Environmental Processes
https://doi.org/10.1007/s40710-020-00456-1

ORIGINAL ARTICLE

Estimation of a Suitable Range of Discharges for the Development of Instream Flow Recommendations

Christina Papadaki[1] · Konstantinos Soulis[2] · Vasilis Bellos[3] · Lazaros Ntoanidis[4] · Elias Dimitriou[1]

Received: 14 February 2020 / Accepted: 17 July 2020/Published online: 26 July 2020

Abstract

Hydrological variability is of great importance for water resources management. Regardless of how rivers are individually managed, numerous research studies have concluded that aquatic organisms are highly dependent on flow regime variability. Nevertheless, natural streamflow regimes are being altered due to human-induced pressures and climate change/variability, and sufficient biological information in not incorporated in efforts to minimize these effects. Thus, there is an urgent need to develop sustainable environmental flow management guidelines to manage the risk associated with alterations to the flow regime particularly in areas where flow-ecology relationships have not been well studied. This study focuses on a stream with high natural flow regime variability, typical in Mediterranean countries. The major finding of this work is that the estimated Suitable Range of Discharges (SRD) could better address environmental water requirements, rather than simply allocating single value minimum ecological flows. SRD was estimated using advocate statistical analysis of hydrological data series, coupled with habitat suitability models to balance the trade-offs between natural flow variability and human water needs. Combination of the aforementioned approaches was made using the West Balkan trout as a biological component which is a very important species for the quantification of environmental flows. Overall implementation of SRD during dry season is likely to provide large habitat areas for 58 to 67% of the time for the small-size fish and 35 to 55% of the time for the large-size West Balkan trout, according to the Weighted Usable Area$_{0.5}$ threshold index.

Keywords Suitable Range of Discharges · Aquatic habitat · Streamflow · Variability

✉ Elias Dimitriou
elias@hcmr.gr

Extended author information available on the last page of the article

Abbreviations

1D-SWE	1D Shallow Water Equations
D	Depth (m)
FDCs	Flow Duration Curves
GVF	Gradually varied flow
HSI	Habitat Suitability Index
PPC	Public Power Company of Greece
W. B. trout	Salmo farioides (Karaman, 1938)
SRD	Suitable Range of Discharges
TL	Total Length
WSE	Water Surface Elevation
V	Water velocity (m/s)
WUA	Weighted Usable Area index
$WUA_{0.5}$	Weighted Usable Area threshold index

1 Introduction

The hydrologic regime is a key element in determining river processes. Hydrological variability is one of the main issues that should be considered for appropriate water resources management practices, without compromising the sustainability of vital ecosystems (Li et al. 2015; Tonkin et al. 2014, Kuriqi et al. 2019). Aquatic biota relies on the flow regime variability. Due to flow regime changes, there is an increasing risk of community collapse and alterations in key ecosystem processes such as nutrient uptake and transformation, organic matter processing, and ecosystem metabolism (Palmer and Ruhi 2019). The movement of water and sediment within the channel and between the channel and floodplain enhance inputs and downstream export of terrestrially derived carbon to rivers but, when associated with sustained hydrologic connectivity with soils, exert particular influence on water chemistry and biogeochemical processes that can influence food webs (Zeiringer et al. 2018).

All flow regime components including floods, medium and low flows are important and influence the river ecosystems (Acreman 2016; Acreman and Dunbar 2004; Poff et al. 2006; Naiman et al. 2008). However, natural streamflow regimes are changing due to human-induced pressures and climate change/variability (Oo et al. 2020), while the applied environmental flows, in most cases, do not incorporate sufficient biological information.

Specifically, river flow alterations could be due to flow regulation by dams, water abstractions, land use changes and climate change/variability. Moreover, river straightening for flood control and/or navigation purposes, morphological alterations, and the disconnection of flood plains are all hydromorphological pressures (Fehér et al. 2012) that alter the natural flow regime of rivers. With so many competing needs for water, there is an urgent need to develop sustainable environmental flow management guidelines to manage the risk associated with alterations to the flow regime (European Commission 2015), especially in areas where flow-ecology relationships have not been well studied.

River water allocation designated for environmental uses can be either flow remaining in the river protected from abstraction, or actively released water from storages to achieve desired ecosystem targets. In a number of cases, oversimplified general rules such as minimum flow requirements (Ahmadi-Nedushan et al. 2006), have been adopted for defining allowable degrees of hydrologic alteration, based on legislative and regulatory framework. Although these methods provide general guidelines, they do not provide a sufficient framework, which can ensure the biological integrity.

In Mediterranean countries, such as Greece, minimum environmental flows are derived as a proportion of the natural flow regime (Muñoz-Mas et al. 2016; Papadaki et al. 2016), based on simplified hydrological methods (De Jalón 2003; Principato and Viggiani 2009; Official Journal of the Hellenic Republic 2011).

The main objective of this study is the estimation of a Suitable Range of Discharges (SRD) that could better address freshwater needs embedded in the Anthropocene and improve water related management practices by providing a range of suitable discharges associated with the corresponding suitability ranges that the managing authorities can work with rather than simply allocating a minimum low flow. SRD is estimated using statistical analysis on hydrological simulated data series and habitat suitability models. Specifically, the focus of this study, is on low-flow periods under which the physical instream habitat is usually bounded. Combination of the aforementioned approaches was made using the West Balkan trout (*Salmo farioides*, Karaman 1938; hereafter W.B. trout) as biological component. Single-species oriented studies have been increasing in the last 5 years (Siddig et al. 2016). W.B. trout was selected as an indicator species of the stream reach for its strophic role and conservation issues. More specifically: this fish species is an important indicator for mountain rivers; it dominates upland cold-water rivers and streams (Economou et al. 2007); it is endemic in the upland streams of the southwestern Balkans (Kottelat and Freyhof 2007); and it is assessed as a vulnerable species (Zogaris et al. 2009). Furthermore, salmonids play a crucial role in cold-water food webs and in the generation of ecosystem services (Schindler et al. 2010) and potential effects of hydrological alteration may affect their habitats (Almodóvar et al. 2012).

In this study, the development of suitability habitat curves is made for two sizes (small-size 5-15 cm Total Length (TL), and large-size > 15 cm TL) of the W.B. trout. Then, physical habitat simulation approach is implemented for the quantification of the fish habitat requirements for thirteen discharge scenarios that were selected from daily simulated hydrological timeseries representative of unimpacted conditions. Simulated streamflow series are analyzed to identify potential changes that would reveal influence from land use changes, climate change/variability etc. For the estimation of the number of days per month these discharges appeared in the simulated timeseries, flow duration curves are incorporated. Finally, the suitable range of discharge is estimated and compared with current Greek legislative framework and low flow indices. SRD is an innovative approach proposed for the development of instream flow recommendations that may better address the instream requirements of aquatic biota especially in rivers with high natural flow variability.

2 Materials and Methods

2.1 Study Area and Fish Community

Habitat mapping procedures (Dolloff et al. 1993) involving discrimination of habitat types at a river segment of 1.5 km in the upper part of Acheloos river (Fig. 1) were applied to select a representative river reach of 200 m during low flow conditions (i.e., summer 2016). The study site is located in Mesochora at 670 m a.s.l., (39.479443°N, 21.326510°E, WGS84). The

