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Review

Ecological flow in southern Europe: Status and trends in non-perennial rivers

Marianna Leone [a,b,*], Francesco Gentile [a], Antonio Lo Porto [b], Giovanni Francesco Ricci [a], Anna Maria De Girolamo [b]

[a] Department of Soil, Plant and Food Sciences, University of Bari Aldo Moro, Bari, Italy
[b] Water Research Institute, National Research Council, 5 Viale F. De Blasio, 70132, Bari, Italy

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ABSTRACT

The concept of environmental flows (E-Flows) describes the streamflow that is necessary to maintain river ecosystems. Although a large number of methods have been developed, a delay was recorded in implementing E–Flows in non-perennial rivers. The general aim of the paper was to analyse the criticalities and the current state of implementation of the E-Flows in non-perennial rivers of southern Europe. The specific objectives were to analyse (i) the European Union (EU) and national legislation on E-Flows, and (ii) the methodologies currently adopted for setting E-Flows in non-perennial rivers in the EU Member States (MSs) of the Mediterranean Region (Spain, Greece, Italy, Portugal, France, Cyprus, and Malta). From the analysis of national legislations, it is possible to acknowledge a step forward toward regulatory unification at the European level, on the subject of E-Flows and more generally toward the protection of aquatic ecosystems. The definition of E-Flows, for most countries, has abandoned the idea of a regime of constant and minimal flow, but it recognizes the importance of the biological, and chemical-physical aspects connected to it. From the analysis of the E-Flows implementation through the review of the case studies, one can surmise that in non-perennial rivers the E-Flows science is still an emerging discipline. The limited availability of hydrological, hydraulic, and biological data as well as the restricted economic resources allocated for managing non-perennial rivers are the main causes of the delay in the E-Flows implementation in MSs. The results of the present study may contribute in setting an E-Flow regime in non-perennial rivers.

1. Introduction

In the territories of the Member States (MSs) of the European Union (EU), about 65% of the rivers are regulated by one or more dams (World Commission on Dams, 2000), which have altered the natural flow regime. Intensive water abstraction from streams and groundwater and flow regime alterations cause habitat loss and represent the main threats to biodiversity by compromising the functionality of aquatic ecosystems (Schneider et al., 2013; Postel et al., 1996). The concept of environmental flow (E-Flows) has been introduced to depict the streamflow that is necessary to maintain river ecosystems. In the past decades, the allocation of water to natural environmental systems has often been recognized as a minimal amount, implemented as a constant flow (Acreman and Ferguson, 2010). Subsequently, many eco-hydrological studies have shown that all components of the flow regime (e.g. duration, magnitude, timing frequency and rate of change of water conditions) affect freshwater ecosystems (Junk et al., 1989; Richter et al., 1996; Poff et al., 1997). Based on the assumption that flow regime and water quality are major determinants of river ecosystems, in 2007, river scientists defined the E-Flows in a more holistic way as the "quantity, quality and timing of flow necessary to support aquatic ecosystems, which in turn support crops, the economy, sustainable livelihoods, and human well-being" in the so-called "Brisbane Declaration" (Arthington, 2012). The European Commission's (EC) supported this concept through the Water Framework Directive (WFD; European Commission, 2000), which while not mentioning the term E-Flows (Ramos et al., 2018) introduced an innovative approach to European water legislation to improve the ecological status of water bodies and to ensure sustainable use of available water resources. In 2015, the EC developed the Guidance Document n.31 - "Ecological flows in the implementation of the Framework Directive" (CIS n.31; European

* Corresponding author. Department of Soil, Plant and Food Sciences, University of Bari Aldo Moro, Bari, Italy.
E-mail addresses: marianna.leone@ba.irsa.cnr.it (M. Leone), francesco.gentile@uniba.it (F. Gentile), antonio.loporto@ba.irsa.cnr.it (A. Lo Porto), giovannif.ricci@gmail.com (G.F. Ricci), annamaria.degirolamo@ba.irsa.cnr.it (A.M. De Girolamo).

