Ecological flow for integrated planning of small hydropower plants: a case study from Greece

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Abstract Mountainous areas, which are the dominant orography of the Greek mainland, are considered ideal locations for small hydropower plants. The development of such projects should comply with legislation on environmental protection, considering also the maintenance of a minimum environmental flow. This flow is necessary mainly during the irrigation period, not only for preserving the hydrological and water quality functions of the stream, but also for contributing to the protection of public health and water-related ecosystems. The aim of this paper is to assess the environmental flow that should be released downstream of small hydro-dams. The proposed analysis is applied in a small mountainous sub-basin located in Northern Greece, where environmental flow regimes are estimated using the Indicators of Hydrologic Alteration (IHA) and Tennant methodologies. The outcomes are compared with that resulting from the empirical methodology specified under Greek Law and a descriptive analysis is conducted for the selection of the most suitable method.

Key words small hydropower plants; environmental flow; ecological functions, water management; Tennant method; IHA method

INTRODUCTION

According to the climate change projections for the 21st century derived by Global Circulation Models (GCMs), Greece, as part of the Mediterranean basin, belongs to a climatic zone where an increase of temperature and yearly fluctuations with a decreasing trend in precipitation are expected (Skoulikaris & Ganoulis, 2011). The impact of these climate variations is bound to affect all water related sectors, such as water supply systems, irrigation systems, renewable energy sources and industrial production, as well as water related ecosystems.

Building water reservoirs is often the best way to adjust the uneven variation of water availability in space and time that occurs in the natural environment. Both historically and recently water reservoirs have been proposed as a tool for mitigating water scarcity and climate change (Kumar *et al.*, 2011). Artificial reservoirs add great benefit to multipurpose hydropower projects, because of the possibility to store water during periods of water surplus, and release it during periods of water deficit. At the same time, it is possible to produce energy, satisfy the irrigation and water supply demands and control possible floods. However, any water-related project should comply with the European Union Water Framework Directive (EU-WFD), which requires that integrated water resources management planning should combine economic and technical benefits, while at the same time environmental and social objectives should be respected. The maintenance of a minimum environmental discharge downstream from small or large dams combining hydro electric plants (HEP) is considered to be one of the measures contributing to meeting the environmental objectives of such integrated projects.

Environmental flow (EF), namely ecological or instream flow, is the water regime provided within a river, wetland or coastal zone in order to maintain healthy ecosystems (Dyson *et al.*, 2003). The minimum level of EF is the amount of a river flow that allows the preservation of specific ecological attributes related to the physicochemical profile, biological traits and their relationship (Acreman & Dunbar, 2005). The integrated process of securing the environmental characteristics and the related ecological functions of river flow, together with the preservation of human needs for water and public health, is defined as Environmental Flow Assessment (EFA). The effective operational quantification of ecological flow can provide one "best solution" for water management amongst alternative conflicting allocations of water resources, both for humans and ecosystems.

In the following sections, different EFA methodologies are presented, and two specific methodologies are applied for the assessment of the environmental flow of a relatively small river, with a dam, in central Greece. The existing irrigation dam is planned to be used for hydropower production. The results are compared with the EF specified under Greek legislation and the advantages and limitations of each method are discussed.

ENVIRONMENTAL FLOW ASSESSMENT METHODS

The first attempts to quantify ecological flow began in the western US in the late 1940s, whilst to date more than 207 different methodologies have been developed in 44 countries around the world (Tharme, 2003). Because of the diversity of the EFA methods, which range from simple rules of thumb to complex multi-year processes integrating modelling and field data, several different categorizations of these methods have been proposed. The most dominant categorizations are those of the IUNC (International Union for Conservation of Nature and Natural Resources) (Dyson *et al.*, 2003), the World Bank (Brown & King, 2003) and the IWMI (International Water Management Institute) (Tharme, 2003).

The IWMI categorization subdivides the EFA methodology into four relatively discrete approaches according to the type of data, with the World Bank and IUNC following almost the same approach. A comprehensive comparison of the four EFA approaches, showing strengths and limitations related to costs for *in situ* measurements, data collection and expert involvement required, is summarized in Table 1.

Table 1 Strengths and limitations of EFA methodologies.