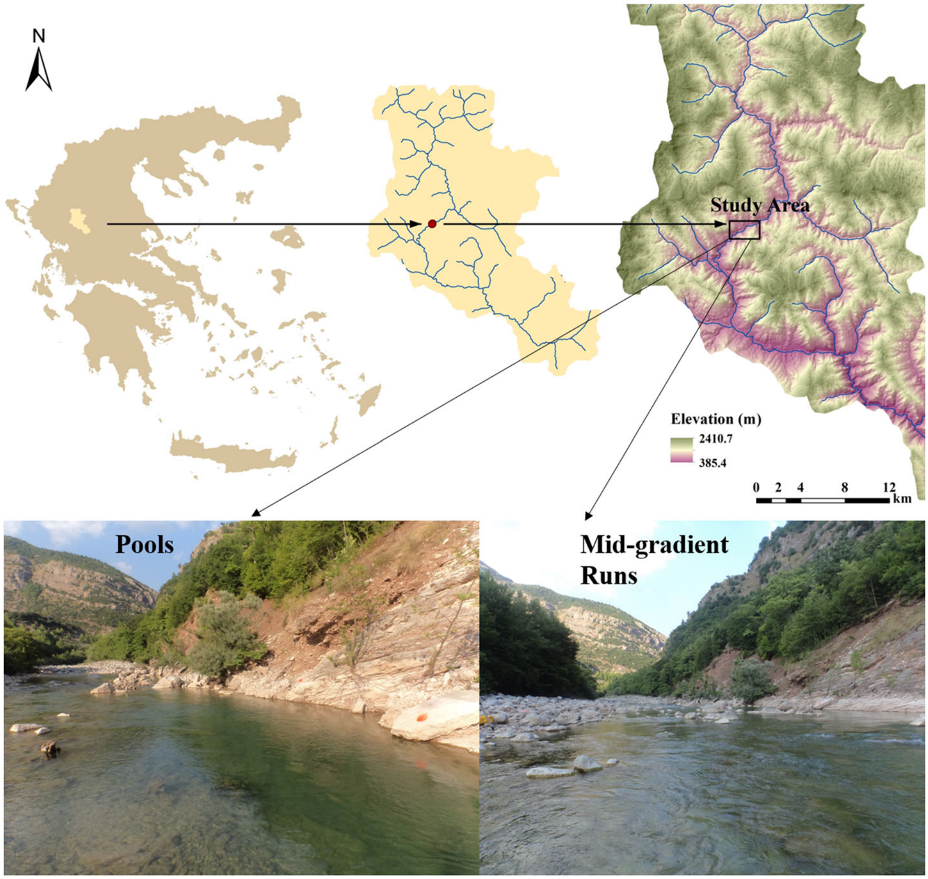

Fig. 1 Study area, watershed, the stream network, and photos from the dominant hydromorphological units (mid-gradient runs and pools) located at the central western mountainous region of Greece

watershed of Mesochora has an area of 632.8 km^2, while its mean annual discharge is 25.3 $m^3 s^{-1}$. The mean annual precipitation in the watershed is about 1898 mm and it mostly falls in the wet period between October and April. The hydrology of the watershed is controlled by snowfall and snowmelt processes, with peak and low flows typically occurring during May and September, respectively.

Typical habitat types are mainly mid-gradient runs and pools (7–12 m wetted river width in summer). Substrate types are mainly cobbles, boulders and gravel. The most common fish species in the river are *Salmo farioides (Karaman, 1938), Barbus peloponnesius (Valenciennes, 1842), Telestes pleurobipunctatus (Stephanidis, 1939), Squalius peloponensis (Valenciennes1844), and Luciobarbus albanicus (Steindachner, 1870). Salmo farioides* (hereafter W.B. trout) is a common native fish species in the Upper Acheloos River and was selected as an indicator species of the stream reach, as it is at the top of the trophic pyramid (trout, barbell, salmon). Moreover, it is assessed as vulnerable in a state-wide, "Red List" conservation status evaluation (Zogaris and

Economou 2009). Two sizes of the W.B. trout were studied: small-size 5–15 cm Total Length (TL), and large-size > 15 cm TL.

2.2 Habitat Quantification and Suitability Curves development

Habitat simulation methods are commonly used for the estimation and quantification of species available habitat. These methods employ hydraulic parameters (depth, velocity, etc.) to define suitable conditions and the water requirements for specific aquatic species. Habitat Suitability Index (HSI) models in the form of univariate curves for depth and velocity were developed to estimate the habitat availability of two size classes of the W.B. trout as indicator species to provide a starting point for biologically sound rules for environmental flow assessment.

Several instream flow studies use univariate depth and velocity suitability curves developed independently by either fitting polynomial regression functions (2nd up to 10th order) to habitat use data according to procedures outlined by Bovee (1986) or use functions in R (R Development Core Team 2015) that fit curves to the input data using polynomials (Theodoropoulos et al. 2019). In this study, microhabitat use fish data were collected from a representative river reach. Microhabitat data were collected during three field campaigns under summer conditions (July 2015, Discharge = 2.1 m^3/s; July 2016, Discharge = 3 m^3/s; and August 2016, Discharge = 1.7 m^3/s) using electrofishing.

Moving in a zigzag pattern from downstream to upstream, all types of available fish habitats were sampled with a modification of the equal effort approach (Bovee et al. 1998). To minimize disturbance, sampling locations were spaced approximately 5 m apart, to avoid fish disturbance. Stunned fish were identified to species level, measured for TL and returned alive to the stream. A total of 144 observations of W.B. trout (65 small and 79 large specimens) were recorded along the study reach. At each microhabitat, two variables were recorded: water velocity, water depth. Water velocity (V, m/s) and depth (D, m) were measured using a propeller current meter (OTT®). For water depths less than 1 m, mean velocity measurements were carried out using the 0.6-depth method, an observation of velocity made in the vertical at 0.6 of the depth below the surface. For water depths higher than 1 m, mean water velocities were estimated by averaging measured velocities at 0.2 and 0.8 of the depth below the water surface. The analysis of the collected data was implemented in R (R Development Core Team 2015), and habitat suitability curves were developed using the *smooth.spline* function which fits smooth curves to the input data using 3rd-order polynomials. Each polynomial allows for a turn within the adjusted curve to be coherent with the ecological gradient theory (Austin 2007). Habitat Suitability Indices (HSI) are dimensionless and they take values from zero to one. The closest to one the better the suitability of the examined hydraulic parameter.

Hydrodynamic model outputs were converted to HSI. Afterwards, a composite suitability index was estimated, for thirteen discharge scenarios, decisive for instream habitats during low flow conditions, ranging from 0.5 to 18 m^3/s, to result in a final threshold index called Weighted Usable Area ($WUA_{0.5}$). The difference between WUA and $WUA_{0.5}$ index is that the $WUA_{0.5}$ represents only the suitable conditions for the target species.

$WUA_{0.5}$ was calculated according to Bovee et al. (1998):

$$\mathrm{WUA}_{0.5} = \sum\nolimits_{i=1}^{n} AiCi$$

where n = total number of grid cells, *Ci* is the composite HSI for values higher than 0.5, and *Ai* is the cell area (m^2). $WUA_{0.5}$ was calculated for thirteen discharge scenarios, and the WUA–discharge curve was obtained. The discharge corresponding to the maximum $WUA_{0.5}$ is regarded as the optimum flow. The outputs, in the form of $WUA_{0.5}$ − Discharge curves for W.B. trout, were used to derive an optimum Suitable Range of Discharges (SRD). More specifically, initially we estimated the discharges for which the corresponding $WUA_{0.5}$ values were at least 70% of the maximum value of both sizes of the W.B. trout, and secondly, we estimated the number of days per month these discharges appeared in the simulated timeseries.

2.3 Hydrodynamic Modelling

Hydraulic variables are integrated with biological requirements, using habitat suitability curves, to quantify habitat availability, which is expressed at the reach scale with the Weighted Usable Area (WUA). The Weighted Usable Area (WUA), as described below, is a well-known general indicator of habitat quality and quantity (Bovee et al. 1998). The required input for the estimation of the Weighted Usable Area is the spatially distributed water depths and flow velocities in a river reach. The derivation of these hydraulic variables can be achieved by using 1-D hydraulic models, with which mean values of the aforementioned hydraulic variables for each cross-section of the reach are calculated, and then, the spatial distribution is performed using an interpolation method (pseudo-2D approach), or by using directly 2-D hydrodynamic models. Both methods have advantages and disadvantages (Benjankar et al. 2015; Crowder and Diplas 2000; Hauer et al. 2013; Boskidis et al. 2018; Papadaki et al. 2017a; Papaioannou et al. 2019). HEC-RAS (Version 4.1) was used here to perform a pseudo-2D hydrodynamic simulation for 15 discharge scenarios. The software solves the Energy equation for steady and gradually varied flow (GVF) using the standard step iterative procedure and the 1D Shallow Water Equations (1D-SWE) for unsteady flow. In the current study, HEC-RAS was used to derive Water Surface Elevation (WSE) profiles, assuming steady flow condition.

