Environmental Modelling & Software 79 (2016) 120–134

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Assessing minimum environmental flows in nonpermanent rivers: The choice of thresholds

Cristina Aguilar [a, *], María José Polo [b]

[a] Fluvial Dynamics and Hydrology Research Group, Andalusian Institute of Earth System Research, University of Granada, Granada, Spain
[b] Fluvial Dynamics and Hydrology Research Group, Andalusian Institute of Earth System Research, University of Cordoba, Cordoba, Spain

ARTICLE INFO

Article history:
Received 29 July 2015
Accepted 1 February 2016
Available online 12 February 2016

Keywords:
Operationality
Minimum environmental flows
Minimum environmental flow regime
Flow cessation periods
Semiarid systems
WiMMed

ABSTRACT

The criteria used in the computation of the minimum environmental flow regime and flow cessation periods in nonpermanent rivers are often left to open criteria. This study proposes a stochastic approach for evaluating the choice of local thresholds in the characterization of minimum environmental flows through both the Monte Carlo technique and local hydrological relationships. This approach is applied to four regimes obtained by hydrologic and hydraulic habitat modeling in a Mediterranean watershed. The operationality, defined as the probability of the calculated environmental regime being satisfied by the natural regime over 25 years, was assessed for eight different scenarios. Two monthly minimum environmental flow regimes were then generated, with 90 and 95% operationality levels. This analysis allows the generation of minimum flow regime prescriptions from a strictly hydrologic point of view. The methodology proposed constitutes a useful tool for the implementation of uncertainty analysis of environmental flows in water resource management.

1. Introduction

The highly variable hydrological response in both space and time justifies the common intensive regulation of water resources through storage reservoir networks in Mediterranean watersheds (Alcázar and Palau, 2010). These networks are designed to guarantee the water supply for irrigated agriculture and the domestic supply, including major increases in the population by tourism along the coast during the summer together with a reduction in the flood risk (Efstratiadis et al., 2014). However, these networks also modify the magnitude and timing of the natural water flow regime and therefore affect the integrity of fluvial ecosystems (Baeza Sanz et al., 2005; García de Jalón, 2003; Hillman et al., 2012; Muñoz-Mas et al., 2014; Navarro et al., 2007).

According to the Water Framework Directive (European Commission, 2000), all River Basin Management Plans (RBMPs) in European countries must include ecological targets in surface waters. To achieve this objective, member states have performed studies of the so-called environmental flow regime (Belmar et al., 2011; Grindlay et al., 2011). The WFD does not use the term environmental flows explicitly (Acreman and Ferguson, 2010), and therefore each European country has set its own environmental standards. Nevertheless, they all must agree with the "natural flow paradigm" introduced by Poff et al. (1997) and supported by most environmental flow experts (Arthington et al., 2006; Bunn and Arthington, 2002; Richter, 2010; Richter et al., 1997, 2012). The key premises of this paradigm are that maintaining some semblance of natural flow regimes is essential to sustaining a healthy river ecosystem.

Five basic components of both maximum and minimum river flows regulate ecological processes in river ecosystems: magnitude, frequency, duration, timing and rate of change of hydrologic conditions (Poff et al., 1997). However, the most critical component of environmental flows in Mediterranean areas is the minimum flow regime because of the seasonal character of hot and dry summers, which leads to water shortages in the summertime when the water demand is high. Thus, the minimum regime constitutes the basis of this study.

In general, two main methodologies for the calculation of minimum environmental flows at medium-small watersheds are available (Belmar et al., 2011; García de Jalón, 2003). 1) Hydrologic methods apply statistical procedures (e.g., percentiles, moving averages) to the historical series of natural flows, such as the Range of Variability Approach (RVA; Richter et al., 1997) or the Basic Flow

* Corresponding author.
E-mail addresses: caguilar@ugr.es (C. Aguilar), mjpolo@uco.es (M.J. Polo).

