European Water 60: 167-173, 2017.

Environmental flow assessment through integrated approaches

M. Tegos, I. Nalbantis and A. Tegos*
Centre for the Assessment of Natural Hazards and Proactive Planning & Laboratory of Reclamation Works and Water Resources Management, School of Rural and Surveying Engineering, National Technical University of Athens, Athens, Greece
* *e-mail: tegosaris@yahoo.gr*

Abstract: The alteration of river flow regime downstream of artificial dams is known to negatively affect the health of the riparian ecosystems, the geomorphology of the riverbed and riparian zone as well as the quantity and quality of river waters. To avoid such impacts releases from dams are scheduled so as to sustain the so called environmental flow. This work aims at investigating the differences and complementarities of various methods used for the assessment of environmental flow. Firstly, we extended the historical daily flow time series through using a rainfall-runoff model so as to overcome the problem of inadequate length of this series. Subsequently, different simple and advanced hydrological methods were applied (Tennant method; minimum monthly flow method; flow duration curve method; the method of basic maintenance flow; the Range of Variability Approach). Also, a hydraulic method (wetted perimeter-discharge technique) was applied using data from several river cross-sections. This method allowed the establishment of an empirical relationship between flow and wetted perimeter. Finally, crucial ecological criteria such as the fish survival requirements under different hydrological and hydraulic regimes were investigated in an effort to formulate an integrated framework for environmental flow assessment. The different approaches were tested on a human modified river with a water supply dam (Mornos), located in the Water District of West Sterea Hellas, Greece.

Key words: Environmental flow; dam operation; human modified river; Mornos river

1. INTRODUCTION

The continuing increase of water demand for irrigation abstractions, drinking water, and hydroelectric power production has led to the construction of large-scale water resources projects (Koutsoyiannis, 2011) that caused modifications to the biotic and abiotic environment of rivers. The constructed works often require scientific explanations regarding the alteration on the physical environment (Koutsoyiannis et al., 2007). The environmental flow (EF) as a key measure in water resources management has been intensively studied during the last five decades (Acreman et al., 2014). Usually, the sustainable use of water resources requires that conflicting water targets are met (Christofides et al., 2005) e.g., keeping water in storage and releasing it for various uses. The environmental flow depends on multiple factors, such as the size of river bed, flow seasonality at both coarse and fine time scales, flow duration characteristics, surface and subsurface water levels (Acreman and Dunbar, 2004), as well as the downstream ecological value and chemical status of the surface water bodies.

In this study, we focus on the assessment of environmental flow in Mornos river, where a water supply dam is operated without provision of environmental releases. We use several methods of wide applicability and discuss the practical use of different environmental flow policies for the maintenance of the riverine ecosystem, considering hydrological, hydraulic and ecological criteria.

2. METHODS FOR ASSESSING ENVIRONMENTAL FLOW

2.1 General

The first systematic attempt for the quantification of environmental flows started in the U.S.

around 1950 with the Tennant Method which was based on the correlation between fish sustainability and hydrological regime (Tennant, 1976). According to bibliography (Tharme, 2003), 207 methodologies have been applied to 44 different countries. These can be divided into four main categories depending on the type, size, quality and availability of the required data, data processing, assumptions time and cost. These categories are the following: (1) hydrological methods (simplified or advanced); (2) hydraulic rating methodologies; (3) habitat simulation methodologies; (4) holistic methodologies.

The first category of methods includes the most elementary approaches, in which EF is usually assessed as a constant percentage of a flow statistic at the annual or monthly scale. Recently, more sophisticated methods have been developed, suggesting a hydrological regime for the maintenance of the river system at acceptable levels. Examples of these advanced methods are the Range Variability Approach method and the Basic Maintenance Flow method.

The second category uses a number of hydraulic, morphological and geometrical characteristics (wetted perimeter, depth, velocity, etc.). The key idea is to equate EF to a critical low flow based on the river cross section geometry (Gippel and Stewardson, 1998).

Methods of the third category, e.g., the Habitat Simulation method, assess EF on the basis of detailed analyses of the quantity and suitability of instream physical habitat, particularly target species or assemblages (mainly fish), observed under different flow regimes. These methods use hydrological, hydraulic and biological data within hydraulic simulation tools, thus allowing for the establishment of a direct link between habitat and discharge (Stalnaker et al., 1995).

The fourth category, referred to as Holistic Methods (Arthington et al., 1992) includes processes that allow aquatic scientists from many disciplines to integrate data and knowledge (King et al., 2003), which is a shift from prescriptive to interactive approaches (Tharme, 2003). Obviously, these are much more demanding than all other approaches, in terms of data and human resources. Details on the selected methods are given next.

