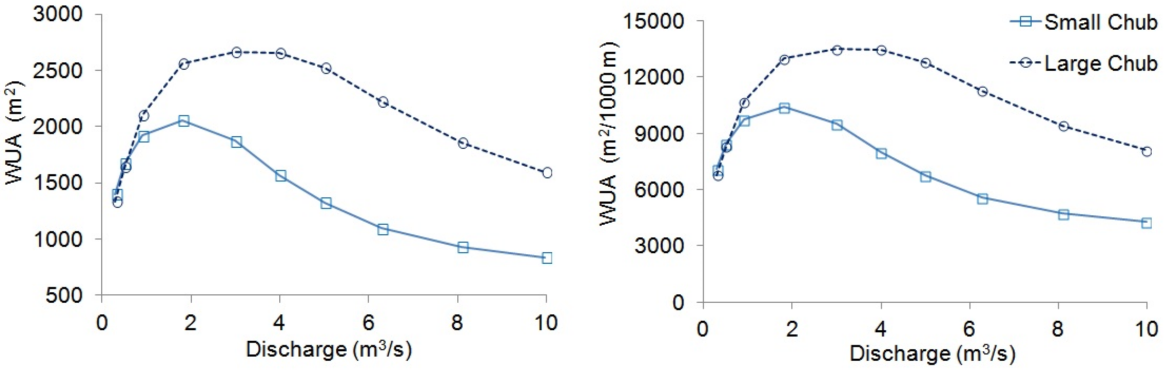


Fig. 10. The Weighted Useable Area (m^2 in the left and m^2/1000 m length of river in the right) vs. discharge (m3/s) curve.

3.2 Hydrological modelling

We applied the hydrological model MIKE-SHE to determine the time series of daily discharges for the natural flow regime, i.e. without abstractions for irrigation. The model has already been calibrated and applied in the calculation of the daily discharges for the current flow regime, i.e. including water abstractions for irrigation, by Mentzafou et al. (2017). The statistical characteristics of the discharge for the current and natural flow regimes are shown in Table 2.

Table 2. Statistical characteristics of the discharge (m^3/s) for the current and natural flow regimes.

	Current Flow Regime					Natural flow regime				
	Summer	June	July	Aug.	Sept.	Summer	June	July	Aug.	Sept.
Average	0.78	1.53	0.74	0.28	0.60	1.25	2.17	1.24	0.63	0.99
Median (Q_{50})	0.35	0.86	0.48	0.17	0.17	0.76	1.44	0.92	0.50	0.53
Maximum	23.69	23.69	19.77	22.73	13.47	24.87	24.87	22.47	22.85	13.62
Minimum	0.01	0.30	0.18	0.03	0.01	0.28	0.68	0.52	0.32	0.28
St. deviation	1.95	2.57	1.57	1.44	1.84	2.10	2.79	1.78	1.44	1.88
Percentile 25% (Q_{25})	0.17	0.54	0.34	0.12	0.08	0.51	1.01	0.73	0.44	0.38
Percentile 75% (Q_{75})	0.65	1.58	0.68	0.24	0.39	1.15	2.31	1.21	0.60	0.86

Table 2 depicts that for the natural flow regime, the median and average discharge values are equal to 0.76 and 1.25 m^3/s, respectively, while the corresponding values for the current flow regime are about 50% of the natural flow values. In August, which is the driest summer month, the median and minimum values for the natural flow regime are 0.50 and 0.32 m^3/s, respectively, while for the current flow regime they are equal to 0.17 and 0.03 m^3/s, respectively.

3.3 Calculations with the Global Environmental Flow Calculator

We applied the GEFC to determine the Flow Duration Curves that are plotted in Fig.11 and the percentiles (non-exceedance) values of discharges that are shown in Table 3 (values lower than 75% are shown in gray background); then, we combined the FDCs of Fig.11 with the WUA-Q curves of Fig.10 to construct the Habitat Duration Curves that are shown in Fig.12.

Fig.11 shows that the differences of the percentiles between the various Classes are less pronounced for discharges lower than 0.5 m^3/s and higher than 2.0 m^3/s, while for the range of discharges 0.8-1.5 m^3/s these differences increase with decreasing discharge. The 75%-percentiles (Q_{75}) are equal to 1.15, 0.96, 0.82, 0.70 and 0.51 m^3/s, for the natural flow regime and Classes A, B, C and E, respectively, while the median values are about 65-75% of their corresponding 75%-percentiles. Fig.12 shows how habitat availability (WUA) decreases as flow conditions deviate from “natural” to Classes A, B, C and E. Generally, Classes A and B are expected to maintain a relatively high level of habitat availability during most of the time, while Classes C and E offer significantly lower appropriate habitat area than the natural flow regime and Classes A and B.