http://dx.doi.org/10.1016/j.envsoft.2016.02.003
1364-8152/

Nomenclature

Symbols

ET_0	reference evapotranspiration
$f_{NQabs\text{-}min}$	relative probability of the variable $N_{Qabs\text{-}min}$
f_{Qmi}	relative probability of the variable Q_{mi}
F	number of cessation period events per year
F_{Ne}	cumulative probability of the variable F
$F_{N0.01}$	cumulative probability of the variable $N_{0.01}$
$F_{NQabs\text{-}min}$	cumulative probability of the variable $N_{Qabs\text{-}min}$
F_P	cumulative probability of the variable P
F_{Qmi}	cumulative probability of the variable Q_{mi}
FN_{Fm}	cumulative probability of the number of days with natural inflow below $Q_{abs\text{-}min}$ and with a minimum operationality m
h	water depth
i	calendar month from 1 (January) to 12 (December)
L	length in number of days of the flow cessation period
l_d	number of days when the flow cessation period can be exceeded
m	operationality (1- p_f)
$N_{0.01}$	number of days per year that have a flow rate that is lower than 0.01 m^3/s
$N_{Qabs\text{-}min}$	number of days per year that have a flow rate that is lower than $Q_{abs\text{-}min}$
p_f	probability of failure (1-m)
p5	5^{th} percentile
p50	50^{th} percentile
p95	95^{th} percentile
P	spatially averaged annual rainfall in the contributing area
$\overline{P}$	Mean rainfall
P_v	spatially averaged annual rainfall in the contributing area for the year v
P_{50}	Median rainfall
Q	flow rate
$\overline{Q}$	Mean flow rate
Q_{50}	Median flow rate
$Q_{abs\text{-}min}$	absolute minimum environmental flow
Q_{di}	monthly flow available to be released from the dam
$Q_{dry\text{-}min}$	minimum environmental flow value for the dry season
Q_{mi}	monthly mean flow of the natural regime
$Q_{wet\text{-}min}$	minimum environmental flow value for the wet season
$Q_{min\text{-}i}$	monthly minimum environmental flow
Q_t	annual total flow
r^2	Pearson's coefficient of determination
S	month when cessation periods take place
std	standard deviation
v	water velocity
$\%WUA_{max}$	percentage of the maximum weighted usable area

Abbreviations

cdf	empirical cumulative probability distribution function
EFC	Environmental Flow Components
IDW	Inverse Distance Weighted
IHA	Indicators of Hydrologic Alteration
Max	maximum
Min	minimum
pdf	empirical probability distribution function
PHABSIM	Physical Habitat Simulation System
RBMP	River Basin Management Plan
RVA	Range of Variability Approach
SWPI	Spanish Water Planning Instruction
WFD	Water Framework Directive
WiMMed	Water Integrated Management for Mediterranean Watersheds
WUA	weighted usable area

Greek symbols

η	Parameter of the mathematical fit
θ	Parameter of the mathematical fit
σ_Q	standard deviation of the rainfall
σ_Q	standard deviation of the flow rate

Method (BFM; Palau and Alcázar, 1996). A review of these methods can be found in Tharme (2003). These methods are easy to apply, although accurate long-term natural flow records must be available (Alcázar et al., 2008). 2) Hydraulic habitat methods such as the Physical Habitat Simulation System (PHABSIM; Bovee, 1982; Milhous et al., 1989; Waddle, 2012). PHABSIM assesses the habitat suitability of the fluvial bed for fish communities as a function of the tolerance of these species to the flow conditions. These methods are even more data-intensive than hydrologic methods as detailed field measurements of the geomorphology, the hydraulics and the instream habitat are required (Liu et al., 2005).

Some of these methodologies have been strongly criticized because they provide a fixed or absolute minimum flow value and ignore the natural temporal variability of river flows (Alcázar and Palau, 2010; Efstratiadis et al., 2014). Thus, certain computations must be applied to obtain the environmental regime that preserves the main ecological functions that natural flow regimes achieve (Acreman and Dunbar, 2004; Poff et al., 1997; Pastor et al., 2013). Moreover, nonpermanent or semiarid rivers (seasonal, intermittent and ephemeral) are frequent in Mediterranean areas, even under the natural regime (Belmar et al., 2011), which constitutes an additional source of complexity in the evaluation of minimum flow regimes. Flow cessation periods constitute a relevant aspect in these areas (Baeza Sanz et al., 2005; Hughes, 2005). Thus, the priority in semiarid areas is to produce the most accurate assessment possible of not only the magnitude but also the timing duration of the imposed minimum flows and flow cessation periods, to provide a certain level of protection for the aquatic environment.

Regardless of the methodology, the legislation usually states fixed indices or ranges of thresholds in the different hydrological descriptors of the minimum environmental flow regime and flow cessation periods (Efstratiadis et al., 2014; Muñoz-Mas et al., 2014; Paredes Arquiola et al., 2013). The final choice of the thresholds within the ranges proposed is quite subjective and left to open criteria, whereas the result is a fixed minimum flow value that must be supplied out of the flow cessation period. Instead, thresholds should be specifically set to avoid unrealistic shifts from the natural conditions at each river stretch following the natural flow paradigm. Moreover, temporal variability in the thresholds applied should be considered to reflect the highly hydrological variability often found in semiarid areas.

This work proposes a stochastic approach for evaluating the choice of local thresholds in the characterization of minimum environmental flow regimes and flow cessation periods that meet