2.2 Simple hydrological methods

The following methods were selected: (1) *Tennant method*: this method specifies percentages of mean flow that provide different river quality habitats, i.e. 10% for poor quality (survival), 30% for moderate habitat, and 60% for excellent habitat; (2) *Minimum Annual Flow (MAF)*: the discharge of the driest month over a long series of monthly flows is selected as EF; (3) *FDC method*: using the flow duration curve, typical flow quantiles are calculated such as Q_{60}, Q_{70} , Q_{80} and Q_{90}.

2.3 Basic maintenance flow (BMF) approach

The method studies the irregularities in the daily mean flow series using a moving average model (Palau and Alcázar, 2012; Efstratiadis et al., 2014). In this work, only two parameters were considered: the basic flow (Q_b) which represents the absolute minimum discharge that should flow in a river and the maintenance flow (Q_m) which represents the minimum instream flow requirements of the river throughout the year, usually calculated on a monthly basis (Peñas et al., 2014).

2.4 Range Variability Approach (RVA)

The method is based on the assumption that hydrological conditions of a river fully determine its ecological characteristics. It uses 32 hydrological parameters describing hydrological variability that influences the quality of ecosystems (Richter et al., 1996). The most important of them are: (1)

the 25% and 75% quantiles of monthly discharge which specify the desirable range of monthly flows; (2) indicators for extreme hydrological conditions, which are expressed as the mean and upper and lower limit for the annual maximum and minimum of d-day flow, where d = 1, 3, 7, 30, and 90 days.

2.5 Wetted perimeter - discharge method

The breakpoint of the wetted perimeter–discharge curve at characteristic cross-sections is typically used as an indicator of the corresponding critical flow. In this work, we employed the maximum curvature approach proposed by Gippel and Stewardson (1998) to define the lower breakpoint of each wetted perimeter–discharge curve; the latter was constructed using the Manning's equation.

2.6 Examination of the restrictions for the habitat growth

In an effort to exploit ideas of modern approaches such as the Habitat simulation and Holistic methods, we use survey data from a fish monitoring campaign downstream the studied dam. Then, we identify a number of fish species and some critical biological parameters related to flow (e.g., water depth, spawning seasonality).

3. STUDY AREA AND DATA

The Mornos dam (Figure 1) started its operation in 1981 as one of the largest clay core earthen dams in Europe. The dam embankment has a maximum height of 139 m from the foundation level, a crest width of 10 m, and a base length of 250 m. The altitude of the dam crest from the mean sea level stands at 446.5 m, while the highest flood level is 435 m. The related Mornos reservoir serves water supply of the Athens metropolitan area (Nalbantis et al., 1992).

Regarding the reservoir characteristics, the average annual water volume is 240×10^6 m^3 and 195×10^6 m^3 for inflows and releases respectively, while the total storage capacity is approximately 764×10^6 m^3. In this work the study area is the river basin at the dam site (Figure 1), as well as the river bed and floodplain downstream of the dam.

The geomorphological and hydrodynamic conditions of the estuary favoured the development of important wetlands, with significant biological diversity. Regarding fish fauna, seven species have been identified, including the five species presented in the results section and also Pseudophoxinus, and Valencia letourneuxi. Birds are the largest group of vertebrates (Aquila chrysaetos, Circaetus gallius, Buteo, Falco, Accipiter, Cachybaptus rufficollis, Alcedo atthis). Finally, there exist several species of reptiles and amphibians that are protected at the international level (e.g., Lutra- Lutra).

The daily streamflow time series is the main dataset for assessing EF. The absence of such series of significant length led us to resort to estimating streamflows using rainfall-runoff modelling. This included the following computational steps: (1) Preparation of the required geographical information; (2) collection of daily rainfall from eight stations for the period 1964-1980; (3) processing of rainfall data; (4) calibration of a lumped conceptual hydrological model for the period 29/1/1964-30/9/1966; the model used by Efstratiadis et al. (2015) was adapted using typical inputs such as rainfall and potential evapotranspiration (Tegos et al., 2013); the Nash-Sutcliffe Efficiency (NSE) was 0.82 in calibration; the agreement between the observed and simulated streamflows was satisfactory (Figure 2); (5) estimation of daily flow for the period 1964-1980 using the calibrated model.