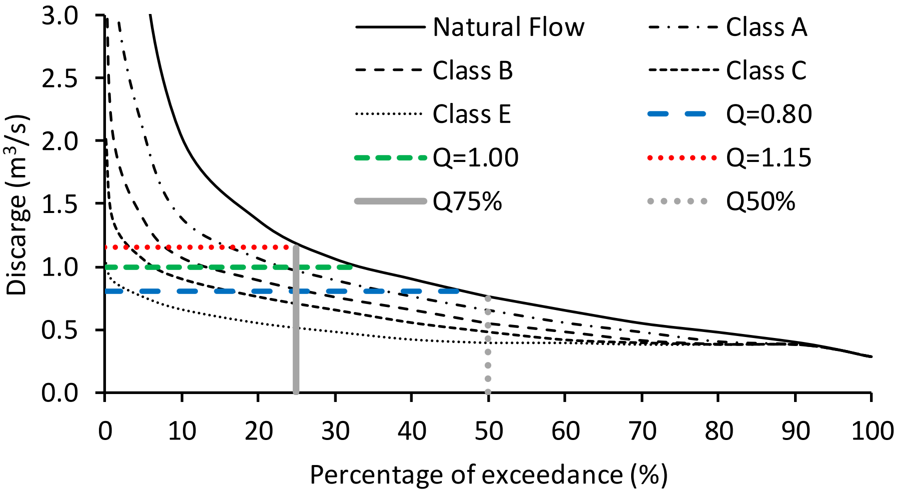


Fig. 11. Flow Duration Curves.

Table 3. Percentiles of discharges.

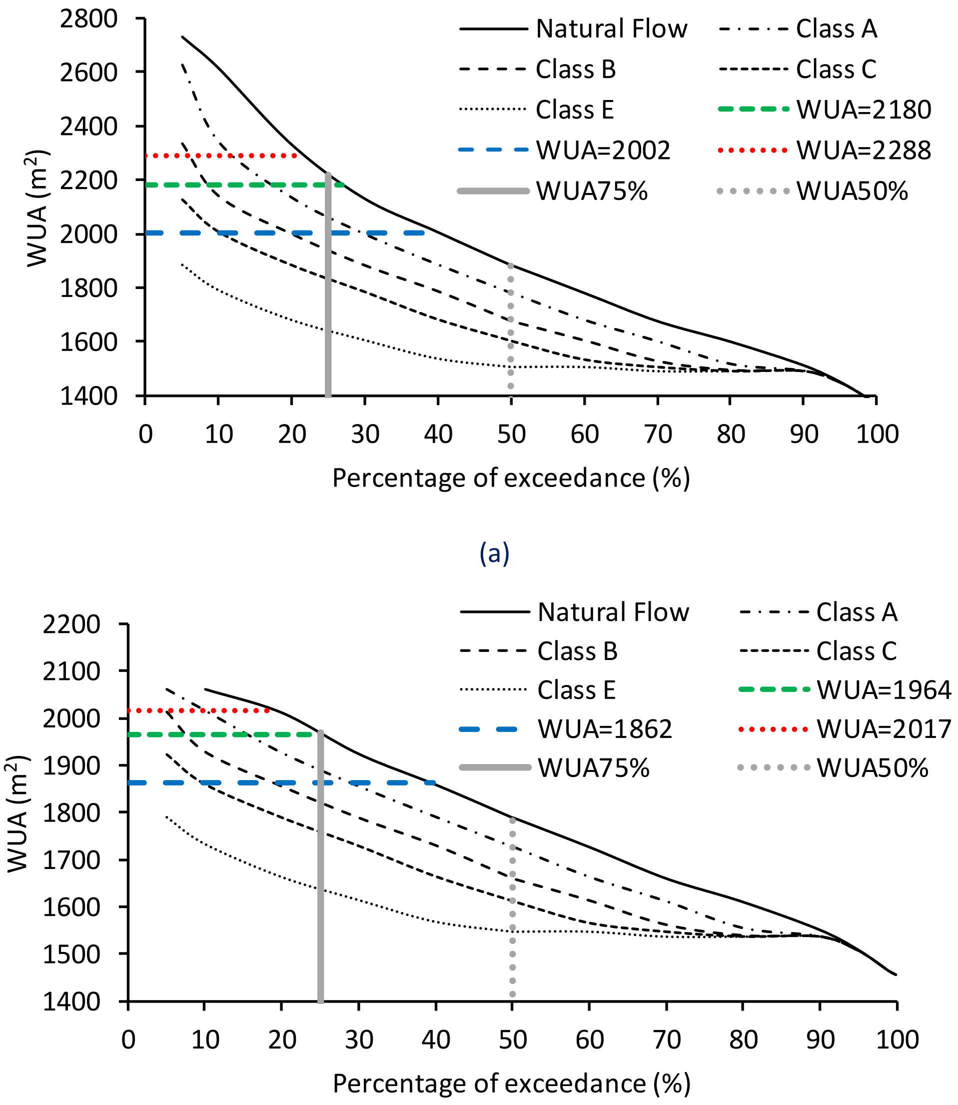
Q (m^3/s)	Natural flow	A Class	B Class	C Class	E Class
0.50	24.70	34.00	43.70	53.80	74.40
0.80	52.81	63.07	73.06	82.80	83.02
1.00	66.90	77.20	87.40	93.70	99.90
1.15	75.00	83.35	91.47	96.28	100.00
1.50	83.20	90.90	95.80	99.20	100.00
2.00	89.70	94.60	98.70	99.90	100.00
2.50	92.20	96.20	99.30	100.00	100.00
3.00	93.80	97.80	99.60	100.00	100.00