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Glossary. Annex A1

C_Ms	Combined Methods
CIS n.31	Guidance Document n.31 - "Ecological flows in the implementation of the Framework Directive"
DMV	Minimum Acceptable Flow
DOEs	Débits Objectifs d'Etiage
EC	European Commission
E-Flows	Ecological Flow regime
EIA	Environmental Impact Assessment
ELOHA	Ecological Limits Of Hydrologic Alteration
EMC	Environmental Management Class
EU	European Union
FDC	Flow Duration Curve
GEFC	Global Environmental Flow Calculator
GEP	Good Ecological Potential
GES	Good Ecological Status
H_Ms	Holistic Methods
HB_Ms	Habitat simulation Methods
HD_Ms	Hydraulic Methods
HH_Ms	Hydrologic-hydraulic Methods
HL_Ms	Hydrological Methods
HMWBs	Heavily Modified Water Bodies
IFIM	Instream Flow Incremental Methodology
IHA	Indicator of Hydrological Alteration
MAF	Mean Annual Flow
MCF	Minimum Constant Flow
MCF	Minimum Constant Flow
MD	Ministerial Decree
MSs	Mamber States
O_Ms	Other Methods
PHABSIM	Physical Habitat Simulation System
PNA	National Water Plan
RBD	River Basin District
RBMPs	River Basin Management Plans
RVA	Range of Variability Approach
SDAGE	Schémas Directeurs d'Aménagement et de Gestion des Eaux
SIMPA	Integrated System for Rainfall-Runoff Modelling
SRD	Suitable Range Discharge
SWAT	Soil and Water Assessment Tool
WCMP	Water Catchment Management Plan
WFD	Water Framework Directive
WiMMED	Water Integrated Management for Mediterranean Watersheds
WPM	Wet Perimeter Method
WUA	Weighted Useable Area

Commission, 2015), providing the definition of "ecological flows" (henceforth "E-Flows") of natural surface water bodies as "a hydrological regime consistent with the achievement of the environmental objectives of the WFD referred to in Article 4 (1)". These environmental objectives refer to (i) non-deterioration of the existing status, (ii) achievement of "good ecological status" (GES) in natural surface water bodies and (iii) compliance with standards and objectives for protected areas (CIS n.31). For the heavily modified water bodies (HMWBs), E-Flow regime was defined distinctively as the flow regime consistent with "good ecological potential" (GEP) that should be very close to the E-Flows. The WFD and CIS n.31 did not differentiate perennial from non-perennial rivers. Indeed, this important issue is not considered by the MSs, and it is rarely contemplated in the E-Flows setting (Acuña et al., 2020).

The countries of the Mediterranean Region are characterized by the presence of non-perennial rivers (i.e., temporary, intermittent, ephemeral), which represent an important source of water supply for the population (Borg Galea et al., 2019). In recent decades, human activities and climate change have been added to the natural causes of intermittency (e.g., climate, geology, lithology), contributing to the shift of the natural flow regime of waterways towards more "temporariness" or "non-perennial" conditions (De Girolamo et al., 2017; Skoulikidis et al., 2017). The streamflow regime of such rivers is highly variable in space and time (D'Ambrosio et al., 2017; Oueslati et al., 2015). These peculiarities together with the scarcity of hydrological and ecological data, which is common for these river systems (Skoulikidis et al., 2017; Tramblay et al., 2021), make it difficult to characterize flow regime and set an E-Flow regime (De Girolamo et al., 2022a).

Several critical reviews investigated the methodologies for setting E-Flows (Annear et al., 2002; Arthington et al., 1998; Arthington, 2012; Dyson et al., 2003; Dunbar et al., 1998; Hatfield et al., 2013; Jowett, 1997; Stalnaker and Arnette, 1976; Pastor et al., 2014), their advantages and disadvantages (Acreman and Dunbar, 2004; Arthington, 2012), the historical perspective (Gopal, 2013), their implementation around the world (Tharme, 2003), or in specific areas (Hatfield and Paul, 2015; Linnansaari et al., 2012; Moccia et al., 2020; Sharma et al., 2022; Ramos et al., 2018). However, these studies did neither investigate how the national legislation of the MSs of the Mediterranean Region defined the E-Flows for non-perennial rivers, nor investigate the causes of the delay recorded in the E-Flows implementation and to our best knowledge, no studies relating to case study applications in non-perennial rivers were published. The general aim of the paper was to analyse the criticalities and the current state of implementation of the E-Flows in non-perennial rivers of southern Europe through a review of the scientific literature. The specific objectives were to: i) explore the evolution of both national and EU legislation on E-Flows, and ii) analyse methodologies currently adopted for setting an E-Flow regime in southern Europe for non-perennial rivers. The work focuses on the EU MSs bordering the Mediterranean Sea: Italy, Spain, Portugal, France, Greece, Cyprus, and Malta, where non-perennial rivers are the most common waterways. The first section of the paper is dedicated to the review of the most important methods for setting up E-Flows. The second section analyses the EU (WFD and CIS n.31) and national legislations of the Mediterranean MSs to highlight their potential and weaknesses in terms of E-Flows and non-perennial rivers. Finally, the Scopus database was used to select case studies on E-Flows implementations in non-perennial rivers. This work provides an overview of E-Flows, and going into the details of the case studies, it highlights the critical points in E-Flows implementation in non-perennial rivers, it provides the basis for improving the approaches and evaluating possible future strategies.