Approach/Type of data	Strengths	Limitations
Hydrological	Low cost, easy to use	Not site-specific, ecological characteristics assumed
Hydraulic	Low cost, site specific	Ecological characteristics assumed
Habitat	Ecological characteristics included	Extensive data collection and use of experts, high cost
Holistic	Covers most aspects	Requires a high level of scientific expertise, very high cost; ecosystem regime is required

Hydrological approaches, namely look-up tables by IUNC, are based on historical monthly or average daily flow records. They are analysed in order to derive standard flow indices, which then produce the recommended environmental flows. Hydrological methodologies are generally used mainly at the planning stage of water resource developments, or in situations where preliminary flow targets and exploratory water allocation trade-offs are required (Abell *et al.*, 2004). Tennant (Tennant, 1976) and IHA (Indicators of Hydrologic Alteration) (Richter *et al.*, 1997) are the most routinely used hydrological methodologies. Hydraulic approaches (desktop analysis by IUNC) take into account the hydraulic characteristics of a river, such as the wetted perimeter or water levels at specific cross-sections. Habitat simulation or habitat modelling approaches make use of hydraulic habitat–discharge relationships, and provide more detailed analyses of the water quantity needed for sustaining the river habitat. In this approach, environmental flow recommendations integrate hydrological, hydraulic and biological data (Abel *et al.*, 2004). Finally, holistic methodologies not only link up the hydrological, hydraulics and habitats data, but also the calculated ecological flow, which should additionally satisfy other criteria such as socio-economic, water quality issues, ecological and geomorphological criteria (Abel *et al.*, 2004). Although holistic methodologies currently represent more than 8% of the total (Tharme, 2003), the ecosystem components required for their implementation is a dissuasive factor in areas with a lack of data.

The IHA and Tennant methods and the empirical EFA in Greece

Due to limited information about the habitat requirements of native biota (i.e. species and communities) and the biogeochemical processes that influence those habitats, two hydrological approaches, namely the IHA and Tennant, were used for the assessment of the EF in the area under investigation. Furthermore, the EFA was also calculated with the use of the empirical method that is adopted in Greece.

IHA method

Richter *et al.* (1997) suggested the IHA (Indicators of Hydrologic Alteration) method in order to evaluate the eco-hydrological characteristics of a river. The rationale of the IHA method is to calculate the mean and the standard deviation of the EF, followed by the calculation of various indices with which the ecological environment of the rivers is defined. This method uses 32 hydrological parameters, which are divided in five groups, providing a detailed representation of the hydrologic regime. The EF calculated with the IHA method can be classified into five categories including the low flows, extreme low flows, high flow pulses, small floods, and large floods. The IHA method uses the Range of Variability Approach (RVA) to make an RVA analysis to compare two time periods. This approach captures the annual variability of natural flow regimes over multiple temporal scales and incorporates a large number of ecologically-based hydrologic indices in its analysis.

Due to the low river flows observed in this case study, the low flows classification method was adopted as the basic ecological flow in the stream. All the hydrologic parameters, such as the magnitude and duration of annual extreme water conditions, the timing of annual extreme water conditions, the frequency and duration of high and low pulses, and the rate and frequency of water condition changes (Risley *et al.,* 2010), were calculated with the use of the appropriate software developed by The Nature Conservancy (TNC) to support the specific hydrologic evaluations (Richter *et al*., 1997).

Tennant method

The Tennant method is based on the correlation between the percentage of mean annual flow during certain years (or months) and the ecological environment in the river course, in order to calculate the water demand needed for the maintenance of certain ecological functions (Tennant, 1976). It is considered that 10% of the mean annual flow is the recommended minimum transient runoff needed by habitats for the survival of most aquatic organisms, 30% is the recommended suitable runoff and 60% is the recommended best runoff for most aquatic organisms (Tennant, 1976). To maintain the “good” river conditions, the Tennant method suggests:

$$EF = Q_1 * 20\ \%\ \text{(wet season)} \quad (1)$$

$$EF = Q_2 * 40\ \%\ \text{(dry season)} \quad (2)$$

where EF is the calculated Environmental Flow, Q_1 is the mean annual flow in the wet season and Q_2 is the mean annual flow in dry season.