3.4 Estimation of the environmental flow-Discussion

Calculations with the HHM indicate an optimum range of environmental flow value that is equal to 2.0-4.0 m^3/s for the large Chub and 1.0-3.0 m^3/s for the small Chub (see Fig.10); the corresponding ranges of the WUA are equal to 2558-2661 m^2 and 1871-2058 m^2 for the large and small Chub, respectively. Therefore, based on the calculations of the HHM model, the environmental flow is ideally within the range 1.0-4.0 m^3/s.

As stated by the Greek legislation, the environmental flow is equal to 30% of the average summer discharge that is equal to 0.38 m^3/s or the 50% of the average discharge in September that is equal to 0.50 m^3/s. These values are significantly lower (even less than 10%) than the suggested range of values by the HHM. Also, the corresponding values of the WUA that are equal to 1334 and 1402 m^2, for the large and small Chub, respectively, are significantly lower than the optimum range of values predicted by the HHM and can be considered as unacceptable from the ecological point of view.

According to the calculations of the hydrological model, for the natural flow regime (see Table 2) the average and 75% percentile discharges in the summer period are equal to 1.25 and 1.15 m^3/s, respectively, while the minimum value throughout all months is about 0.30 m^3/s. In the current flow regime, the corresponding average and 75% percentile values are equal to approximately 60% of the natural flow regime values, while the minimum discharge may reach practically zero values (0.03 m^3/s) in August. Based on the hydrological calculations, it seems extremely difficult from the practical point of view to ensure an environmental flow rate that is higher than 1.0-1.5 m^3/s.



(a)

(b)

Fig. 12. Habitat duration curves for (a) the large Chub and (b) the small Chub.

The GEFC calculations for the range of discharges 0.5-3.0 m^3/s that are summarized in Table 3, show that an environmental flow rate in the range 1.00-1.15 m^3/s is generally satisfactory. The 75%-percentile for the natural flow conditions Q_{75}=1.15 m^3/s seems to be a very satisfactory choice of environmental flow, since it corresponds to percentiles 83.4 and 91.5 % of Classes A and B, respectively. This is supported by Table 4, in which the percentiles values of discharges and habitat availability (WUA) for discharges 0.80, 1.00, 1.15 and 1.50 m^3/s are shown (values lower than 75% are quoted in grey background). Table 4 depicts that the 75%-percentiles for Classes A and B are consistently higher than 87.6% for Q=1.15 m^3/s. Furthermore, the discharge of 1.00 m^3/s can also be considered as a satisfactory choice, since it corresponds to percentiles higher than 77.2% of Classes A and B for the discharge and higher than 83.5 % for habitat availability. While a discharge value of Q ¼ 1.50 m3/s would be a preferred choice from an ecological perspective, this cannot be practically achieved, based on the results of the hydrological modelling (see Table 2).