2. Approach

To fill the gaps of the previous studies, the evolution of the legislation about the E-Flows in the Mediterranean MSs was analysed, and the research was conducted using the websites managed by national institutions (e.g., Boletin Oficial de Estado, https://www.boe.es/). It is acknowledged that information extrapolated from the research is incomplete. Some works were not available for consultation and others were written in the native language, compromising their usability at a scientific level. Articles reporting case studies were analysed to investigate the status of the E-Flow regime implementation in non-perennial rivers in the MSs of the Mediterranean Region. To this aim, potentially relevant papers were selected in Scopus by searching in the title, abstract, and keywords for the following words: *environmental flows*, *ecological flows*, *instream flows,* and *minimum legal flow* (Fig. 1). By using

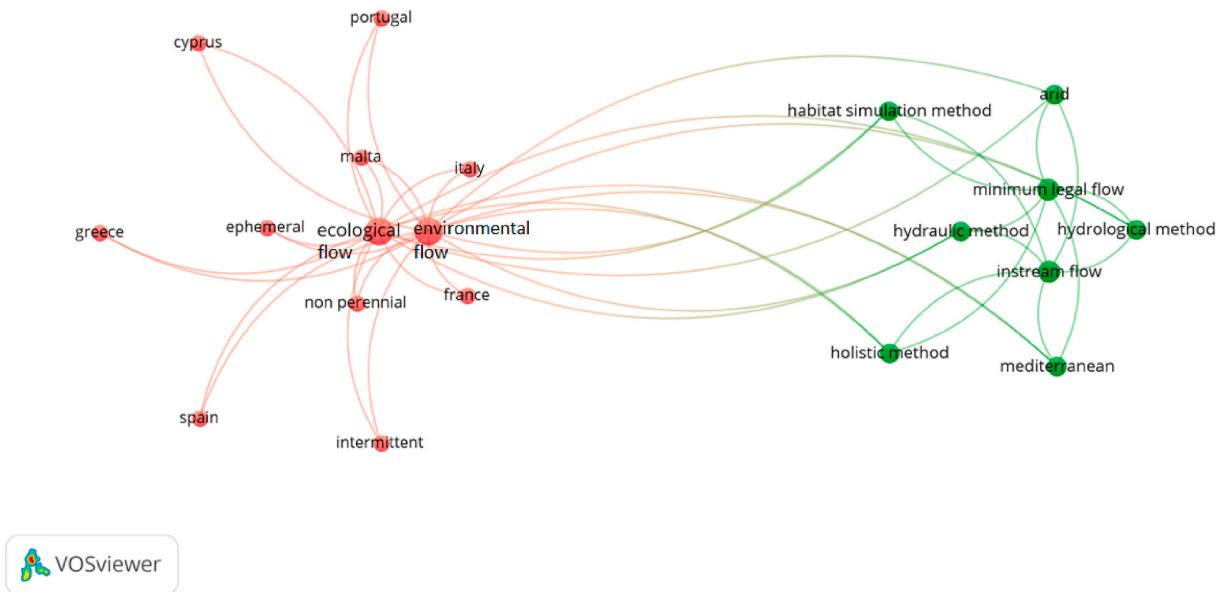


Fig. 1. Keywords used for the review (VosViewer).

the "AND" function of Scopus, the research was skimmed in terms of methods (*hydraulic*, *hydrological*, *holistic,* and *habitat simulation*) "AND" ecosystem type (*rivers* or *streams* and *ephemeral*, *intermittent*, *temporary, and non-perennial*). As many studies did not explicitly report the nature of the rivers, subsequent skimming was carried out based on the location of the study area: *semi-arid, Mediterranean area, France, Italy, Portugal, Spain, Greece, Malta, and Cyprus*. An initial set of 132 articles was analysed. All abbreviations used in the paper are summarized in the Glossary (Annex A1).

3. Environmental flow methods

Since 1940, many methods (specific assessment), approaches (ways of working), and frameworks (strategy for flow management) have been developed to assess an E-Flow regime (Dyson et al., 2003; Tharme, 2003). Tharme (2003) classified the E-Flow methods reported in the literature into four groups: hydrological methods (HL_Ms), hydraulic methods (HD_Ms), habitat simulation methods (HB_Ms), and holistic methods (H_Ms) and he identified two additional groups: combined methods (C_Ms) that incorporate hydrological, habitat-discharge and holistic elements, and other methods (O_Ms) (Table 1). The latter were not developed "ad-hoc" to set the E-Flows but are tools for a subsequent evaluation of the E-Flows (e.g., classification of the flow regime or classification of fluvial invertebrates). Dyson et al. (2003) and Acreman and Dunbar (2004) proposed the following classification of the methods for setting an E-Flow: *Look-up tables* (based on simple indices), *Desktop analysis* (based on whole flow regime and ecological data if available), *Habitat modelling* (identify relationships between physical habitat and flow which will then be connected to scenarios of river flow), *Functional analysis* (integrate hydrological, hydraulic and biological data and the expert contribution) (Table 2). Lastly, The Nature Conservancy has divided the E-Flow frameworks in three levels. Level 1 relates to the application of a method (i.e., HL_Ms, HD_Ms, HB_Ms, O_Ms); Level 2 develops initial flow recommendations on a multidisciplinary expert judgment basis; Level 3 is a complex process that examines trade-offs and predicts the results of operational changes.

