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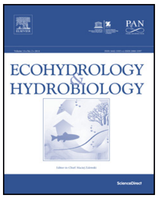

Original Research Article

Evaluation of ecological flows in highly regulated rivers using the mesohabitat approach: A case study on the Nestos River, N. Greece

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ABSTRACT

Preservation of a good ecological status in riverine habitats emerged as a priority for water management policies in Europe since the negative impact caused by the construction and operation of dams on the ecohydrology and habitat availability became more evident. Ecological flows, as reported in the recently published European guidance, represent a link between water and habitat EU Directives. This study presents the application of a mesohabitat simulation model (MesoHABSIM) to evaluate and quantify ecological flows in a highly regulated Mediterranean watershed (Nestos River, Northern Greece). Data collection was performed through GIS/GPS mapping surveys, hydro-morphological measurements (water depth, flow, substratum type, etc.) and electrofishing samplings at mesohabitat scale under different discharge conditions. In total, 81 hydro-morphological units were surveyed and 7532 fish samples were collected to develop habitat suitability predictions. Ecological flows were calculated in the range 10–15 m^3/s as the required discharge which assures the welfare and sustainability of protected fish species populations. In the lower course of the Nestos River habitat time-series indicated irrigation abstractions as a major stressor since summer was the period where habitat availability thresholds were mostly violated. Application of a revised water management plan is required for the downstream part of the Nestos River in order to maintain high ecological standards in the Natura 2000 sites of the Delta.

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1. Introduction

Since the global dam construction bloom in the 70s, riverine ecosystems experienced an unprecedented alteration of their flow regime, water quality and ecology (Rosenberg et al., 2000; Malmqvist and Rundle, 2002). Nowadays, there are more than 7000 major dams in Europe (EEA, 2007). Therefore, in semi-arid regions – as are Mediterranean countries – regulated basins endure a constant perturbation of their natural flow regime, according to irrigation and/or electric power needs and thus tend to be more vulnerable to extreme drought events (Gasith and Resh, 1999; Kondolf and Batalla, 2005). Furthermore, dams are responsible for disruption of hydrological continuity (Ward and Stanford, 1983), reduction of sediments deposition to the estuaries (Hupp et al., 2009) and alteration of water physicochemical features (Poff and Hart, 2002). The susceptibility of Mediterranean watersheds to water scarcity under a changing climate, as well as the unique biodiversity they support – 253 endemic fish species according to Cuttelod et al. (2008) – accentuate the need for water management actions toward a viable aquatic future.

In the context of the common European water policy, ecological (or environmental) flows gained a growing interest among water management specialists as a holistic approach that combines the applied hydrological and the ecological approaches into one (Zalewski, 2011, 2015) with regard to human activities in a watershed. Ecological flows is a term that describes ‘a hydrological regime consistent with the achievement of the environmental objectives of the WFD 2000/60/EC in natural surface water bodies’ (European Commission, 2015). The WFD requires EU Member States to maintain at least ‘good ecological status’ to the freshwater ecosystems and to confirm it by monitoring aquatic fauna and/or flora populations (Acreman and Ferguson, 2010). Therefore, ecological flows can be considered as a link between the WFD and the Habitats Directive 92/43/EEC, providing a multidisciplinary documentation of the ecological status of rivers, conformed to the actual status of hydrological networks in Europe. A long scientific discussion was triggered from the adoption of different approaches on interpreting the common acceptance that a minimum water quantity is essential to achieve sustainable freshwater ecosystems in regulated rivers.

The definition of ecological flows is today recognized as a valuable tool for the achievement of the ecological goals of European Directives and they should be assessed in an integrated way by considering hydrological, ecological, geomorphological and environmental elements of a watershed (DFO, 2013). Quantification of ecological flows can be carried out with numerous methods, each one involving hydrological assessment, riverine habitat analysis and expert opinion at a different degree (Jowett, 1997; Tharme, 2003; Acreman and Dunbar, 2004; Linnansaari et al., 2013). According to Annex V of the WFD, there are three elements that could be used to assess the ecological status of the surface water: the biological, the hydromorphological and the chemical/physical–chemical element (European Commission, 2000). These three elements are closely related since the last two elements support the first one (Navarro and Schmidt, 2012). Especially the hydro-morphological element is the one that mostly affects the integrity of the biological community since it is influenced by the quality and quantity of water (Karr, 1981). Therefore, due to the interconnection of these elements, the assessment of the water quality requires a synthetic approach, combining any two or even all of the above elements (Navarro and Schmidt, 2012; DFO, 2013).

Since current ecohydrological research in Europe suggests that both environmental and biological components of a riverine ecosystem should be considered to calculate ecological flows, a habitat simulation approach was implemented in the case of Nestos River. In this context, the quantification of the impact of a dam on the downstream part of a river requires the production of a habitat time-series corresponding to the upstream (reference conditions) and the downstream (altered conditions) section. Habitat simulation methods incorporate data on the fish fauna inhabiting a specific section of the river and the hydromorphological characteristics of the same section by considering the impact of the flow regime on them. Parasiewicz (2001) introduced an innovative habitat modeling method, which examines the riverine habitat at the mesohabitat scale and involves both biotic and abiotic components of the aquatic ecosystem, in a hydro-morphological comprehensive manner. This approach is known as MesoHABitat SIMulation Model (MesoHABSIM) and has been successfully implemented for river restoration planning (Parasiewicz, 2001, 2007b, 2008), fish fauna conservation (Parasiewicz et al., 2012; Vezza et al., 2015a) and ecological flow definition (Vezza, 2010; Vezza et al., 2012, 2017; Parasiewicz et al., 2016). To the purpose of ecological flows calculation, MesoHABSIM simulates the modifications occurring to the fluvial hydromorphology under multiple flow regimes and depicts a reference habitat which is shaped under particular flow conditions. The specific flow condition represents the ecological flows.

The aim of the present study was to quantify the ecological flows of River Nestos, a highly regulated river in North Greece. More precisely, the flow regime which supports a minimum required quality and quantity of habitat for fishes as well as its impact on their distribution across the examined river section, was researched. Lacking any fish reference habitat, we suppose that a fish species would occur in the river channel depending on field observation and authors' experience.

