A METHODOLOGY FOR THE DETERMINATION OF ENVIRONMENTAL FLOW RELEASES FROM DAMS BASED ON HYDRODYNAMIC HABITAT MODELLING AND BENTHIC MACROINVERTEBRATES

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EXTENDED ABSTRACT

Dams and water abstraction facilities are used worldwide to supply societies with water and energy or prevent flooding. These benefits however are often counterbalanced by serious ecological consequences derived from flow-regime alterations, depriving humans of the valuable goods and services, which healthy rivers provide. Environmental flows are currently considered an essential measure to mitigate these ecological impacts.

Hydrodynamic habitat models have long been used worldwide to facilitate Environmental Flow Assessments (EFAs) in deriving defensible flow recommendations. However, these models have been primarily focused on fish, neglecting the habitat requirements of other biotic elements of the aquatic ecosystem. EFAs are currently shifting towards a holistic framework, requiring to assess the flow needs of multiple ecosystem elements, including not only fish, but also macroinvertebrates, macrophytes and riparian vegetation, through multi-disciplinary expert judgment. Habitat modelling has simultaneously evolved from simplistic 1D to advanced 2D or 3D models of great accuracy, offering a great basis for data-driven hydro-ecological approaches.

In the present paper, a methodology is proposed to enable the development of a hydrodynamic habitat model for environmental flow assessments based on benthic macroinvertebrates. This methodology is based on a European intercalibrated sampling protocol, modified appropriately to focus on microhabitat and could be replicated in a broader Mediterranean/European scale. To provide with time-efficiency and reduce possible error, macroinvertebrates are identified to the family level. The integrated habitat suitability (IHS) is innovatively derived based on the rationale that macroinvertebrates are adapted to the changing habitat (water depth, flow velocity, substrate) interactively and not to each variable independently. IHS is then introduced into habitat hydrodynamic modelling as the most comprehensive approach to derive defensible environmental flow recommendations, according to the European Water Framework Directive 2000/60/EC (WFD Guidance Document No. 31). Incorporated in a holistic framework, where the IHS of various elements of the aquatic ecosystem are included, defensible flow recommendations can be derived to facilitate the provisioning of environmental flows downstream of dams towards a sustainable water resources management.

Keywords: holistic, hydrodynamic models, integrated habitat suitability, environmental flows

1. INTRODUCTION

Dams are considered as environmentally friendly sources of water and energy, simultaneously providing societies with additional benefits, such as flood control and protection. In this perspective, a massive dam construction took place over the past decades, resulting to a global operation of 48,000 large dams and 800,000 smaller ones. Almost 60% of the world's large rivers are currently fragmented and the indisputable benefits of dams are often counterbalanced by specific environmental impacts, which deprive humans of the valuable goods and services provided by healthy river/aquatic ecosystems. Dams alter the natural flow regimes and influence aquatic communities. While there is much debate on how a dam could be operated in a more environmental-friendly way towards sustainability (Richter and Thomas, 2007), water abstraction for irrigation also threats river ecosystems by reducing flow during the dry period of the year, often until "artificial desiccation" of river occurs (Skoulikidis *et al.,* 2011). It is recognized (Tharme, 2003) that a volume of water (with specific quality, quantity, duration, timing and rate of change) should continue flowing downstream of dams (environmental flow) to maintain the functionality of freshwater ecosystems. Traditional environmental flow assessments (EFAs), which have been initially applied in the USA for the protection of fish species of interest (Tharme, 1996), were transformed either to data-driven habitat simulation models (Milhous and Waddle, 2012) or to expert-judgment-based holistic methodologies, addressing the needs of various ecosystem components, such as the Building Block Methodology in South Africa (King *et al.,* 2008). In Europe, only recently a WFD Guidance Document (No. 31, 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) are used to estimate the amount of in-stream habitat for aquatic organisms of interest, expressed as a unique combination of physical river characteristics (microhabitat), such as flow velocity (U), water depth (D), substrate (S) and water temperature (T). HHMs relate these physical characteristics with habitat suitability criteria for the aquatic organisms to calculate the amount of in-stream habitat for these organisms (Stamou, 2015) for various flow rates; habitat suitability criteria are usually expressed as indexes of frequency or abundance with which the aquatic organisms are found in the particular habitats, such as the Habitat Suitability Curves (HSCs). The amount of in-stream habitat is calculated as area of usable habitat and is called Weighted Usable Area (WUA). In almost all the existing HHMs, fishes are used as aquatic organisms, with only few studies focusing on benthic macroinvertebrates. In the present paper, a methodology is critically presented to develop a new HHM based on the integrated habitat suitability (IHS) of benthic macroinvertebrates, innovatively derived through the interaction between D, U, S (and optionally T).