Environmental flow assessment in Greece

In Greece, the application of ecological flow is based on the institutional framework of the Ministerial Decree (MD) 12160/1999. This framework is also used by the Regulatory Authority for Energy (RAE) and the Ministry of Environmental Energy and Climate Change for the operational licensing of small hydro projects. The method followed in Greece is an empirical method and was created to protect rivers from overexploitation in cases where hydroelectric projects operate. The EF is calculated as:

– 30% of the summer flow of the river, or
– 50% of the flow in September, or
– 30 L/s (0.03 m^3/s) at any time

In large rivers in Greece, the ecological flow is empirically defined by specific constant values throughout the year. In the case of the Nestos River for example, the designated EF is 6 m^3/s. This value has since become a *de facto* standard in all impact studies carried out in the river basin and is considered as being the minimum water flow that should reach the river delta (Skoulikaris *et al.*, 2012).

AREA UNDER INVESTIGATION

An elevated agricultural area in Western Macedonia was selected to apply the EFA methods. The area consists of the watershed of the Ano Melas stream and the existing irrigation dam. The watershed, which is located in the Prefectures of Kastoria and Florina, covers an area of over 20 km^2, with a stream length of 8 km, average slope of 9% and belongs to the drainage network of the Aliakmon River. The minimum discharges were observed during the summer period (Qmin = 0.1–0.15 m^3/s), maximum discharges in March and April (Qmax = 0.6–0.8 m^3/s) and the average rainfall in the sub-basin ranges between 700 and 750 mm per year. Downstream of the stream, there is an irrigation dam, which was constructed in 2006 to cover the irrigation needs of the region and to protect the area from frequent and intense floods. The elevation at the construction site of the dam is 1036 m, the hydraulic height is 18 m and the maximum inflow in the reservoir has been estimated at 15 m^3/s

For the integrated hydrological modelling of the sub-basin, the MIKE SHE hydrological model was applied using all the available hydrological data from the specific area. Daily rainfall time series covering a period of 25 years (1980–2005), as well as the digital terrain model, land cover, cultivation data and permeability characteristics were used as input data. Calibration of the model was conducted with observation discharges from three hydrological years, from October 2000 to September 2003. The hydrological year 2000–2001 was a dry year, in contrast with the years 2001–2003, which were characterized as wet years. The simulated discharges of a period of 25 years (1980–2005) were used to calculate the environmental flow.

RESULTS

In the given region, the authors applied the IHA and Tennant EFA hydrological methodologies, as well as the empirical method specified under Greek Law. For the winter period, the IHA method gave the highest EFs $Q_{max(IHA)}$= 0.33 m^3/s, while the EF calculated using the Tennant method was much lower $Q_{max(Tennant)}$= 0.1 m^3/s. For the summer, both methods resulted in relatively