2. Materials and methods

2.1. Study area

The watershed of Nestos River is a transboundary basin extending from Rila Mountain (Bulgaria) to the Aegean Sea (Greece), with a surface of 5479 km^2 and traveling a distance river length of 234 km. In the Hellenic territory, Nestos Basin occupies 2843 km^2 and traverses 130 km through the Rhodope mountain range to the sea (Ganoulis et al., 2008). The use of water was regulated at an

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international level between Greece and Bulgaria following negotiations in 1975, 1982, 1988 and 1992, while in 1995 it was agreed that Greece would be entitled to use 29% of Nestos waters (Mylopoulos et al., 2004). The flow of the Greek part of Nestos River is regulated by two major hydropower dams (Thissavros and Platanovrisi) and a minor irrigation dam (Toxotes) located 30 km upstream its mouth. Nestos Delta and adjacent lagoons are included in the Natura 2000 Network, both as Special Protection Areas (SPA) and Sites of Community Importance (SCI), and are part of the East Macedonia & Thrace National Park. The Nestos basin is mostly mountainous; while its alluvial plain represents 18.2% of the total watershed area and is covered by arable agricultural land. The irrigation network is served by Toxotes dam and consists of two channels which distribute water to the east (11 m^3/s) and west (9 m^3/s) section of the plain (Kamidis, 2011). The minimum flow arriving to the Nestos Delta was established legally at 6 m^3/s, with the Common Ministerial Decision 16492/19.10.1996.

This study focused on a site 650 m below Toxotes dam which is representative of the downstream part of Nestos River (Fig. 1). This section of the river accumulates pressures from the operation of dams and endures stresses from agricultural abstractions. Moreover, the selection of this sampling site ensured that the hydromorphology of the surveyed downstream habitats was influenced exclusively from the function of Toxotes dam without other water gain or loss. Therefore, estimating ecological flows for this river section will permit to quantify the amount of released water that is required for the whole downstream area and the Delta.

2.2. Model theory

MesoHABSIM is a methodological approach that models fluvial habitats. It provides a habitat time-series analysis and predicts the magnitude and duration of stressful events for fluvial fauna, based on flow frequency patterns in different bioperiods (Parasiewicz, 2008). It computes habitat availability for selected species under variable flows or other environmental parameters. It is composed by three individual models (Parasiewicz, 2007a):

1. A hydromorphologic model that describes the fish-relevant physical features of the spatial environment.
2. A biological model describing the habitat use by the fish species.
3. A habitat model quantifying the amounts of habitat usage and relating it to flow.

The hydromorphologic model is structured for fast data collection compared to other habitat models (e.g. PHABSIM), and it is based on a robust hydromorphological classification of river systems (Belletti et al., 2017). This model quantifies biologically sound variables that were collected in the field and uses them as structural elements to describe different habitats.

For the development of the biological model, presence and abundance of fish species were estimated using conditional models, following the indications reported in Parasiewicz et al. (2013). In particular, information obtained from previous studies carried by the authors and from a literature review on the selected target species were used to select range of velocities, depths, substrate

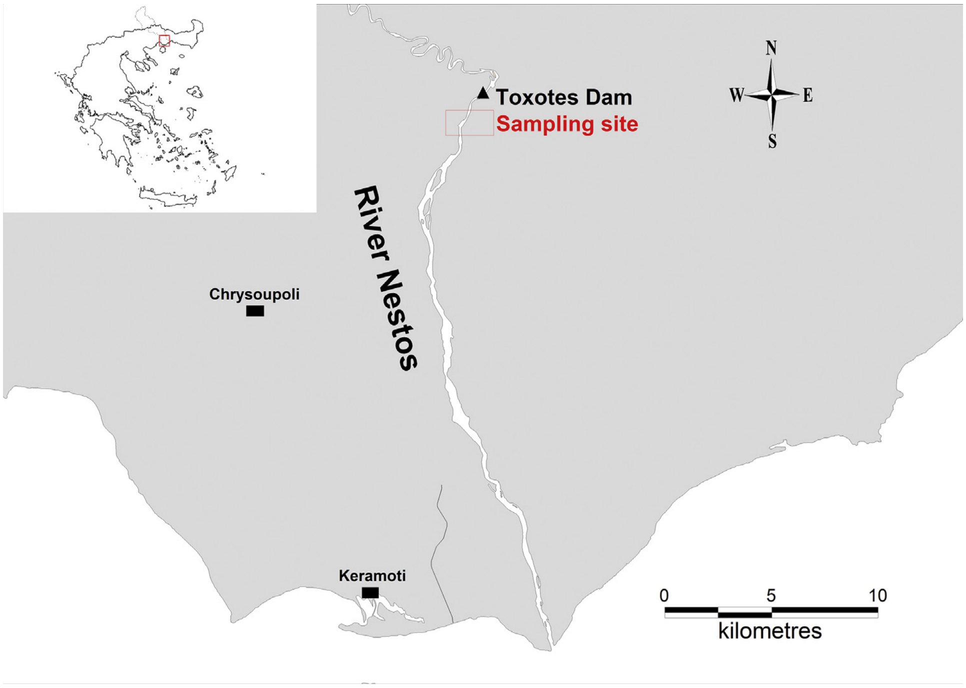

Fig. 1. Nestos Delta, the downstream part of Nestos River and its estuary in northern Aegean Sea; the dam of Toxotes, the sampling site and Natura 2000 sites are indicated.

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conditions and cover attributes that have been determined as adequate for the species presence and abundance (suitability HMU attribute values). When HMU attributes from the field surveys fall within the specified ranges of the developed suitability values, then the HMU was determined to be suitable (or optimal) for a particular species. An example of conditional models for selected target species are reported in Fig. 2 and, for clarity, depicted using decision trees. These conditional models, built for target species and life stages, were then validated by comparing their prediction with fish data collected in the field. This validation performance of the predictive models was evaluated using four performance metrics, i.e., accuracy, sensitivity, specificity, and true skill statistic (TSS), which are commonly used in ecological modeling (Vezza et al., 2015b). The latter (TSS) (Allouche et al., 2006) was used as performance metrics independent of model prevalence (Mouton et al., 2010).