2. HYDRODYNAMIC MODELLING AND BENTHIC MACROINVERTEBRATES

2.1. The importance of using benthic macroinvertebrates in EFAs

The use of HHMs in EFAs has been primarily focused on fish (Milhous and Waddle, 2012). Considering that river habitats appropriate for fish survival and diversity may not benefit macroinvertebrates or other aquatic organisms, the integration of all elements of the aquatic ecosystem into habitat modelling is a crucial step towards defensible, holistic environmental flow recommendations. Benthic macroinvertebrates are considerably less mobile than fish, with less tolerance to changes in the water volume and a reduced ability to colonize habitat-poor areas (Gore, 1989). Related studies have shown that, in contrary to fish that may be limited or not present in many small streams, a diverse benthic macroinvertebrate fauna is supported and benthic macroinvertebrates are abundant in most low-order streams (Barbour *et al.,* 1999). While several authors acknowledge that fresh water macroinvertebrates are ideal candidates for the development of hydro-ecological models (Niu and Dudgeon, 2011), only a limited number of studies has focused on quantifying/modelling the response of freshwater macroinvertebrates to flow/habitat alteration (e.g. Waddle and Holmquist, 2011).

2.2. Quantification of macroinvertebrate response to flow/habitat alteration

Currently, there is no specific consensus on the appropriate taxonomic level for the quantification of macroinvertebrate response or on the spatial scale of habitat models. Macroinvertebrates are identified to family level (McIntosh *et al.,* 2002), genus or species (Qiuwen *et al.,* 2011) or metrics are used instead, such as the EPT (Waddle and Holmquist, 2011). Most studies focus on microhabitat, while recently, a shift towards the meso-scale has been applied (Vezza *et al.,* 2014), defining as mesohabitats the areas with consistent hydraulic patterns described by D and U.

3. PRESENTATION OF THE METHODOLOGY

Based on the above mentioned, a new methodology is proposed for application in Greek streams and rivers which consists of 4 steps that are described below; see Figure 1.
<u>Step 1: Determination of the habitat suitability (IHS) for benthic macroinvertebrates.</u> Field work is performed in a sufficient number of sites with no water quality degradation. Although, generally 3-4 sites are usually sufficient, it is recommended to involve 7-10 sites in 5-7 rivers to produce IHS of general applicability. We propose a modified STAR-AQEM sampling methodology (AQEM Consortium, 2002) requiring a sample of 20 replicates, distributed randomly in a 100-200m river reach (site) taken using a 0.25m x 0.25m surber sampler (or hand net) with a mesh size of 500μm. During this field campaign D, U and S are measured at each replicate, which is preserved separately. To increase the accuracy and time-efficiency of the procedure, benthic macroinvertebrates are identified to the family level. IHS is determined based on the interaction between the various physical river characteristics comprising the microhabitat. A unique code is assigned at each microhabitat to represent the unique combination of D, U and S. The suitability of each microhabitat is expressed as an index derived by a specific combination of taxa richness, diversity and abundance.
<u>Step 2: Formulation of a Hydrodynamic Habitat Model (HHM)</u>. A new 2-D hydrodynamic model can be built or alternatively an existing tested model, such as TELEMAC (see http://www.opentelemac.org/), can be used. The hydrodynamic model determines D and U in a properly constructed computational grid; optionally but ideally, it may include two additional sub-models for the calculation of T and sediment transport that are solved to determine T and S (Yao *et al*., 2014). Alternatively, T and S can be measured. Then, the HHM combines calculated D, U, S (and T) values with IHS to calculate suitability indexes at each cell of the computational grid and finally integrate them to determine the WUA.
<u>Step 3: Validation of the HHM</u>. Three hydrologically altered river reaches of approximate length equal to 100-150 m are selected and used as test cases; for these cases geomorphological data are collected and used to construct the corresponding computational grids and to estimate initial values for the coefficient of Manning (n) and S. Furthermore, two series of independent field data (D, U and S) are collected, at 6-8 cross sections. These data will be used for the calibration and verification of the hydrodynamic model; calibration may include the determination of n. We run the HHM using the IHS that are determined in step 1 to calculate WUA for current conditions. During the data campaign, it is suggested to collect some data regarding the identification of macroinvertebrates, which can be used for the verification of the HHM.
<u>Step 4: Application of the HHM to determine the environmental flow.</u> The validated HHM is applied to calculate the WUA for various flow rate scenarios and finally select the optimum "environmental flow". The selection of the optimum scenario can be adjusted according to the availability of long-term hydrological flow-rate data.

