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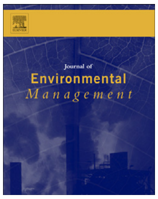

Research article

Determination of environmental flows in rivers using an integrated hydrological-hydrodynamic-habitat modelling approach

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ABSTRACT

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

1. Introduction

In recent decades, over-exploitation of water resources has caused serious ecological problems worldwide (Vörösmarty et al., 1997; Saito et al., 2001; Meador et al., 2003; Paukert et al., 2011). River water abstraction is a typical case of such over-exploitation that alters flow-regime and may threaten river ecosystem (Pearce, 2012) to "artificial desiccation" (Skoulikidis et al., 2011) and fish extinction (Vörösmarty et al., 2010). Various researchers have demonstrated the important effect of flow regime alteration on the amount of habitat, distribution, abundance and diversity of river organisms, ranging from microorganisms, algae and aquatic plants to invertebrates, fish and other vertebrates (Bunn and Arthington, 2002; Arthington, 2012). In Mediterranean rivers, various environmental pressures, including alteration of the flow regime, resulted in the decline of fish population and in some cases in the

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extinction of native species (Smith and Darwall, 2006). Moreover, various characteristics of the flow regime, such as the minimum monthly flow during spawning, exerted a strong effect on the patterns of presence-absence and population densities of extended fish species, such as the Eastern Iberian Barbel (*Luciobarbus guiraonis*) (Olaya-Marín et al., 2016).

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

A global review of the environmental flow methodologies at the beginning of the 21st century revealed the existence of more than 207 individual methodologies that can be categorized as hydrological, hydraulic rating, habitat simulation and holistic (Tharme, 2003). One of the first widely-used hydrological methods, was the US Tennant method (Tennant, 1976), while later other similar methods that were developed, analyzed the diverse hydrological components to study and apply environmental flows in the framework of an adaptive management process (Henriksen et al., 2006; Mathews and Richter, 2007). Although some hydrological approaches were usually favoured due to their simplicity, they do not consider biological requirements and interactions of aquatic organisms (Li et al., 2015). Nevertheless, the hydrological methods based on hydrological alteration have been successfully incorporated in holistic methods, such as the Building Block Methodology (BBM) by King et al. (2000) and the Ecological Limits of Hydrologic Alteration (ELOHA) by Poff et al. (2010). However, the habitat simulation methods, firstly developed within the framework of the Instream Flow Incremental Method (IFIM) by Bovee (1982), are fundamental to interpret the hydrological information and to understand the ecological consequences of environmental flows on habitats and biota. Also, in holistic methodologies such as the BBM and the DRIFT, the interpretation of hydrological information with hydrodynamic models is fundamental to understand flow–ecology relationships (Arthington et al., 2003; King and Brown, 2006). Generally, there is no explicit method or criteria to determine the actual ecological regime without considering the river water demands and availability, as well as its natural variability. Thus, the final decision upon environmental flow requirements is a multifactorial process that involves prioritization of water uses, knowledge of the replenishing water resources and risk assessment efforts.

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

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

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

2. Materials and methods

2.1. Study area

The area of study is shown in Fig. 1; the Sperchios River originates from Tymfristos Mountain, it then flows to the east through the village of Agios Georgios, enters a wide plain and finally discharges into the Maliakos Gulf. The total length of Sperchios River is ca. 82 km, its catchment area is 1660.9 km^2, while the average and highest altitudes are 641 m and 2285 m above sea level, respectively. Approximately 32% of the entire catchment is covered by agricultural land, about 20% of which is regularly irrigated (rice paddies, corn, alpha-alpha grass and vineyards are the most common crop types in the area), 2% by built-up areas and 66% by natural or semi natural vegetation and bare land. Sperchios River is characterized by a Mediterranean climate with low discharges in summer and high discharges in late autumn, winter and spring. The most important hydromorphological alterations of the Sperchios River are water abstractions, primarily for irrigation and to a lesser extent for industrial activities, such as small manufacturing units of agricultural products and olive oil refineries (Skoulikidis et al., 2011).

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

2.2. Integrated modelling procedure

The conceptual diagram of the integrated modelling procedure