Next, the habitat model analyzed how habitat suitability is affected by the river discharge. At this step, MesoHABSIM implements the Sim-Stream software running in QGIS (Zanin et al., 2016) to combine hydro-morphological data and biological models, and applies habitat time series analysis to calculate Uniform Continuous Under Threshold (UCUT) curves and to conduct habitat suitability predictions (Parasiewicz et al., 2013). This software facilitates data management by offering to its user a comprehensible interface in GIS environment.

Finally, in order to evaluate environmental thresholds, the magnitude, the duration and the frequency of low flow events were considered. UCUT curves represent projected contours of a habitat area in a three-dimensional space (x axis: frequency, y axis: duration and z axis: habitat area). They refer to a particular bioperiod and were implemented to examine the duration and frequency of continuous

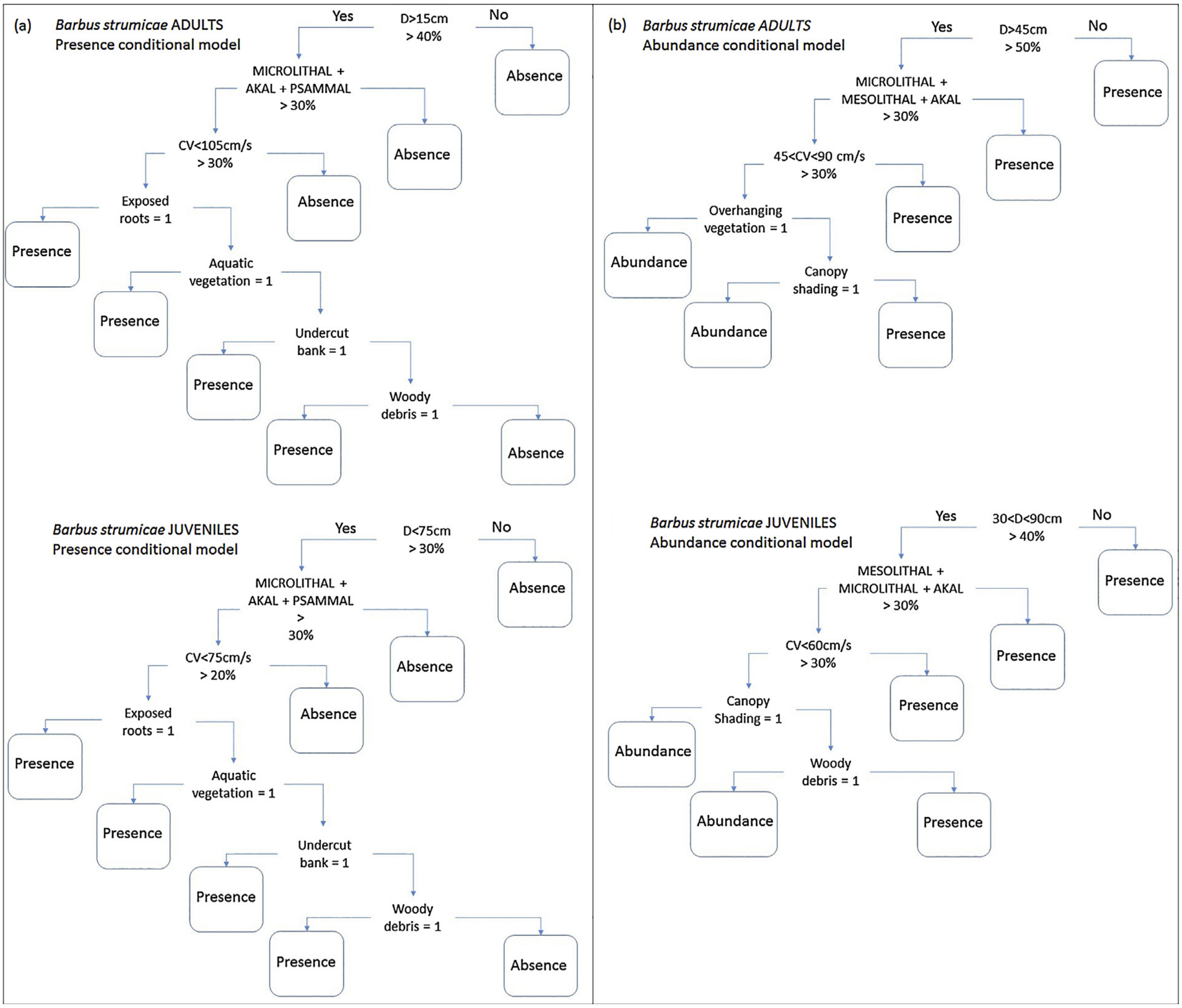

Fig. 2. Representation of conditional models predicting fish presence or abundance of *Barbus strumicae* using decision trees. In accordance with the MesoHABSIM approach two binary models were built: (a) presence/absence and (b) presence/abundance model.

events with habitat lower than a specified threshold. Thus, the total length of all events of the same duration within bioperiods was computed as a ratio of a total duration of all bioperiods in the record and the proportions are plotted as a cumulative frequency (Vezza et al., 2014).

As example of applications, the MesoHABSIM approach was used to identify the optimal flow for the protection of dwarf wedge mussel (*Alasmidonta heterodon*) in upper Delaware River (Parasiewicz et al., 2016) to model habitat requirements of bullhead (*Cottus gobio*) in Alpine streams (Vezza et al., 2013) and to model habitat availability in high-gradient streams (Vezza et al., 2014). Detailed information and functions of MesoHABSIM model can be found in Parasiewicz (2001, 2007a,b), and Vezza et al. (2014).

2.3. Data collection

The main purpose of the sampling effort was to examine the study area under different discharge conditions in terms of fish abundance, hydrological attributes, instream morphology and spatial extent. Thus, the application of MesoHABSIM required the collection of biological, hydrological and morphological data under different discharge values. However, abrupt, diurnal variations (Boskidis, 2011) of the discharge due to the operation of the hydropower dams imposed the samplings to be organized according to a range of discharge values (Table 1) instead of absolute values. Discharge measurements in the studied section of the river were conducted before and after each sampling in order to confirm that a specific discharge class was represented. In addition, discharge data was obtained from a water level sensor installed at the sampling area. This sensor was recording the water level every 15 min, so this dense flow time-series ensures that a specific discharge class per sampling effort was maintained.