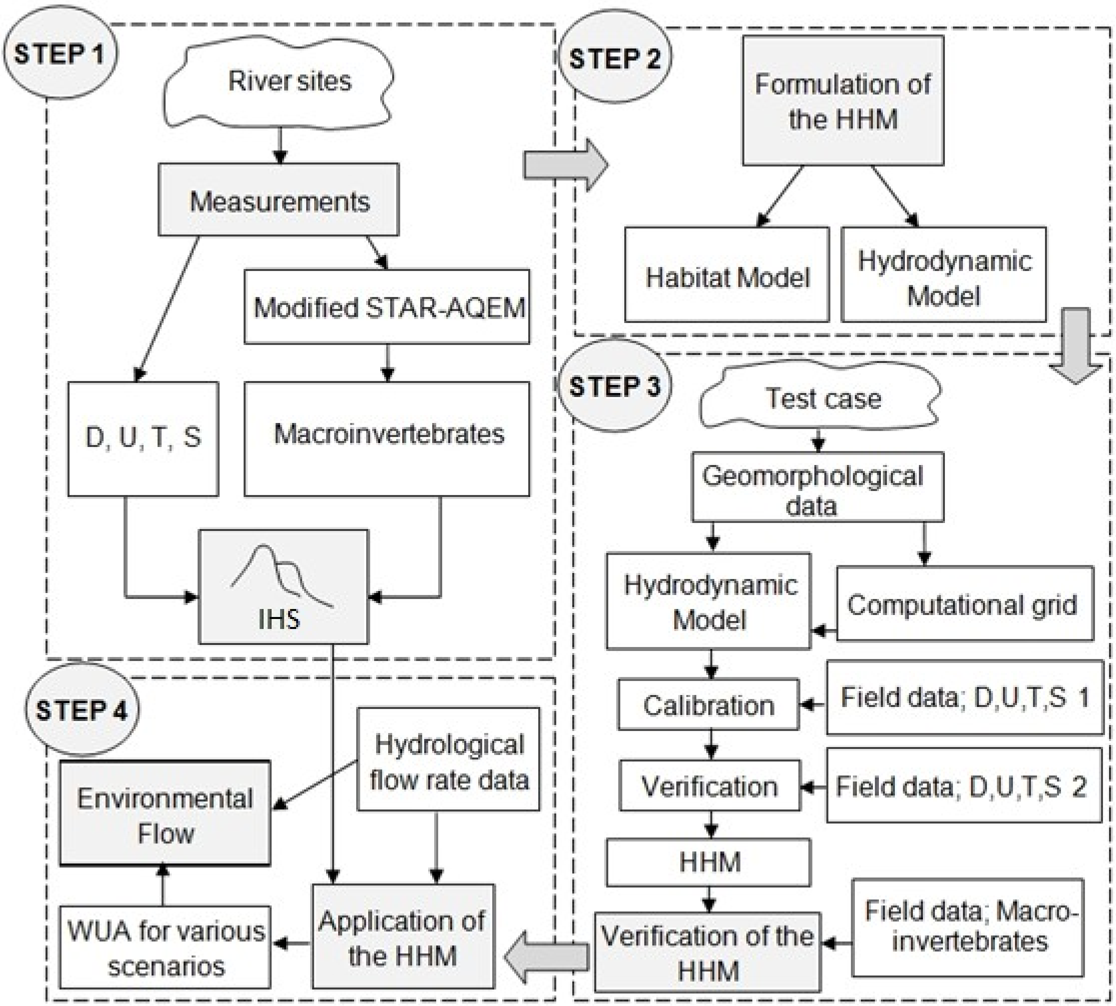

Figure 1. The 4 steps of the suggested methodology

4. CONCLUSION

An innovative methodology is proposed to enable the development of a hydrodynamic habitat model for environmental flow assessments based on benthic macroinvertebrates. This methodology is based on a European inter-calibrated sampling protocol, modified appropriately to focus on microhabitat and could be replicated in a broader Mediterranean/European scale. Identification of macroinvertebrates to family level provides with time-efficiency and reduces possible error in identification of samples. Habitat suitability is innovatively determined using the IHS and integrated into hydrodynamic modelling as the most comprehensive approach to derive defensible environmental flow recommendations, according to the European Water Framework Directive 2000/60/EC (WFD Guidance Document No. 31). Incorporated in a holistic framework, where the habitat preferences of various elements of the aquatic ecosystem are included, defensible flow recommendations can be derived to facilitate the provisioning of environmental flows downstream of dams towards a sustainable water resources management.

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