To account for the pseudo-2D hydraulic simulation, every cross section was subdivided into a number of cells both in the main channel and the overbank area. The number of cells was primarily a function of the number of water velocity measurements and substrate variation along the cross sections. For every cross section a single water stage was simulated by the standard solving procedure, while velocities were calculated separately for each cell for the simulated water stage (procedure described in details in HEC-RAS v4.1; Hydraulic Reference Manual 2010; Papadaki et al. 2017a).

For the hydrodynamic modelling, the 200 m river reach was divided in 12 cross sections based on changes in longditudinal bedslope and reach geometry. Furthermore, each cross-section was subdivided in 6 to 9 cells and velocities were calculated separately for each cell for the simulated water stage. An indicative figure of the velocity distribution for 5 m^3/s flow is depicted at Fig. 2. Friction losses were calculated using Manning's equation. The Manning roughness coefficients for every cross section were selected according to the characteristics of the riverbed based on literature (Barnes 1967; Chow 1959; Cowan 1956). Furthermore, roughness coefficient was horizontally varied to account for substrate variation. The values of Manning coefficient ranged from 0.04 $s/m^{1/3}$ to 0.07 $s/m^{1/3}$. Due to the topography of the channel and the flow order of magnitude, the flow was found to be subcritical in the whole length, and so, boundary conditions were set only at the downstream cross section using the normal depth.

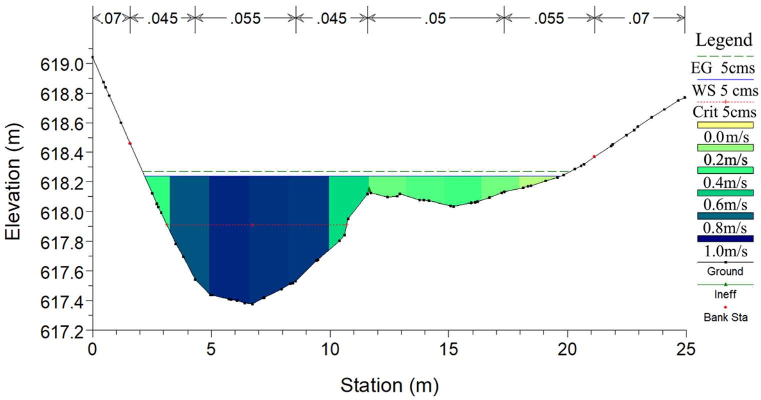

Fig. 2 Velocity distribution for 5 m^3/s flow using the pseudo-2D approach

Several simulations were performed in order to estimate the $WUA_{0.5}$ in relation to discharge. Therefore, for each steady-state simulation, we used different discharge values as input to the hydraulic model, covering the range from 0.7 m^3/s to 18 m^3/s.

2.4 Methods Used for Ecologically Targeted Environment Flows

2.4.1 Seasonal Flow Regime Analysis

Flow regime analysis was made using Flow Duration Curves (FDCs) developed from daily hydrological modelled data. Within the study area, there is limited hydrological information from gauging stations representing unaltered regimes. Simulated streamflow time series representative of minimally impacted (e.g., historic) conditions, for the period 1986 to 2004, were used as the hydrologic baseline (reference period) due to limitations in meteorological data availability in the study area. The required meteorological daily time series were only available from 1983 to 2004, but the three first years were used as the warm up period of the model. Optimally, a 30-year reference period is required in order to consider the potential impact of longer shifts in weather conditions; however, daily streamflow records for a period of about 20 years (measured or simulated) may adequately capture the natural interannual temporal variability of flow conditions (Sanford et al. 2007; Mathews and Richter 2007; Monk et al. 2007). More details about the hydrological modelling outputs (e.g., calibration and validation of the model) have been presented in previous studies (Papadaki et al. 2016, 2017b). In the current analysis, the data corresponding to the low flow period (dry season, e.g., June to October) were used. The flow duration curves are developed for each month (June, July, August, September and October) of the dry season and for the entire dry season (by using all the daily values of the dry season).

Moreover, a statistical test (Mann Kendall) was applied to investigate trends in daily streamflow for the study area and the examined period. The particular test was implemented using the R package Exploration and Graphics for RivEr Trends (EGRET; Hirsch and De Cicco 2015) for the estimation of a trend slope expressed in percent for the examined period of each year, and a p-value for the Mann-Kendall trend test. The slope was computed using the

Thiel-Sen slope estimator. The p-value for the Mann-Kendall test was estimated using the adjustment for serial correlation introduced in the Prewhitened Nonlinear Trend Analysis Package (ZYP); R package, (https://rdrr.io/cran/zyp/). Finaly, the Q95 flow was selected and compared with a Suitable Range of Discharges (SRD) as a significant low flow parameter particularly relevant to the assessment of ecological flows (Overton et al. 2014).

2.4.2 Suitable Range of Discharges (SRD)

The methodological approach followed for the Suitable Range of Discharges (SRD) estimation is presented in Fig. 3. Thirteen discharge scenarios, ranging from 0.5 to 18 m^3/s decisive for instream habitats during low flow conditions (June to October), were selected from the examined seasonal period (season consisting of the months June to October; for the years 1986 − 2004), based on daily hydrological simulated data series using the Soil and Water Assessment Tool (SWAT; Arnold et al. 1998; Papadaki et al. 2016). $WUA_{0.5}$ index was estimated for the monthly median values of the aforementioned period. Data were analyzed

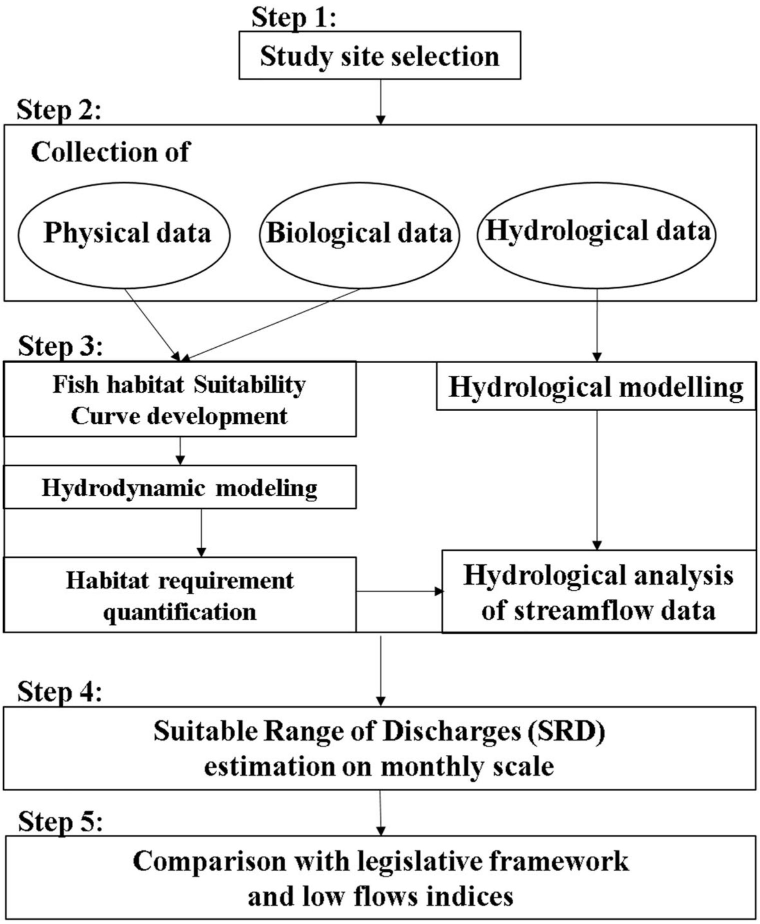

Fig. 3 Methodological approach applied for the estimation of the Suitable Range of Discharges (SRD)

using analysis of linear models in the R Statistical Package (R Development Core Team 2015). $WUA_{0.5}$ – Discharge relation curves were developed for both sizes of the W.B. trout (Fig. 4).