Table 4. Percentiles values of discharge and habitat availability

Dis-charge	Percentiles			Large Chub	Percentiles			Small Chub	Percentiles		
Q (m^3/s)	Natur. Flow	Class A	Class B	WUA (m^2)	Natur. flow	Class A	Class B	WUA (m^2)	Natur. flow	Class A	Class B
0.80	52.8	63.1	73.1	2002	60.3	71.1	81.6	1862	59.8	70.3	82.1
1.00	66.9	77.2	87.4	2180	71.9	83.5	90.7	1964	74.1	85.0	92.1
1.15	75.0	83.4	91.5	2288	77.6	87.6	94.1	2017	81.9	90.8	95.3
1.50	83.2	90.9	95.8	2467	85.5	98.1	98.1	2082	93.6	96.2	98.3

The above-mentioned discussion demonstrates that the selection of the “optimum” environmental flow is not an easy task, since many different parameters should be considered jointly, including the hydrodynamic characteristics of the river, the habitat availability, the abstractions for irrigation, and the legal constraints. In the present case, the hydrodynamic-habitat model alone suggests relatively high discharge values that cannot be practically achieved, based on the results of the hydrological model. Considering the relatively high accuracy of the hydrological and the hydrodynamic model, as evidenced by their satisfactory calibration, and the relatively lower accuracy of the habitat model, we chose the “optimum” environmental flow rate equal to 1.0 m^3/s for the following reasons. Firstly, this value satisfies the habitat requirements as expressed by the values of WUA that are equal to 2180 and 1964 m^2 for the large and small chub, respectively, and correspond to 82 and 95% and of their respective maximum values. Secondly, it is consistent with the requirements of the higher Environmental Management Classes A and B, whose percentiles are higher than 75% for both discharge (77.2%) and habitat availability for both large (>83.5%) and small chub (>85.0%); moreover, the values of the Habitat Suitability Index are also satisfactory. Thirdly, it is higher than the value proposed by the Greek legislation. Fourthly, it is practically achievable from the hydrological point of view, since the difference between the average discharge in the current flow regime and the proposed environmental flow (0.22 m^3/s), leading to a water deficit in the summer period of 2.8 x 10^6 m^3, which could, however, be covered by water from reservoirs, recycling or drainage reuse.

4 CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH

In this work, we presented the integrated modelling procedure 3H-EMC for the identification of ecologically optimal discharge ranges and the selection of the minimum acceptable discharge that satisfy ecological requirements based on habitat suitability, environmental criteria, the natural and anthropogenic hydrological water availability and legal constraints. From the application of the 3H-EMC in the Sperchios River in Central Greece, in which water abstractions for irrigation cause significant environmental impacts, we derived the following conclusions:

(1) To determine the "optimum" environmental flow; firstly, we calculated (a) the hydrodynamic characteristics and the habitat availability in the river with a hydrodynamic-habitat model, and (b) the natural and anthropological hydrological characteristics of the river with MIKE-SHE. Then, we combined these calculations with (a) the Environmental Management Classes A and B that represent unmodified and largely natural conditions of the river, which we estimated with the GEFC tool, and (b) the existing legal constraints.

(2) Calculations of the hydrodynamic-habitat model, in which the large and the small Chub are the main fish of interest, suggest values of discharges that range from 1.0 m^3/s to the relatively high value of 4.0 m^3/s. However, hydrological modelling indicates that it is practically difficult to achieve discharges that are higher than about 1.0-1.5 m^3/s. Furthermore, legislation suggests significantly lower values (0.4-0.5 m^3/s) that are unacceptable from the ecological point of view. This behavior shows that a non-integrated approach, which is based solely on a hydrodynamic-habitat model, does not necessarily result in realistic environmental flow rate values.

(3) We determined the environmental flow rate equal to 1.0 m^3/s, because this value satisfies the habitat requirements, it is consistent with the requirements of the Environmental Management Classes A and B, it is higher than the value proposed by the Greek legislation, and it is practically achievable from the hydrological point of view. The water deficit during the summer-dry period is expected to be covered by another water source, such as a reservoir and water saving measures.

For the formulation, calibration and validation of the process-based mathematical models of the 3H-EMC, we obtained field measurements and data in Sperchios river that we used together with other existing available data; generally, the quality of data can be characterized as satisfactory. The 3H-EMC can be applied to any river or stream by other researchers using other similar modelling tools and building the required algorithms for the coupling of the various modelling components. It is suggested (also, it is planned by the authors) to expand the present hydrodynamic-habitat model to include additional physical variables of the river that affect fish behavior, such as the type of the substrate, the cover-vegetation and the water temperature. Such variables are significant for the suitable habitat selection by fish and therefore they can affect the output of an environmental flow assessment study.

Moreover, additional fish species or even other important organisms can be included, such as macroinvertebrates (Theodoropoulos et al. 2015 and 2017), because the value of the environmental flow rate must satisfy the needs of all organisms that live in the river and only the requirements of just one species (Poff et al. 2010). In any case, the present effort is important for a Mediterranean river, such as Sperchios River, in which long-term data or environmental flow assessments are not available.

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