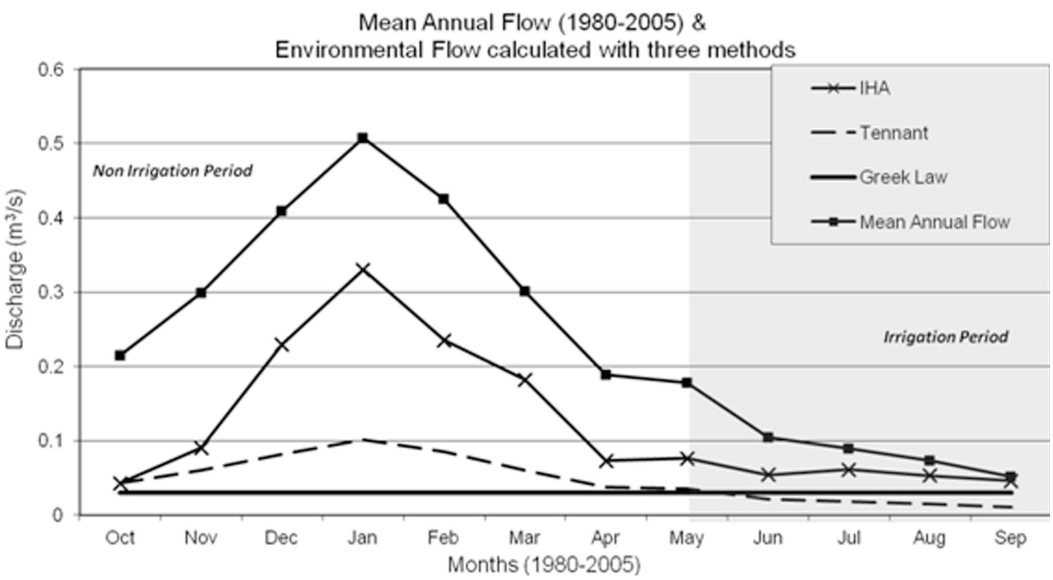

Fig. 1 The calculated environmental flow using the three different methods for a period of 25 years (1980–2005) in comparison with the river discharges.

low EFs with $Q_{min(IHA)}$= 0.05 m^3/s and $Q_{min(Tennant)}$= 0.01 m^3/s, in accordance with the low discharges. The EF based on the empirical method specified under Greek Law was fixed ($Q_{GreekLaw}$= 0.03 m^3/s) throughout the year.

The EF calculated using both the IHA and the Tennant methods follow the pattern of the simulated discharges. This value results from the mean annual flow of the stream on which the calculation of the EF is based. This means that low EFs are predicted for late summer and increased EFs for early- to mid-spring. In the case of the IHA method, the EF varies from 0.05 m^3/s at the end of the irrigation period in September to 0.33 m^3/s in February, while in the case of the Tennant method, lower values are predicted for August and increased values for March. An illustration of the results for the hydrological years 1980–2005 is presented in Fig. 1. The irrigation period lasts five months from May until the end of September. The critical period for the discharges released by the dam is during the summer, when the irrigation demands need to be met.

DISCUSSION

When designing a hydropower project it is necessary to have a firm estimation of the total water volumes transported by the river, in order to define the potential availability of stored water in the reservoir. Although the type and magnitude of impacts varies from project to project, even small scale constructions on a river course may leave a significant environmental footprint at local and regional scales (Kumar *et al.*, 2011). The quantity of water released in the riverbed for the maintenance of the EF should definitely have been considered during the planning phase of any small HEP. In cases where hydropower projects are coupled with a demand for water for irrigation purposes, the irrigation period, which coincides with the lower seasonal river runoff, is critical if all demands are to be met.

According to the results obtained from the application of two EFA methods and the empirical method, the recommended amount of water that should flow from the dam in the Ano Melas stream varies according to which method is applied. The empirical method proposed under Greek Law suggests a constant EF throughout the whole year, satisfying increased instream flow during the summer period. However, this method does not take into consideration the surplus water available in winter, and is generally somewhat unrealistic and dissimilar to any other EFA method. As shown in Fig. 1, the curve of the environmental flow calculated using hydrological methods has the same trend as the flow duration curve of the stream.

The implementation of the IHA method revealed that it is quite a complicated method and it is difficult if not impossible to calculate some of the parameters involved using standard spreadsheet or statistical software (Risley *et al.*, 2010). The IHA software package calculates the entire suite of parameters by using daily streamflow data. In the case of this study, the lack of long time series of observations was overcome by the use of simulated discharges derived from a hydrology model. The results demonstrated that this method is suitable for small watersheds, and that it pays particular attention to the minimum calculated values. In comparison with the other methods, the estimated EF increases when there is excess runoff, i.e. in winter, and is quite low when there is water scarcity, i.e. in summer time. The Tennant method is best suited to rivers with large basins, since the results obtained for the case of the small watershed of Ano Melas River indicate an underestimation of the yearly environmental flow regime, even during the winter. Particularly during the irrigation period, the EF calculated was extremely low, especially if the losses due to evaporation are taken into account.

To sum up, in small watersheds with discharges having the same trends as those of the Ano Melas River, irrigation demands cannot be covered without the existence of water related projects such as dams. The dam releases can also serve to maintain a minimum EF, even in summer when a runoff shortage is observed. For small watersheds, the assessment of the environmental flow regime is best approached using the IHA method as this produces the most rational results. In the case of multipurpose dams, a compromise between all uses should be achieved, with the EF having the highest priority amongst other water demands.

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