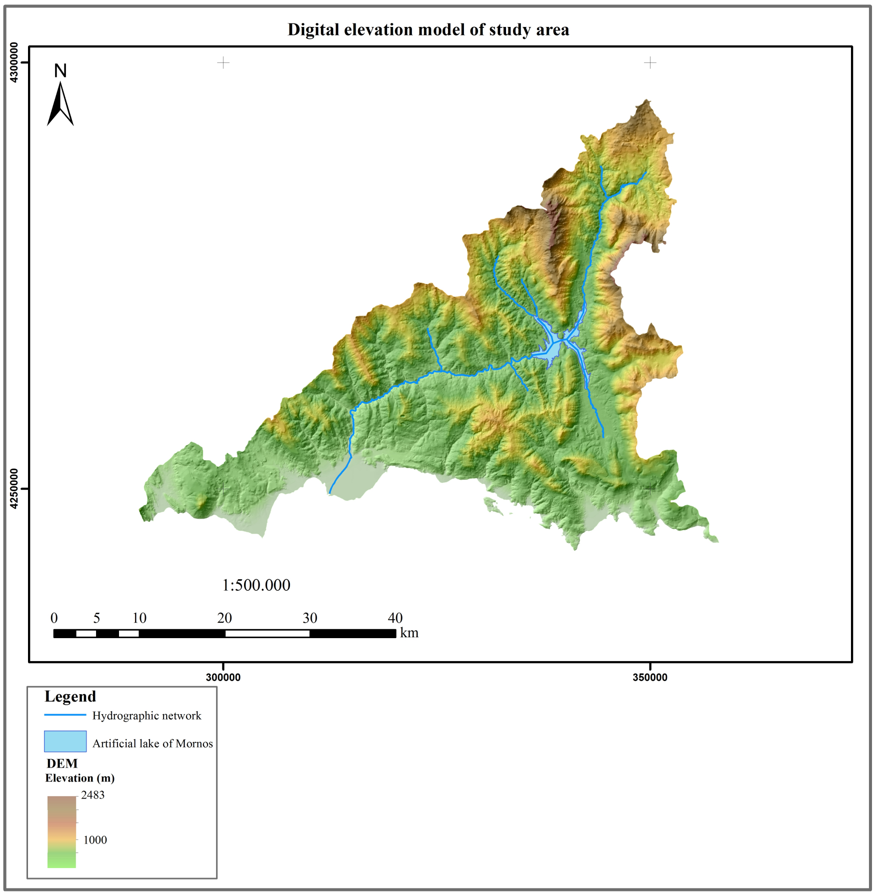

Figure 1. Digital Elevation Model of the Mornos river basin

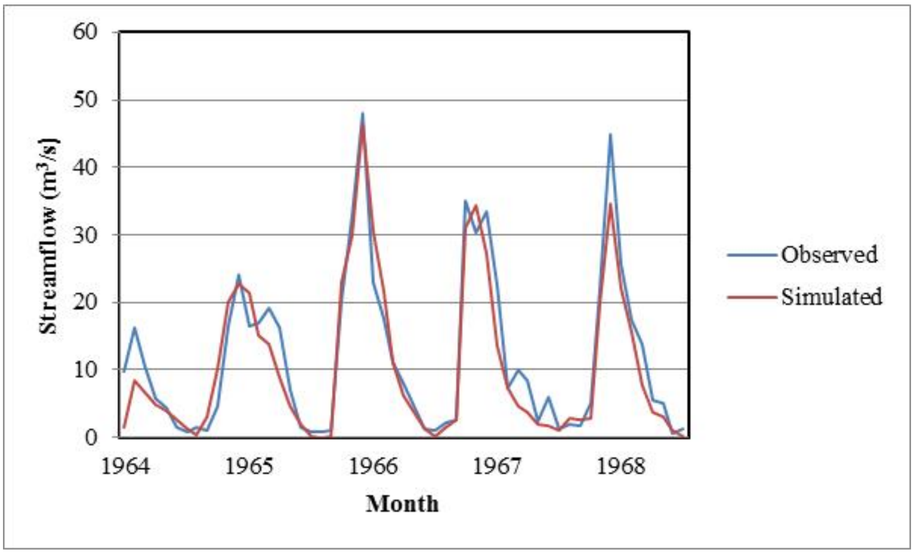

Figure 2. Monthly simulated and observed flows for both the calibration and validation periods

4. RESULTS

The simple hydrological methods provided the following results: (1) The Tennant method gave critical flow values for poor, moderate and excellent quality of habitat respectively 0.93, 2.80 and 5.60 m^3/s; (2) following the MAF method the driest month was August and its minimum flow over the period 1964-1980 equal to 0.85 m^3/s; (3) the FDC method yielded $Q_{60} = 4.2$ m^3/s,

$Q_{70} = 3.0$ m^3/s, $Q_{80} = 2.0$ m^3/s and $Q_{90} = 0.9$ m^3/s.