The sampling site was divided to hydro-morphologically discrete subareas (geomorphic units, Belletti et al., 2017) for each discharge rate by considering flow velocity, depth and fluvial planforms (Table 2). Such unique instream subareas are documented as channel geomorphic units or hydro-morphological units (HMUs) and correspond in size and location to mesohabitats (Parasiewicz, 2007a; Belletti et al., 2017).

Collection of biological data was performed with a backpack electrofishing device (Hans Grassl, ELT60 IIHI). Electrofishing was selected as the most appropriate technique, since it is considered as an unbiased method and reduces fish sample mortality when correctly applied (IMBRIW, 2013). Biological sampling was organized per HMU and targeted four endemic fish species; the Strumica barbel (*Barbus strumicae*, Karaman, 1955), the Orpheus chub (*Squalius orpheus*, Kottelat and Economidis, 2006), the European bitterling (*Rhodeus amarus*, Bloch, 1782) and the Strymon spirlin (*Alburnoides strymonicus*, Chichkoff, 1940). The Strumica barbel and the European bitterling are included in the Habitats Directive 92/43/EEC and thus protected by European legislation. Electrofishing was performed in all HMUs, in an effort to identify all suitable habitats for the four aforementioned species and record the hydrological and morphological characteristics. All collected individuals were classified per species and their total length (TL, mm) was measured before being released back to the river.

Hydrological and morphological data were collected and recorded in a geodatabase by implementing mobile mapping techniques (Vezza, 2010). For the geodatabase recording, a mobile mapping system consisting of a laser rangefinder (LTI, Trupulse 360R), a rugged GNSS data collector (CHC, LT 500U) and a mobile geographic information system (GIS) software were used. This technique allows to its user to topographically define the sampled HMUs as polygon shapefiles on a map and to instantly register all the desired morphological parameters in their attribute tables. In total, 9 independent predictors were recorded in the field with regard to biological needs of targeted fish species (Table 3).

For each HMU the flow velocity (m/s) was measured in at least 10 points using a propeller flow probe (Global Water FP101 Flow Probe). At the same points the water depth and the substrate composition were recorded. Substrate ingredients were classified by granulometry

Table 1
The discharge classes at which the study area was sampled and the corresponding water level values provided by the Toxotes telemetric station.

	Discharge classes				
	1	2	3	4	5
Rated value (m^3/s)	5	12	22	32	42
Discharge range (m^3/s)	3–6	9–14	19–24	29–34	39–44
Water level range (m)	0.04–0.07	0.1–0.17	0.22–0.28	0.33–0.39	0.45–0.51

Table 2
Classification of HMUs according to their hydrological features and habitat features.

HMU type	Hydrological features		Habitat
Glide	Smooth flow, moderate to high velocity	Shallow to deep	Suitable for pelagic species with dynamic movement
Riffle	High velocity flow, intense mixing, surface ripples	Shallow	Suitable for dynamic, oxygen demanding species
Pool	Low velocity flow	Deep	Suitable for juveniles or as a refuge for most species under high discharge values
Backwater	Negligible flow velocity	Shallow	Suitable for juveniles in early life stages

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Table 3
Biological variables recorded in the sampling site for each HMU.

Variable	Type	Values	Brief description
HMU type	Categorical	Riffle, Pool, Glide, Backwater	Estimated according hydro-morphological features
Rocky banks	Logical	True/False	Presence of rock/boulders in riverbanks
Shading	Logical	True/False	Watercourse shading by riparian vegetation
Overhanging vegetation	Logical	True/False	Overhanging branches touching the water surface
Root systems	Logical	True/False	Presence of submerged root systems of riparian vegetation
Submerged vegetation	Logical	True/False	Presence of aquatic plants
Emerging vegetation	Logical	True/False	Vegetation emerging from wetted margins
Undercut banks	Logical	True/False	Eroded banks with obvious soil erosion
Woody debris	Logical	True/False	Woody debris transported by the river

measurements according to Hauer et al. (2006). Spatial and hydro-morphological information was further examined and organized with GIS software (QGIS Development Team, 2009) to produce detailed maps of the aquatic habitat in the study area.

Finally, a daily average discharge time-series from upstream and downstream of Toxotes dam was introduced to the model in order to simulate habitat alterations at the downstream part. This validated daily time-series for the period October 2006–May 2008 was provided by Boskidis et al. (2012). This time-series was the only available daily, continuous discharge dataset and included both yearly maximum and minimum discharge values observed in Nestos River. It also provides discharge values both for the upstream and downstream part of the Toxotes dam which is a prerequisite for describing reference and altered conditions.

3. Results

Overall, 81 mesohabitats were sampled during 18 surveys from May to September 2016. Samplings were conducted within a discharge value ranging from 5 to 42 m^3/s. The wetted area for the sampling site varied between 11,092.6 m^2 (5 m^3/s) and 22,308.7 m^2 (42 m^3/s) (Fig. 3). Generally, the prevalence of more dynamic hydro-morphological types (like glides and riffles) was obvious under higher discharges, while static types (pools and backwaters) were favored by lower discharge values.

Biological samplings produced a dataset of 7532 fishes, representing 13 species from 8 families. Cyprinidae was the most abundant family (6 species), while families of Anguillidae, Bleniidae, Cobitidae, Nemacheilidae, Percidae, Poeciliidae and Salmonidae were represented by a single species each. The most abundant species was *B. strumicae* (56.17%), while *Cobitis strumicae* and *A. strymonicus* were also common (17.68% and 13.38% respectively) (Table 4). Conditional models worked well to predict fish distribution (presence or abundance) showing an overall accuracy from 76% to 84% and a True Skill Statistics from 0.54 to 0.68.