The Suitable Range of Discharges (SRD) was estimated (Table 1), according to the specific fish species habitat requirements. Specifically, we considered a SRD according to $WUA_{0.5}$ values that are at least 70% of the maximum value of both sizes of the W.B. trout, concluding to a range of 3 to 9 m^3/s (Fig. 4). Subsequently SRD was compared with current Greek legislation demands regarding to ecological flow rules (Muñoz-Mas et al. 2016).

2.4.3 Methodology Limitations

Unfortunately, due to time and resource limitations, it was not possible to measure and incorporate diverse aquatic ecosystems, riparian vegetation, fluvial geomorphology, and groundwater contribution in overall flow allocation. The methodology presented is based on limited historical hydrological data. Furthermore, physical habitat models are expensive to implement and typically describe only a short length of stream. Future studies should incorporate more habitat requirements of instream organisms. Complementarity studies of single species and ecosystem-based research, to promote increased and more systematic links between the two kinds of approaches are necessary to enhance our understanding of the river functionality (Lindenmayer et al. 2007).

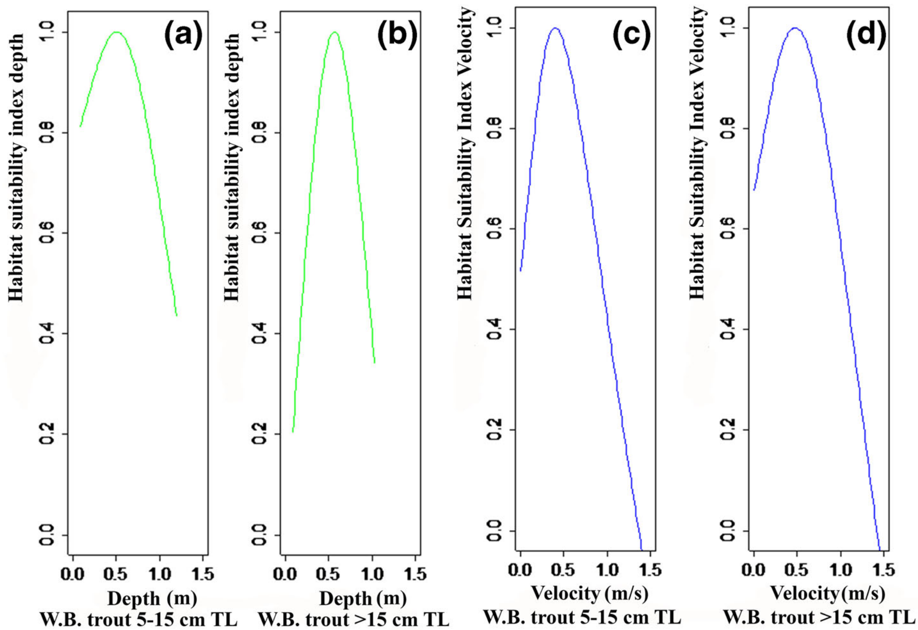

Fig. 4 Habitat suitability use curves for depth (left) and velocity (right), small-size 5-15 cm Total Length (TL) (**a**, **c**), and large-size > 15 cm TL (**b**, **d**) of W.B. trout, based on *smooth.spline* function implemented in R (R Development Core Team 2015), Upper Acheloos River

Table 1 Descriptive statistics for the examined period 1986 to 2004, which were simulated at the study site

Months	Medians	Coefficient of dispersion	Min	Max
June	7.3	0.9	5.1	37
July	4.7	0.5	3.3	24.5
August	3.1	0.7	2.2	19.2
September	2.3	1.2	1.7	27.1
October	3.9	1.9	1.3	156.2

3 Results and Discussion

The integration of habitat and hydrodynamic models involving $WUA_{0.5}$ determination have proved to be useful tools in the assessment of ecological flows. This study focuses on those streams with high natural flow regime variability such as the ones in Mediterranean countries (Trigo et al. 2004).

3.1 Habitat Suitability Curves

The habitat suitability curves for water depth are depicted in Fig. 4a (small-size W.B. trout) and Fig. 4b (large-size W.B. trout), and for velocity in Fig. 4c (small-size W.B. trout) and Fig. 4d (large-size W.B. trout). Small W.B. trout occupied locations with relatively small depth values (0.2 to 0.6 m) and medium velocities (0.3 to 0.6 m/s). Large W.B. trout occupied locations with higher depth values (0.3 to 0.8 m) and relatively higher velocities. In an effort to simplify the estimation of SRD, and avoid uncertainty resulting from misrepresented substrate and cover conditions, as in other studies (Ayllón et al. 2012), these conditions were not included as components of habitat suitability. Furthermore, the use of cover in such models is neglected because it is difficult to quantify the refuges or the instream areas where fish can hide from predators (Wilding et al. 2014). Thus, Habitat Suitability Curves were developed only for the parameters of depth and velocity.

Additionally, the weighted usable area ($WUA_{0.5}$) for each size class of the W.B. trout is presented in Fig. 5. Different $WUA_{0.5}$ −Discharge curves for each W.B. trout size were developed, since the different sizes have different habitat requirements (represented by different habitat use suitability curves). The $WUA_{0.5}$ of the small W.B. trout is considered acceptable at discharges between 2 and 11 m^3/s and peaks above 5 m^3/s, while the $WUA_{0.5}$ of the large W.B. trout is considered acceptable at discharges between 3.5 and 15 m^3/s and peaks above 6.7 m^3/s. The $WUA_{0.5}$ value for both W.B. trout sizes increase with flow rapidly, until the stage where the curve slope smoothes out and the $WUA_{0.5}$ curve eventually reaches the maximum value.

3.2 Hydrological Analysis Results

The monthly flow duration curves, for each month of the dry season and for the entire dry season for the examined period 1986 to 2004, were developed based on the daily simulated streamflow time series, due to availability limitations in historical hydrological information. More specifically, only a two-year period (October 1986–September 1988) of historical streamflow time series provided by the Public Power Company of Greece (PPC) was available

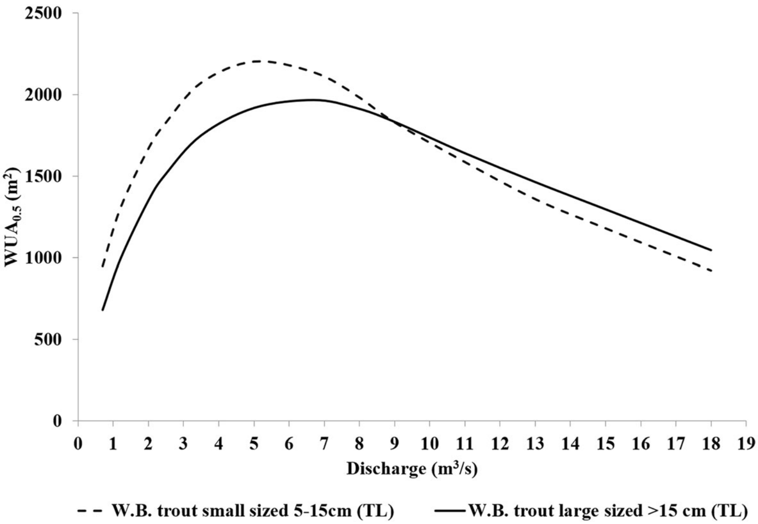

Fig. 5 $WUA_{0.5}$ for small-size 5-15 cm Total Length (TL), and large-size > 15 cm TL W.B. trout

and was used for the calibration and validation of the hydrological model that was used for the generation of a longer period synthetic streamflow data series representing minimally impacted conditions in the study area. This period was considered sufficiently representative of long-term conditions for the present study (Kennard et al. 2010).

General descriptive statistics of the study area are presented in Table 1. The Coefficient of dispersion was calculated as (75th percentile − 25th percentile) / 50th percentile.