The BMF method provided us with a basic flow estimated at 0.85 m^3/s and a monthly maintenance flow ranging between 1.06 and 5.33 m^3/s. The RVA method yielded the 25% and 75% flow quantiles shown in Table 1 as well as the indicators for extreme hydrological conditions given also in Table 1.

To apply the wetted perimeter–discharge method we selected eighteen representative river cross-sections along the lower course of Mornos river. Next, we constructed the wetted perimeter–discharge curve for each one of the selected cross-sections. The critical flow over the eighteen cross-sections was found to range from 2.36 to 9.75 m^3/s.

With regard to modern integrated approaches we collected fish survey data downstream the Mornos dam. Seven species were identified (Economou et al., 2004) and some critical biological parameters are related to flow variables which are given below. These constitute crucial restrictions for decisions regarding flow releases from Mornos reservoir.

1. *Salmo trutta macrostigma*, max height 40 cm, spawning period October- January.
2. *Knipowitschia Sp*, max height 40 cm, spawning period February- April
3. *Barbus peloponnesius*, max height 20 cm, spawning period May- June
4. *Bαrbus albanicus*, max height 30 cm, spawning period May.
5. *Leuciscus cephalus*, max height 22 cm, spawning period February

Additionally, the worldwide significant species of Lutra-lutra is susceptible to water quality and quantity changes and possible loss of the riparian vegetation (Koutsos et al., 2011).

Table 1. Monthly flow values and characteristic flows for Mornos river (m^3/s), calculated using the RVA method.

For flow in month	Mean (m^3/s)	Lower limit (m^3/s)	Upper limit (m^3/s)
January	21.38	10.41	32.36
February	19.64	12.55	26.72
March	13.46	8.62	18.29
April	9.56	6.17	12.96
May	5.39	3.05	7.73
June	3.03	1.80	4.26
July	1.55	0.67	2.42
August	0.85	0.39	1.29
September	1.36	0.36	2.36
October	4.38	0.41	8.35
November	13.32	5.97	20.67
December	21.49	12.46	30.52
Characteristic flow			
1-day minimum	0.15	0	0.50
3-day minimum	0.15	0	0.51
7-day minimum	0.18	0	0.57
30-day minimum	0.36	0	0.92
90-day minimum	0.92	0.24	1.60
1-day maximum	94.66	67.97	121.36
3-day maximum	70.21	49.85	90.57
7-day maximum	47.57	34.76	60.37
30-day maximum	29.60	21.55	37.66
90-day maximum	23.28	16.73	29.82

Table 2 summarizes the results of our analyses which showed the following: (1) The simplified hydrological methods (Tennant, MAF, FDC) propose a lower hydrological threshold which is compulsory; (2) the hydraulic method, even without streamflow data, constitutes a reliable alternative, but, in our case, the information on ground elevation in river bed and floodplain was inadequate and led to a significant overestimation of EF with respect to other methods; (3) the advanced hydrological methods (BFM, RVA) yield a seasonally varying EF regime which is physically consistent and hence more suitable.

Table 2. Summary of results

Category of method	Method	EF (m^3/s)	Flow regime
Hydrological	Tennant	0.93-5.60	Steady flow
	MAF	0.85	Steady flow
	BMF	1.06-5.33	Monthly seasonal flow
	FDC	0.9-4.2	Steady flow
	RVA	0.36-12.55	Monthly seasonal flow
Hydraulic	Wetted perimeter-discharge	2.36-9.75	Steady flow

5. CONCLUDING REMARKS

The assessment and selection of environmental flow is a complicated technical problem depending on the quantity and quality of the existing data (topographical, hydrological, hydraulic and biological) which, in turn, determines the type of approach to be followed. The most representative hydrology-based approaches, as well as the wetted perimeter – discharge method were employed to assess the environmental flows for the Mornos dam in Western Sterea Hellas, Greece. The methods provided a wide range of values, in terms of critical flows or allowable range of them. We recommend a seasonally varying flow, which can better preserve the eco-hydrological regime of the river. The simplified hydrological methods fail to provide such seasonally varying regime which is known to exist in the Mediterranean region. Among two well-known methods accounting for seasonal flow variation, i.e., the Basic Maintenance Flow (BMF) and the Range of Variability Approach (RVA), the former is more suitable than the latter, which is quite complex, difficult to interpret and thus difficult to implement in practice. Finally, the use of data from biological surveys regarding biological parameters of the fish populations is necessary and useful for further optimization and validation of the EF releases.

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