Habitat suitability variation in terms of available, suitable and optimal habitat area is displayed in Table 5. This table considers the habitat extent as a percentage of the wetted area under the discharge class of 42 m^3/s which was the highest measured flow rate and related to the maximum wetted area (MWA) registered in the field. This analysis revealed an impressive increase of available, suitable and optimal habitat for almost all target species and age categories when discharge increased from 5 to 12 m^3/s.

More specifically, available habitat for both *A. strymonicus* juveniles and adults doubled (from 15.4 to 30.4% of MWA and from 16.8 to 31.8 of MWA respectively). Available habitat for *B. strumicae* juveniles also doubled (from 16.6 to 34.9% of MWA), while it dramatically increased for *B. strumicae* adults (from 8.6 to 44.7% of MWA). Equally, *R. amarus* – which was examined as a single age class – experienced an important increase of habitat (from 17.3 to 23.8% of MWA). Respectively, available habitat for *S. orpheus* juveniles nearly doubled (from 15.6 to 26.5% of MWA), while it vastly augmented for *S. orpheus* adults (from 8.7 to 35.2% of MWA).

As discharge increased from 12 to 22 m^3/s the available habitat increment continued, but at a less pronounced rate. As discharge continued to rise (>22 m^3/s) the amount of available habitat reduced for most species. Some exceptions to these trends were observed in suitable habitat figures (e.g. reduction of suitable habitat for juvenile *A. strymonicus* and *B. strumicae* adults) but they represent a minor proportion and the described trend is considered as dominant.

Since this study was conducted under multiple discharge classes, a range of ecological flows values was determined for Nestos River. These flow ranges satisfied the requirements of all four target species by shaping a suitable habitat. Minimum ecological flows were defined within the area of the habitat/flow rating curve (Fig. 4) where species habitat curves deflected (Gippel and Stewardson, 1998). As shown by the habitat/flow curve, with the exception of adult *S. orpheus* and adult *A. strymonicus* curves whose deflection points are located within the range of 20–25 m^3/s, curves of *B. strumicae*, *R. amarus* and juveniles of all target-species displayed a deflection point within the range from 10 to 15 m^3/s. Below 10 m^3/s the available habitat for all target-species vastly reduced. These findings are highly supported by the increase of habitat for fishes revealed in Table 5 and show that the maximum deviation in terms of habitat events below threshold was related to the ecological flows.

MesoHABSIM plotted the changes occurring in the available habitat over time which were examined by interpreting discharge (Fig. 5) and habitat (Fig. 6) time-series for all target species. Habitat analysis at below threshold discharge values for Nestos River (e.g. $Q_{97} = 10.79\ m^3/s$) for both reference (upstream) and

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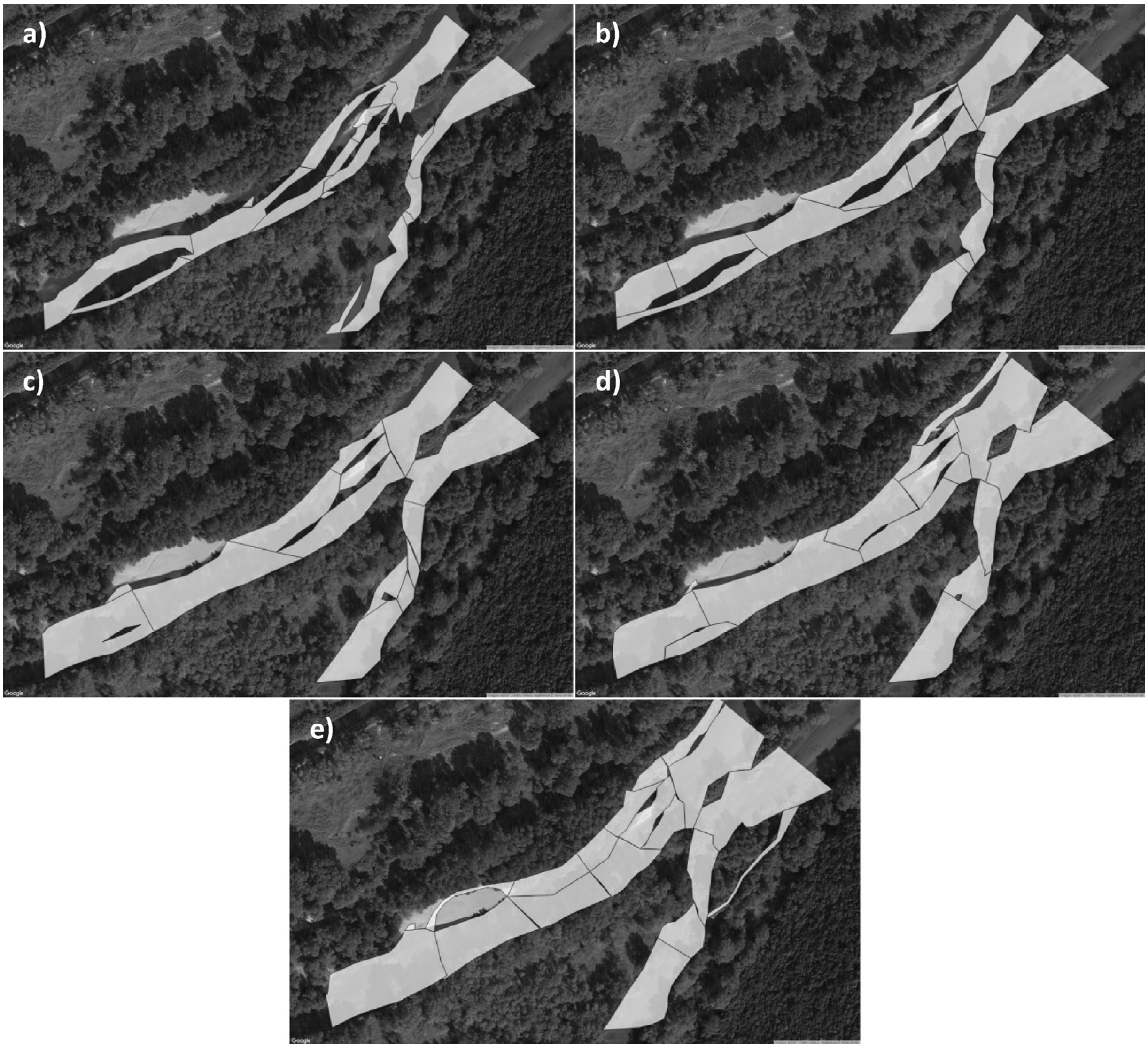

Fig. 3. Variation of wetted area in the sampling site under (a) 5 m^3/s, (b) 12 m^3/s, (c) 22 m^3/s, (d) 32 m^3/s and (e) 42 m^3/s.