In Fig. 6, the dots indicate the dry season median discharge of each year in the period of record. The dry season consists of the months June, July, August, September, and October. The slope of the trendline was estimated as 1.1% per year and the p-value for the Mann-Kendall trend test of the data was 0.576. In accordance with Yue and Pilon (2004), there is no statistical evidence for trend at any part of the examined flow range since the p-value is close to 0.5. Therefore, there is no clear evidence of alteration due to external interactions (climate change/variability, land use changes etc.), and the simulated timeseries can be considered representative of low impacted flow conditions.

3.3 Suitable Range of Discharge

As can be seen in Fig. 7, the shape of the obtained flow duration curves (FDC) is smoother and generally flat in the low flow region for the summer months (June, July and August) indicating that the watershed is able to sustain large base flow for most of the summer period, while flood events have a short duration and are not so frequent. On the other hand, the FDCs obtained for September and October are much steeper, especially for October. This observation indicates that the watershed illustrates a high flow variability in these particular months. Furthermore, as can be seen in the same figure, low flows are reducing from June to October. The flow duration curve for the entire dry season presents a mixed picture incorporating the different characteristics of the monthly FDCs. The difference of the shapes of the FDCs developed for each month of the dry season highlights the temporal variability in the flow conditions that

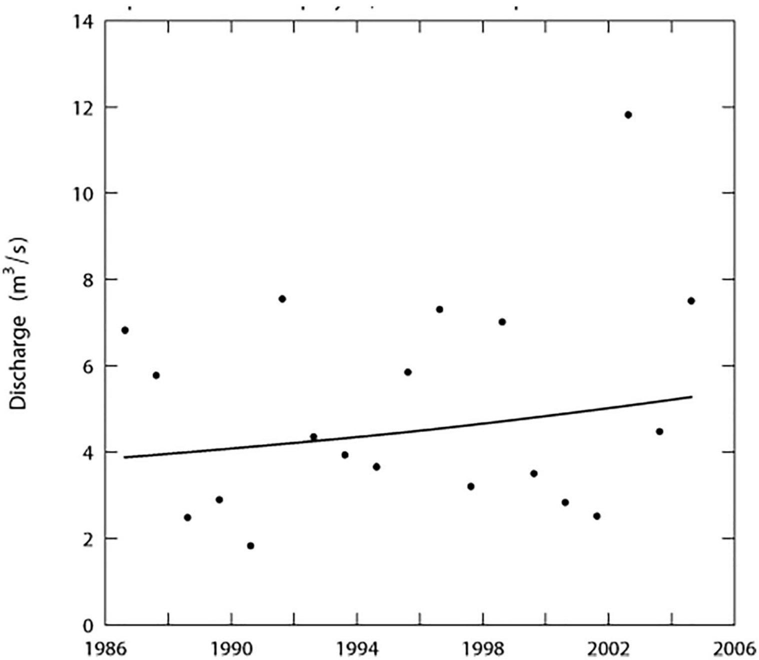

Fig. 6 Variation of the dry season median discharge. The dry season consists of the months June, July, August, September, October

complicates the selection of a single suitable minimum environmental flow that is derived as a proportion of the natural flow regime (Papadaki et al. 2016).

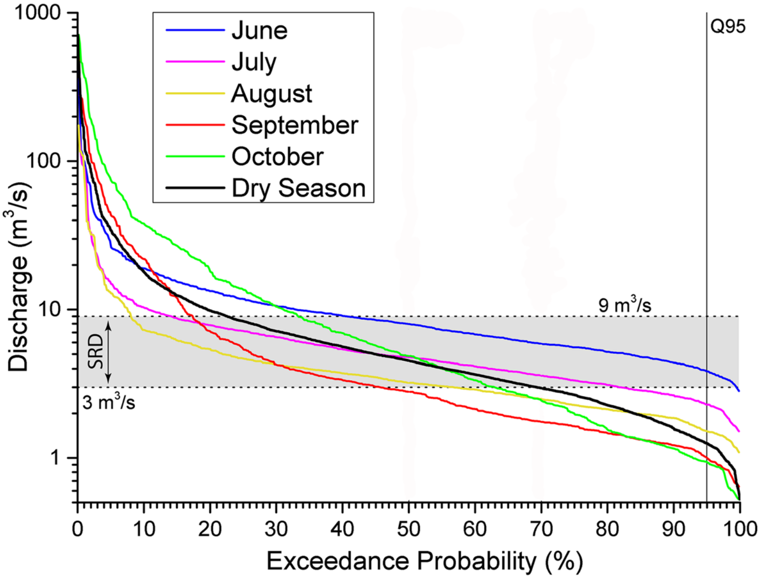

Fig. 7 Monthly flow duration curves for each month of the dry season and for the entire dry season for the examined period 1986 to 2004

Flow duration curves in Fig. 7 illustrate discharges versus percent of time that a particular discharge was equaled or exceeded. The part of the FDCs which coincide with the average daily flows in the grey area represent the SRD. SRD exceedance probability is high (more than 80%) for the months June and July, while for August and October is 63%. September has the lowest exceedance probability 50% from all months examined. Black line represents the entire dry season where SRD has exceedance probabilities from 20 to 70%. Extreme large floods and large flood flows are present with relatively low exceedance probabilities (lower than 10%).

SRD was identified on a monthly scale for the examined period 1986 to 2004 and results are presented in Table 2. SRD ranged from 3 m^3/s to 9 m^3/s, under which the main ecological functions of both sizes of the W.B. trout are possible to remain in good conditions according to the habitat simulation approach results (Fig. 5).

Considering the habitat duration curves of the large-size fish (Fig. 8), there is an evident contrast between the months June, July and September, October. Specifically, SRD is likely to provide relatively large habitat areas for 73% of the time for June and 72% of the time for July, while for September 32% and October 35% of the time. August is likely to have large habitat areas for 55% of the time.

SRD was then compared with the current Greek legislative framework of minimum ecological flows for the examined period. The examined legislation framework requirements correspond to a minimum ecological flow (5.7 m^3/s) which is translated to a relatively large habitat area according to the $WUA_{0.5}$ index. This is expected considering the fact that the large-size fish habitat area maximizes with a discharge of 6.7 m^3/s. Nevertheless, the habitat area corresponding to the 5.7 m^3/s discharge has small exceedance probability (less than 30%) for both sizes of fish (Figs. 8 and 9). Overall, implementation of SRD during the dry season is likely to provide large habitat areas to the large W.B. trout for 53% of the time, according to the $WUA_{0.5}$ index (Fig. 8).

SRD impact on habitat areas of the small-size fish is translated to 1850 m^2 to 2200 m^2 $WUA_{0.5}$ index values (relative difference 350 m^2). SRD is likely to provide large habitat areas for 80% of the time for July and 63% of the time for June and August, while for September and October for 38% of the time. Overall implementation of SRD during dry season is likely to provide large habitat areas for 56% of the time for the small-size fish, according to the $WUA_{0.5}$ index (Fig. 9).

Furthermore, September is characterized by a much steeper FDC (Fig. 6), a single discharge value obtained from the relative legislative framework which is based only on the average

Table 2 Days for which Suitable Range of Discharges (SRD) occurred, for each month, as well as days with higher and lower discharges than SRD and general statistics for the examined period 1986 to 2004

Statistics	Days SRD occurred					Days with higher discharges					Days with lower discharges				
Months	Jun	Jul	Aug	Sept	Oct	Jun	Jul	Aug	Sept	Oct	Jun	Jul	Aug	Sept	Oct
Average	18	21	15	9	9	12	4	3	5	10	0	6	13	16	12
STDev	11.3	9.1	9.8	7.6	6.7	11.4	6.2	4.0	7.2	8.8	0.7	9.3	10.8	11.1	9.6
Min	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0
Max	29	31	31	23	27	30	24	14	30	31	3	30	29	30	30
$Range_{Max-Min}$	29	30	29	23	27	30	24	14	30	31	3	30	29	30	30

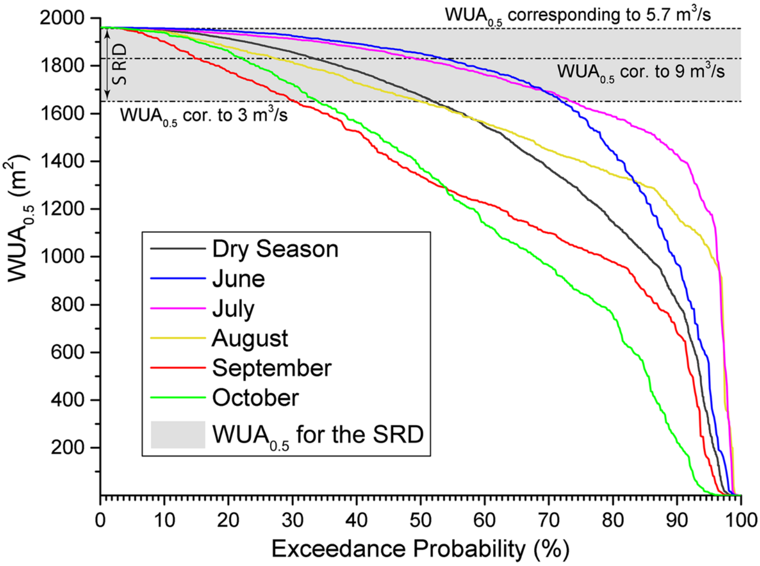

Fig. 8 Habitat duration curves for the large-size W.B. trout for each month of the dry season and for the entire dry season

discharge value of the month is not necessarily reflecting the actual conditions influencing aquatic ecosystems. Moreover, to incorporate realistic representations, especially for rivers with high flow variability (such as the rising limb, the time and the height of the peak, and volume of flow), daily timeseries are important to be implemented in the analysis. Thus, the lack of significant slope changes in FDCs at the seasonal scale or annual scale could lead to misinterpretation about the flow variability. For comparison reasons, Q95 (the flows that are

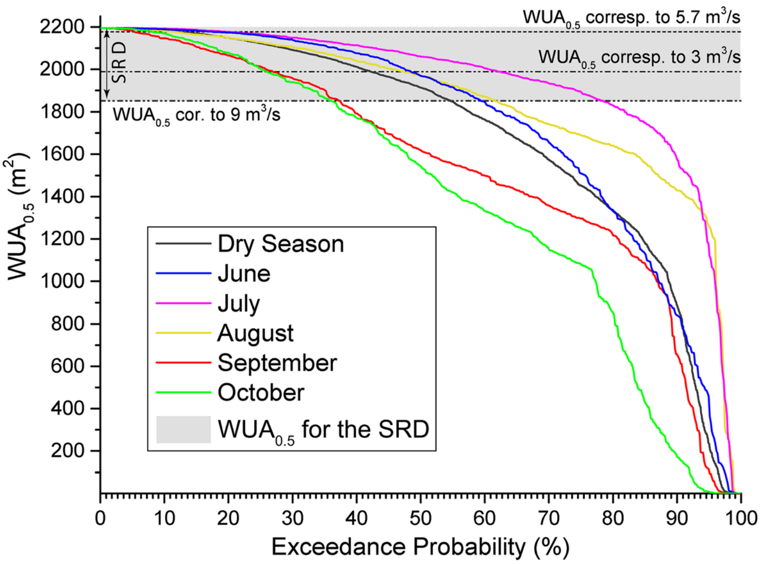

Fig. 9 Habitat duration curves for the small-size W.B. trout for each month of the dry season and for the entire dry season

equaled or exceeded 95% of the time) is estimated as a low flow index. This method is quite important for the estimation and assessment of environmental flows in projects requiring environmental licenses (Lozano Sandoval et al. 2015). Q95 is below 3 m^3/s for the months July (2.3 m^3/s), August (1.5 m^3/s), September (1.0 m^3/s) and October (0.9 m^3/s), and for the entire dry season (1.3 m^3/s). These values represent high water restrictions to the river ecosystem, especially for October.

SRD is proposed for the development of instream flow recommendations that may better accommodate the flow requirements of living organisms, especially in rivers where natural flow variability is high, in contradiction to a static minimum ecologically relevant discharge. Our results are in accordance with those of Armas-Vargas et al. (2017), who suggested an increase in habitat during the dry season. Moreover, our findings agree with Sharma and Dutta (2020), who stated that hydrological methodologies are lacking in recommending the river flushing flow requirements and addressing the seasonal flood pulse and lean flow. Nevertheless, variability among environmental flow assessment methods results is crucial, especially relating to instream flow estimates (Caissie et al. 2007). Environmental flow assessment methods have evolved considerably over the past 40 years. Hydrological methods are still widely used for the estimation of environmental flows. Nevertheless, the traditional approaches (Tennant method, Tennant 1976; 7Q10 method, FDCA method; Abdi R and Yasi 2015) may be inadequate to deal with hydrological heterogeneity and complexity, especially when there is absence of high-quality hydrometric data (Książek et al. 2019), and they are not directly related to any prescribed ecological preservation levels (Sharma and Dutta 2020). The combination of hydrological methods and physical habitat methods improve the relationships between flow and ecological conditions of the riverine ecosystems. Our approach, in terms of habitat availability for W.B. trout, quantifies the expected days of the suitable physical habitat conditions (high physical habitat availability values) with a modeled flow regime, representative of minimally impacted conditions, measured from $WUA_{0.5}$/discharge curves. Results from this study define spatially variable rules that have consistent consequences rather than using hydrological rules of thumb that are not explicitly linked to clear objectives and that have inconsistent consequences. Moreover, this approach could be used to assess the consequences of various allocation scenarios covering a range of objectives for acceptable percentage loss of physical habitat and/or risks of restriction. Third, by applying this approach to a range of scenarios the trade-off between environmental protection and water resources availability and reliability could be explicitly quantified, providing a more transparent basis for defining environmental flow rules.

4 Conclusions

The focus of this study is on low-flow periods that might limit the physical instream habitat of the W.B. trout as an indicator species. Suitable Range of Discharges (SRD) is proposed for the development of instream flow recommendations, especially in rivers where natural flow variability promotes not only an absolute minimum discharge value, but also other important management aspects influencing the maintenance of the biological functioning of a river. SRD provides for both sizes of the W.B. trout large habitat areas. Native fish species adapt more easily to local discharge conditions that is why they can survive under stress conditions, nevertheless a minimum stable ecological flow will completely alter the natural flow regime behavior. More research will be required in the future with respect to ecological flows and ecology relationships to better address questions and produce new knowledge in the water resources management field.

The main conclusions derived from this research efforts are:

1. The selection of one single discharge is usually problematic.
2. Implementation of SRD is likely to better balance the trade-offs between different water uses, and the ecological adverse effects caused by a constant minimum ecological flow.
3. Annual and seasonal variability of the natural flow regime are considered among the main factors structuring river biota.
4. The representation of biologically relevant data is very important in the quantification of environmental flows. Lack of ecological justification may lead to unrealistic recommendations.
5. The examined legislation framework requirements correspond to a minimum ecological flow (5.7 m^3/s) which is translated to a relatively large habitat area according to the $WUA_{0.5}$ index.
6. Due to the fact that September is characterized by a steep FDC, the single value obtained as the average discharge value of September is not necessarily representative of the actual conditions influencing aquatic ecosystems.
7. Due to the natural stream complexity there will always be characteristics that may be ignored by the models. Nevertheless, more aquatic organisms should be involved in future relevant studies that aim to analyze the aquatic ecosystems in a more holistic manner.
8. The approach to developing SRD indicates the potential to establish ecologically based objectives for decision making in water resources policy and management.

Acknowledgements The authors Dr. Christina Papadaki and Dr. Vasilis Bellos are also grateful to the Greek State Scholarships Foundation (IKY) for funding part of this work (data analysis results). More specifically:

This research is co-financed by Greece and the European Union (European Social Fund- ESF) through the Operational Programme «Human Resources Development, Education and Lifelong Learning» in the context of the project "Reinforcement of Postdoctoral Researchers – 2nd Cycle" (MIS-5033021), implemented by the State Scholarships Foundation (ΙΚΥ).