Table 4
Analysis of the fish fauna samples collected during the sampling period downstream Toxotes Dam, and age composition for target-species (indicated with *).

Species	Sample size	% of total	Adults (%)	Juveniles (%)
*Barbus strumicae**	4232	56.17	55.39	44.61
*Squalius orpheus**	429	5.70	49.18	50.82
*Rhodeus amarus**	243	3.23	93.83	6.17
Cobitis strumicae	1332	17.68	–	–
Chondrostoma vardrense	40	0.53	–	–
*Alburnoides strymonicus**	1008	13.38	95.04	4.96
Perca fluviatilis	14	0.19	–	–
Gobio vulgaricus	27	0.36	–	–
Salaria fluviatilis	49	0.65	–	–
Oxynoemacheilus bureschi	150	1.99	–	–
Anguilla anguilla	1	0.01	–	–
Oncorhynchus mykiss	6	0.08	–	–
Gambusia holbrooki	2	0.03	–	–
Total sample size	7532	100	–	–

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Table 5
Analysis of habitat suitability for all target species under multiple flow regimes as a percentage of maximum wetted area, indicated with bold fonts.

Discharge (nominal) (m^3/s)	Wetted area (m^2)	*A. strimonicus* (juvenile)	*A. strimonicus* (adult)	*B. strumicae* (juvenile)	*B. strumicae* (adult)	*R. amarus*	*S. orpheus* (juvenile)	*S. orpheus* *(adult)*
		Available habitat (% maximum wetted area)						
5	11,092.6	15.4	16.8	16.6	8.6	17.3	15.6	8.7
12	15,275.4	30.4	31.8	34.9	44.7	23.8	26.5	35.2
22	17,812.5	35.7	52.7	35.0	47.0	20.1	23.9	51.6
32	20,052.5	24.6	50.5	28.6	49.4	19.2	28.3	49.9
42	**22,308.7**	13.1	41.8	18.1	47.7	11.5	12.5	47.2
		Suitable habitat (% maximum wetted area)						
5	11,092.6	10.1	3.8	11.4	27.5	10.1	29.3	24.1
12	15,275.4	4.9	21.3	32.9	13.3	23.2	24.2	2.4
22	17,812.5	27.6	0.0	47.1	23.1	57.2	66.5	0.4
32	20,052.5	30.0	4.7	45.3	7.2	64.2	56.7	12.2
42	**22,308.7**	7.6	51.4	24.0	49.5	37.2	12.3	46.2
		Optimal habitat (% maximum wetted area)						
5	11,092.6	17.1	21.1	18.3	2.3	19.7	11.1	3.6
12	15,275.4	38.8	35.3	35.6	55.2	24.0	27.3	46.1
22	17,812.5	38.3	70.3	31.0	54.9	7.8	9.6	68.7
32	20,052.5	22.8	65.8	23.1	63.5	4.2	18.9	62.4
42	**22,308.7**	14.9	38.7	16.1	47.0	2.9	12.6	47.5

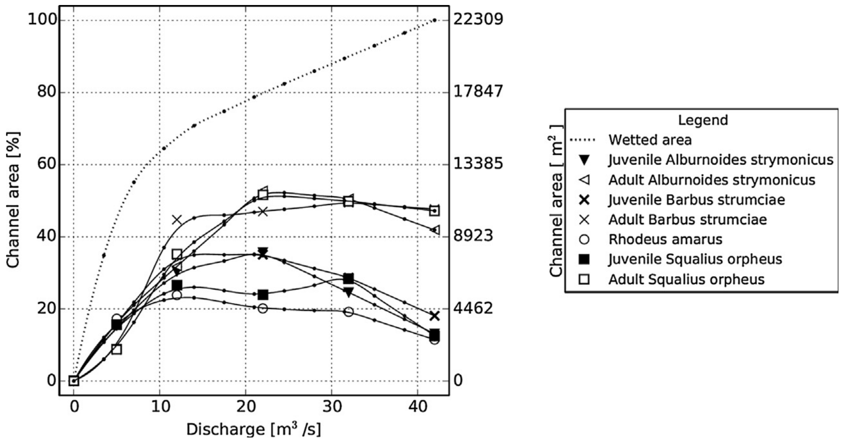

Fig. 4. Variation of total available wetted area (%) per discharge class and available habitat (%) per species for the whole fish community.

altered (downstream) conditions was performed in terms of available habitat under threshold (AQ_{97} in m^2). To this purpose, Uniform Continuous Under-Threshold (UCUT) curves for reference and altered conditions were created and the habitat Stress Days Alteration index (iSDA) was calculated to indicate the increase of habitat stress days. In this study Q_{97} was selected as a threshold for rare habitat events (minimum amount of available habitat), since it was the rare habitat threshold that better separates rare events from most persistent and common ones (Parasiewicz et al., 2013) and it represented the minimum ecological flow rate selected to maintain fish populations in the river.