References

Abdi R, Yasi M (2015) Evaluation of environmental flow requirements using eco-hydrologic-hydraulic methods in perennial rivers. Water Sci Technol 72:354–363. https://doi.org/10.2166/wst.2015.200

Acreman M (2016) Environmental flows-basics for novices. Wiley Interdiscip Rev Water 3:622–628. https://doi.org/10.1002/wat2.1160

Acreman MC, Dunbar MJ (2004) Defining environmental river flow requirements – a review. Hydrol Earth Syst Sci 8:861–876. https://doi.org/10.5194/hess-8-861-2004

Ahmadi-Nedushan B, St-Hilaire A, Bérubé M, Robichaud E, Thiémonge E, Nathalie Bobée B (2006) A review of statistical methods for the evaluation of aquatic habitat suitability for instream flow assessment. River Res Appl 22:503–523. https://doi.org/10.1002/rra.918

Almodóvar A, Nicola GG, Ayllón D, Elvira B (2012) Global warming threatens the persistence of Mediterranean brown trout. Glob Chang Biol 18:1549–1560. https://doi.org/10.1111/j.1365-2486.2011.02608.x

Armas-Vargas F, Escolero O, De Jalón DG, Zambrano L, Del Tánago MG, Kralisch S (2017) Proposing environmental flows based on physical habitat simulation for five fish species in the Lower Duero River Basin, Mexico. Hidrobiologica 27:185–200. https://doi.org/10.24275/uam/izt/dcbs/hidro/2017v27n2/armas

Arnold JG, Srinivasan R, Muttiah RS, Williams JR (1998) Large area hydrologic modeling and assessment, Part 1: model development. Am Water Resour Assoc 34:73–89. https://doi.org/10.1111/j.17521688.1998.tb05961.x

Austin M (2007) Species distribution models and ecological theory: a critical assessment and some possible new approaches. Ecol Model 200:1–19. https://doi.org/10.1016/j.ecolmodel.2006.07.005
Ayllón D, Almodóvar A, Nicola GG, Elvira B (2012) The influence of variable habitat suitability criteria on PHABSIM habitat index results. River Res Appl 28:1179–1188. https://doi.org/10.1002/rra
Barnes HH Jr (1967) Roughness characteristics of natural channels. US GeolSurv Water Supply Pap 1849 7:219. https://doi.org/10.1016/0022-1694(69)90113-9
Benjankar R, Tonina D, Mckean J (2015) One-dimensional and two-dimensional hydrodynamic modeling derived flow properties: Impacts on aquatic habitat quality predictions. Earth Surf Process Landf 40:340–356. https://doi.org/10.1002/esp.3637
Boskidis I, Kokkos N, Sapounidis A, Triantafillidis S, Kamidis N, Koutrakis E, Sylaios GK (2018) Ecohydraulic modelling of Nestos River Delta under low flow regimes. Ecohydrol Hydrobiol 18(4):4391–400. https://doi.org/10.1016/j.ecohyd.2018.06.004
Bovee KD (1986) Development and evaluation of habitat suitability criteria for use in the instream flow incremental methodology. Instream Flow Information Paper #21 FWS/OBS-86/7 assessed from: https://pubs.er.usgs.gov/publication/70121265
Bovee KD, Lamb BL, Bartholow JM, Stalnaker CB, Taylor J, Henriksen J (1998) Stream habitat analysis using the instream flow incremental methodology. In: U.S. Goelogical Survey, Biological Resources Division Information and Technology Report. Assecced from: https://apps.dtic.mil/dtic/tr/fulltext/u2/a361209.pdf
Caissie D, El-Jabi N, Hébert C (2007) Comparison of hydrologically based instream flow methods using a resampling technique. Can J Civ Eng 34:66–74. https://doi.org/10.1139/L06-095
Chow VT (1959) Open Channel Hydraulics. McGraw-Hill B. Co. 728 assessed from: http://web.ipb.ac.id/~erizal/hidrolika/Chow%20-%20OPEN%20CHANNEL%20HYDRAULICS.pdf
Cowan WL (1956) Estimating hydraulic roughness coefficients. Agric Eng 37:7
Crowder DW, Diplas P (2000) Using two-dimensional hydrodynamic models at scales of ecological importance. J Hydrol 230:172–191. https://doi.org/10.1016/S0022-1694(00)00177-3
De Jalón DG (2003) The Spanish experience in determining minimum flow regimes in regulated streams. Can Water Resour J 28(2):185–198. https://doi.org/10.4296/cwrj2802185
Dolloff CA, Hankin DG, Reeves GH (1993) Basin wide estimation of habitat and fish populations in streams. USFS Southeastern Forest Experiment Station, Asheville. https://doi.org/10.2737/SE-GTR83
Economou AN, Zogaris S, Chatzinikolaou Y, Tachos V, Giakoumi S, Kommatas D, Koutsikos N, Vardakas L, Blasel K, Dussling U (2007) Development of an ichthyological multimetric index for ecological status assessment of Greekmountain streams and rivers. Technical Report. Hellenic Center for Marine Research — Institute of Inland
European Commission (2015) Ecological flows in the implementation of the Water Framework Directive. Common Implementation Strategy (CIS) Guidance Document nº31. European Union, 2015, Luxembourg, Assessed from: https://publications.europa.eu/en/publication-detail/-/publication/b2369e0f-d154-11e5-a4b5-01aa75ed71a1/language-en
Fehér J, Gáspár J, Szurdiné Veres K, Kiss A (2012) Hydromorphological alterations and pressures in European rivers, lakes, transitional and coastal waters. VITUKI, NIVA, IWRS, Ecologic, Ecologic Institute, Stichting Deltares, SYKE, CENIA, Prague. ISBN: 978-80-85087-98-7. Assessed from: https://www.ecologic.eu/11663
Hauer C, Unfer G, Holzmann H, Schmutz S, Habersack H (2013) The impact of discharge change on physical instream habitats and its response to river morphology. Clim Change 116:827–850. https://doi.org/10.1007/s10584-012-0507-4
Hirsch RM, De Cicco LA (2015) User guide to Exploration and Graphics for RivEr Trends (EGRET) and dataRetrieval: R packages for hydrologic data (version 2.0, February 2015): U.S. Geological Survey Techniques and Methods book 4, chap. A10, 93 p., https://doi.org/10.3133/tm4A10
Kennard MJ, Mackay SJ, Pusey BJ, Olden JD, Marsh N (2010) Quantifying uncertainty in estimation of hydrologic metrics for ecohydrological studies. River Res Appl 26:137–156. https://doi.org/10.1002/rra.1249
Kottelat M, Freyhof J (2007) Handbook of european freshwater fishes. 646 (Kottelat, Cornol, Switzerland and Freyhof, Berlin, Germany)
Książek L, Woś A, Florek J, Wyrębek M, Młyński D, Wałęga A (2019) Combined use of the hydraulic and hydrological methods to calculate the environmental flow: Wisloka river, Poland: case study. Environ Monit Assess 191:254. https://doi.org/10.1007/s10661-019-7402-7
Kuriqi A, Pinheiro AN, Sordo-Ward A, Garrote L (2019) Influence of hydrologically based environmental flow methods on flow alteration and energy production in a run-of-river hydropower plant. J Clean Prod 232:1028–1042. https://doi.org/10.1016/j.jclepro.2019.05.358

Li W, Chen Q, Cai D, Li R (2015) Determination of an appropriate ecological hydrograph for a rare fish species using an improved fish habitat suitability model introducing landscape ecology index. Ecol Modell 311:31–38. https://doi.org/10.1016/j.ecolmodel.2015.05.009

Lindenmayer DB, Fischer J, Felton A, Montague-Drake R, Manning AD, Manning D, Youngentob K, Saunders D, Wilson D, Felton AM, Blackmore C, Lowe A, Bond S, Munro N, Elliott CP (2007) The complementarity of single-species and ecosystem-oriented research in conservation research. Oikos 116:1220–1226. https://doi.org/10.1111/j.2007.0030-1299.15683.x

Lozano Sandoval G, Monsalve Durango EA, García Reinoso PL, Rodríguez Mejía CA, Gómez Ospina JP, Triviño Loaiza HJ (2015) Environmental flow estimation using hydrological and hydraulic methods for the Quindío River basin: WEAP as a support tool. Inge CUC 11:34–48. https://doi.org/10.17981/ingecuc.11.2.2015.04

Mathews R, Richter BD (2007) Application of the indicators of hydrologic alteration software in environmental flow setting. J Am Water Resour Assoc 43:1400–1413. https://doi.org/10.1111/j.1752-1688.2007.00099.x

Monk WA, Wood PJ, Hannah DM, Wilson DA (2007) Selection of river flow indices for the assessment of hydroecological change. River Res Appl 23:113–122

Muñoz-Mas R, Papadaki Ch, Martínez-Capel F, Zogaris S, Ntoanidis L, Dimitriou E (2016) Generalized additive and fuzzy models in environmental flow assessment: A comparison employing the West Balkan trout (Salmo farioides; Karaman, 1938). Ecol Eng 91:365–377. https://doi.org/10.1016/j.ecoleng.2016.03.009

Naiman RJ, Latterell JJ, Pettit NE, Olden JD (2008) Flow variability and the biophysical vitality of river systems. Comptes Rendus - Geosci 340:629–643. https://doi.org/10.1016/j.crte.2008.01.002

Official Journal of the Hellenic Republic, 196978/2011 (2011) Off J Hell Repub (FEK) 518/B/5/04/2011 7411–7418

Oo HT, Zin WW, Thin Kyi CC (2020) Analysis of streamflow response to changing climate conditions using SWAT model. Civ Eng J 6:194–209. https://doi.org/10.28991/cej-2020-03091464

Overton IC, Smith DM, Dalton J, Barchiesi S, Acreman MC, Stromberg JC, Kirby JM (2014) Implementing environmental flows in integrated water resources management and the ecosystem approach. Hydrol Sci J 59:860–877. https://doi.org/10.1080/02626667.2014.897408

Palmer M, Ruhi A (2019) Linkages between flow regime, biota, and ecosystem processes: Implications for river restoration. Science 365: 6459 https://doi.org/10.1126/science.aaw2087

Papadaki Ch, Soulis K, Muñoz-Mas R, Martinez-Capel F, Zogaris S, Ntoanidis L, Dimitriou E (2016) Potential impacts of climate change on flow regime and fish habitat in mountain rivers of the south-western Balkans. Sci Total Environ 540:418–428. https://doi.org/10.1016/j.scitotenv.2015.06.134

Papadaki Ch, Bellos V, Ntoanidis L, Dimitriou E (2017a) Comparison of west Balkan adult trout habitat predictions using a Pseudo-2D and a 2D hydrodynamic model. Hydrol Res 48:1697–1709. https://doi.org/10.2166/nh.2016.352

Papadaki Ch, Soulis K, Ntoanidis L, Zogaris S, Dercas N, Dimitriou E (2017) Comparative assessment of environmental flow estimation methods in a Mediterranean mountain river. Environ Manag 60:280–292. https://doi.org/10.1007/s00267-017-0878-4

Papaioannou G, Papadaki Ch, Dimitriou E (2019) Sensitivity of habitat hydraulic model outputs to DTM and computational mesh resolution. Ecohydrology 2020:13:e2182. https://doi.org/10.1002/eco.2182

Poff NLR, Olden JD, Pepin DM, Bledsoe BP (2006) Placing global stream flow variability in geographic and geomorphic contexts. River Res Appl 22:149–166. https://doi.org/10.1002/rra.902

Principato G, Viggiani G (2009) Hydrologic alteration assessment in Mediterranean rivers: Perspective from a South Italy case study. Int J River Basin Manag 7:365–377. https://doi.org/10.1080/15715124.2009.9635395

R Core Team (2015) R: a language and environment for statistical computing. Version 3.2.1

Sanford SE, Creed IF, Tague CL, Beall FD, Buttle JM (2007) Scale-dependence of natural variability of flow regimes in a forested landscape. Water Resour Res, 43(8) https://doi.org/10.1029/2006WR005299

Schindler DE, Hilborn R, Chasco B, Boatright CP, Quinn TP, Rogers LA, Webster MS (2010) Population diversity and the portfolio effect in an exploited species. Nature 465(7298):609–612. https://doi.org/10.1038/nature09060

Sharma U, Dutta V (2020) Establishing environmental flows for intermittent tropical rivers: Why hydrological methods are not adequate? Int J Environ Sci Technol 17:2949–2966. https://doi.org/10.1007/s13762-020-02680-6

Siddig AAH, Ellison AM, Ochs A, Villar-Leeman C, Lau MK (2016) How do ecologists select and use indicator species to monitor ecological change? Insights from 14 years of publication in ecological indicators. Ecol Indic 60:223–230. https://doi.org/10.1016/j.ecolind.2015.06.036

Tennant DL (1976) Instream flow regimens for fish, wildlife, recreation and related environmental resources. Fisheries 1(4):6–10. https://doi.org/10.1577/1548-8446(1976)001<0006:ifrffw>2.0.co;2

Theodoropoulos C, Papadaki Ch, Vardakas L, Dimitriou E, Kalogianni E, Skoulikidis N (2019) Conceptualization and pilot application of a model-based environmental flow assessment adapted for intermittent rivers. Aquat Sci 0:0. https://doi.org/10.1007/s00027-018-0605-0

Tonkin JD, Jähnig SC, Haase P (2014) The rise of riverine flow-ecology and environmental flow research. Environ Process 1:323–330. https://doi.org/10.1007/s40710-014-0024-8

Trigo RM, Pozo-Vázquez D, Osborn TJ, Castro-Díez Y, Gámiz-Fortis S, Esteban-Parra MJ (2004) North Atlantic oscillation influence on precipitation, river flow and water resources in the Iberian Peninsula. Int J Climatol 24:925–944. https://doi.org/10.1002/joc.1048

Wilding TK, Bledsoe B, Poff NLR, Sanderson J (2014) Predicting habitat response to flow using generalized habitat models for trout in Rocky Mountain streams. River Res Appl 30:805–824. https://doi.org/10.1002/rra.2678

Yue S, Pilon P (2004) A comparison of the power of the t test, Mann-Kendall and bootstrap tests for trend detection. Hydrol Sci J 49:21–38. https://doi.org/10.1623/hysj.49.1.21.53996

Zeiringer B, Seliger C, Greimel F, Schmutz S (2018) River hydrology, flow alteration, and environmental flow. In: Schmutz S, Sendzimir J (eds) Riverine Ecosystem Management, vol 8. Springer, Cham. https://doi.org/10.1007/978-3-319-73250-3. Aquatic Ecology Series

Zogaris S, Economou AN (2009) West Balkan Trout, Salmo farioides. In: A. Legakis, P. Maragou (eds) Red data book of threatened animals of Greece Hellenic Zoological Society, pp 141–143. ISBN:978-960-85298-8-5

Zogaris S, Economou AN, Dimopoulos P (2009) Ecoregions in the southern Balkans: should their boundaries be revised? Environ Manag 43:682–697. https://doi.org/10.1007/s00267-008-9243-y

Affiliations

Christina Papadaki[1] • Konstantinos Soulis[2] • Vasilis Bellos[3] • Lazaros Ntoanidis[4] • Elias Dimitriou[1]

[1] Hellenic Centre for Marine Research, Institute of Marine Biological Resources and Inland Waters, Anavyssos, Greece

[2] Department of Natural Resources Management and Agricultural Engineering, Division of Water Resources, Agricultural University of Athens, Athens, Greece

[3] Laboratory of Reclamation Works and Water Resources Management, School of Rural and Surveying Engineering, National Technical University of Athens, Athens, Greece

[4] Lazaros Ntoanidis, D. Argyropoulos & Associates, Tinou 2 str, Cholargos 15562, Greece