The habitat threshold for juveniles *A. strymonicus* related to low discharge in reference conditions (Q_{97}) was $AQ_{97} = 6132.6$ m^2. The habitat stress days variation, expressed as iSDA was 0.44, indicating an increase in the number of habitat stress days up to 44% due to the function of the dam. The habitat threshold for *A. strymonicus* adults related to low discharge in reference conditions (Q_{97}) was $AQ_{97} = 6514.1$ m^2. The habitat stress days variation, expressed as iSDA was 1.6, indicating an increase in the number of habitat stress days up to 160%. The habitat threshold for juveniles and adults *B. strumice* related to low discharge in reference conditions (Q_{97}) was $AQ_{97} = 6984.8$ m^2 and 8399.2 m^2, respectively. For both age categories the habitat stress days variation, expressed as iSDA was 0.46, and 1.26, respectively, indicating an increase in the number of habitat stress days up to 46% for juveniles and 126% for adult individuals. Similar information can be extracted from the UCUT curves of *S. orpheus* and *R. amarus*. More specifically, for *S. orpheus*

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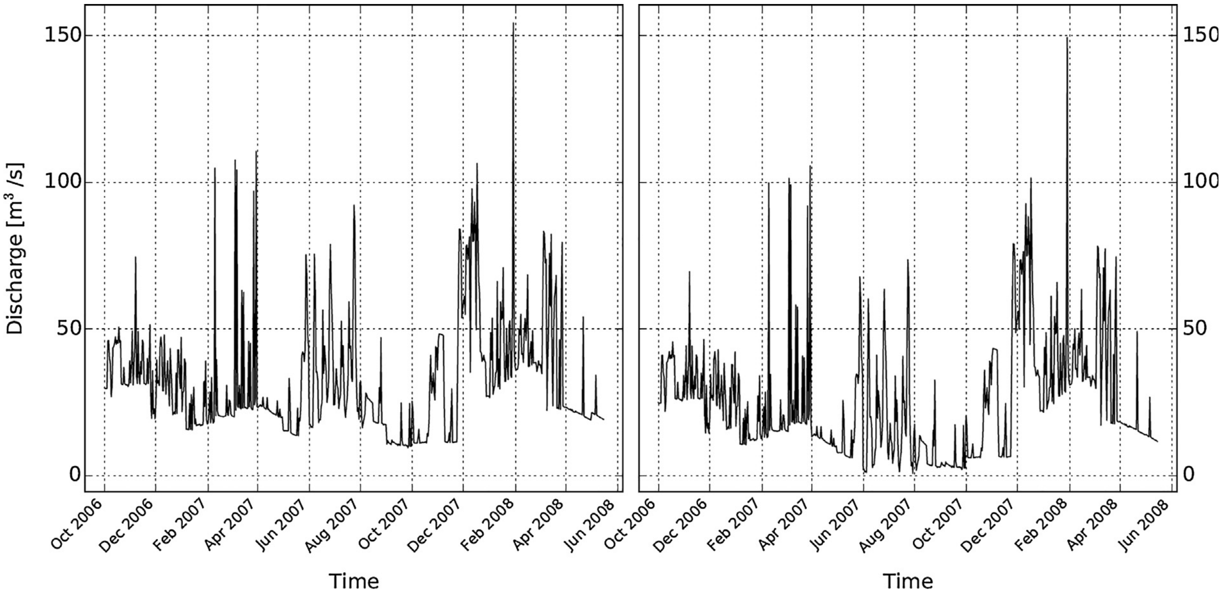

Fig. 5. Daily average discharge time-series of Nestos River from October 2006 to May 2008 provided by Boskidis et al. (2012); on the left are reference conditions (upstream Toxotes dam) and on the right are altered conditions (downstream Toxotes dam).

juveniles and adults, the habitat threshold related to low discharge in reference conditions (Q_{97}) for juveniles and adults was measured at $AQ_{97} = 5432.1\ m^2$ and $6752.8\ m^2$, respectively, while the habitat stress days variations (iSDA) were found at 0.67 and 1.6, indicating an increase in the number of habitat stress days up to 67% for *S. orpheus* juveniles and 160% for adults. Finally, the habitat threshold for *R. amarus* (one age class) related to low discharge in reference conditions (Q_{97}) was $AQ_{97} = 5012.7\ m^2$. The habitat stress days variation, expressed as iSDA was 0.66, indicating an increase in the number of habitat stress days up to 66%.

4. Discussion

This study examined the ecohydrological status of Nestos River in Northern Greece by attempting an innovative evaluation of the ecological flows. The results showed a seasonal problem to maintain an adequate flow and habitat for fishes during low discharge events as a result of irrigation water abstractions in the alluvial plain. A flow of at least $10\ m^3/s$ downstream the Toxotes dam is suggested, in order to achieve a sustainable ecosystem, and meet the standards established by the WFD. Habitat time-series analysis showed that fishes in the downstream part of the river experienced more stress days (ranging from 44 to 160% more) due to the function of the Toxotes dam. The most affected species seemed to be adult *A. strymonicus* and adult *S. orpheus* (iSDA = 1.6).

Mesohabitat survey was carried out using the MesoHABSIM approach and the hierarchical morphological unit classification (Belletti et al., 2017) was the key-element in order to describe how the habitat is currently varying with flow. The assessed habitat conditions were used as a reference over time. More dams and more water abstractions are currently planned in the upstream part of the Nestos catchment and these new water uses will affect both the hydrological regime and the morphological river characteristics (Aristeidis and Konstantinos, 2013). River Nestos already narrowed and deepened in the last few decades due to large dam contractions (less sediment available for downstream reaches leaded to channel degradation (Wohl et al., 2015)). Therefore, the data collected in this study constitute a crucial starting point, to monitor future morphological changes in terms of distribution and extent of geomorphic unit distribution and the related habitat availability. The mesohabitat approach therefore can fit with the developed WFD methodologies for river hydromorphological assessment and monitoring and can provide good evaluation of habitat quality over time and over morphological river modifications (Rinaldi et al., 2015).

In addition, habitat suitability models developed in this study can be the starting point of a large application of the MesoHABSIM model at the national scale. Further hydromorphological surveys, fish data collection, suitability model validation is indeed needed to understand the level of habitat alteration in Greek rivers. Indeed, there is the need to test the transferability potential of the developed conditionals models for fish is real, in order to produce mesohabitat suitability models that can be applied at a catchment or at a regional scale (Vezza et al., 2014).

From a methodological point of view, the MesoHABSIM approach demonstrated its flexibility to be applied in large braided rivers, providing reliable and quantitative information on the real habitat available for the fish fauna in the studied reach.

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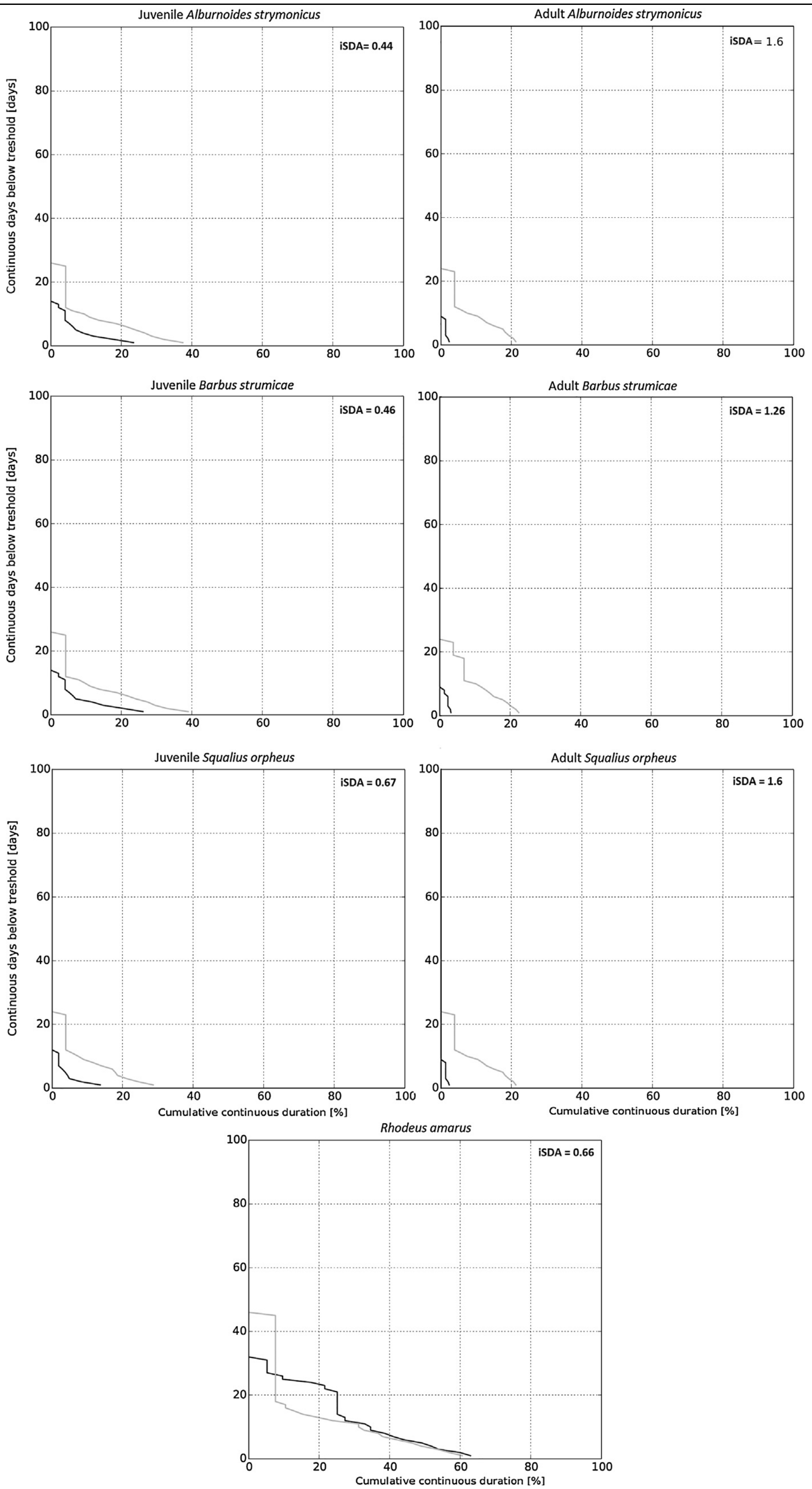

Fig. 6. UCUT curves representing the alteration of habitat for target species for periods below discharge threshold (Q_{97}) – iSDA represent the average increase of habitat stress days and thus compare reference (black line) and altered (gray line) conditions.

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The WFD requires a synthetic approach for the conservation of the aquatic systems while the Habitats Directive 92/43/EEC requires the existence of specific environmental conditions for the protection of aquatic species (EEA, 2010, 2012). One of the required conditions is to maintain specific water flow conditions in order to safeguard species habitats, since the over-abstraction of water reduces the available amount of water for the species to sustain healthy populations and thus to the reduction of the biodiversity (EEA, 2010). One method that allows to comply with these two Directives is the determination of the ecological flows, which according to DFO (2013) is defined as "the flow regimes and water levels required to maintain the ecological functions that sustain fisheries associated with that water body and its habitat".

5. Conclusions

In the current study, a multidisciplinary analysis of the ecohydrological status of a 4th class was performed, on a highly regulated Mediterranean river in terms of habitat availability for fishes in its downstream section. A habitat simulation approach was adopted to quantify variations of habitat and to finally suggest a minimum ecological flow which will ensure the viability of fishes' populations. To attain this goal, the modernization of the existing irrigation network by establishing an underground irrigation system in the whole alluvial plain is imperative to adapt to a reducing water budget. Efficient practices in irrigation (e.g. drop irrigation) should expand across Nestos alluvial plain and, if necessary, cultivated crops may change to less water demanding species. As it concerns the upstream part, the construction of the regulatory dam of Temenos could reduce the negative impact of hydropeaking to downstream habitats by releasing water in a smoother way. Ultimately, the water management plan should be revised by a committee of scientists, stakeholders and authorities and applied with respect to the European obligations and rationalized stakeholders needs.

The transboundary status of Nestos basin complicates decision-making for water management. In this framework a closer cooperation between the two countries is of high importance and the application of the same methodology to the Bulgarian part of the river would allow the definition of the ecological flow in the whole river basin.

Further research should focus on the simulation of a different ecohydrological status in Nestos River by considering the construction of a regulatory dam, the modernization of irrigation network and the application of efficient irrigation techniques under the pressure of a declining water budget. Moreover, the impact of stressors on habitat should be assessed in terms of severity of low discharge events. Thus could be assessed the sustainability of a new water management plan by meeting the WFD requirements for instream habitats.

Conflict of interest

None declared.

Ethical statement

Authors state that the research was conducted according to ethical standards.

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