3.1. Hydrological methods

HL_Ms constitute a valid approach for setting an E-Flow regime when biological and hydrological data are limited (Arthington, 2012). In the

Table 1
Tharme classification (Tharme, 2003).

Method	Data input required	Examples	Abbreviation
Hydrological	Long-term time series of measured or estimated streamflow under natural conditions.	Tennant method, Tessman method, RVA	HL_M
Hydraulic	Flow-dependent ecological data	Wetted Perimeter method	HD_M
Habitat simulation	Relationship between the hydraulic characteristics of the river stretch and the dataset of the chosen target species (e.g., habitat suitability)	IFIM, PHABSIM	HB_M
Holistic	Combination of hydrological, hydraulic, and expert knowledge	ELOHA	H_M
Combined	Hydrological, habitat-discharge, and holistic elements	3H-EMC (hydrological, hydrodynamic, and habitat modeling with the use of the Environmental Management Classes (EMCs))	C_M
Other	multivariate regression analyses	Classification	O_M

Table 2
Dyson classification (Dyson et al., 2003) and Acreman and Dunbar classification (Acreman and Dunbar, 2004).

Method	Description
Look-up table	Based on simple indices
Desktop analysis	Consider the entire flow regime and ecological data if available
Habitat modeling	Relationship between the hydraulic characteristics of the river stretch and the dataset of the chosen target species (e.g., habitat suitability)
Functional analysis	Integrate hydrological, hydraulic, and biological data and expert knowledge.

past, HL_Ms were based on minimum flow thresholds (Pastor et al., 2014), but over the years they have been modified by incorporating the scientific evidence that river ecologists have demonstrated: all the components of the hydrological regime influence aquatic life (Poff et al., 1996). Based on this paradigm, an E-Flow should mimic the natural hydrological regime (Richter et al., 1996). HL_Ms operate at any species-specific level, providing the necessary flow for ecological sustenance (Linnansaari et al., 2012). Although these methods are accompanied by uncertainty about the flow-ecology relationship (Acreman and Dunbar, 2004), they are the most widely used methods (Gopal, 2013). HL_Ms are based on streamflow data able to describe the flow regime in natural conditions. To include the inter-annual flow regime variability, long-term time series of streamflow are needed (at least 20 years). Among the plethora of HL_Ms, the Tennant method (also called the Montana method; Tennant, 1976) is one of the oldest (Pyrce, 2004). The method, which has been developed for the needs of fishes, defines the relationship between flow and aquatic habitat suitability. It expresses the E-Flow recommendations in terms of the percentage of the Mean Annual Flow (MAF) (i.e., 10%–30% MAF) (Shaeri Karimi et al., 2012; Pyrce, 2004). Several modifications were proposed for improving this method, differentiating high flow and low flow periods (Orth and Maughan, 1981) or incorporating the seasonal or monthly variability (i.e., specifying for each month a percentage of mean monthly flows). Tessman (1980) defined E-Flow for each month by using different rules based on a threshold (40% MAF) and including a 14-day period of 200% MAF during the wettest month for channel maintenance. Hatfield and Paul (2015) suggested differentiating E-Flow assessment based on the fish presence or absence and, in the latter case, they suggested a minimum flow (i.e., median monthly flow during the low flow period). For flashy streams, which are characterized by quick increases and decreases in streamflow, Matthews and Bao (1991) suggested using median annual flow instead of MAF. Methods based on the flow duration exceedance (Longobardi and Villani, 2020; Pyrce, 2004) or on single low flow indices (i.e., 7Q2, 7Q10) have been widely used (Olden and Poff, 2003; Pyrce, 2004) for protecting biota and fishes (Smakhtin, 2001; Smakhtin and Toulouse, 1998). Methods based on a shift of the flow duration curve (FDC) to the left of a certain amount defined through expert judgment have been adopted in data-limited regions (Hughes and Smakhtin, 1996). In the Range of Variability Approach (RVA) (Richter et al., 1997), the temporal variability of the streamflow is considered fundamental for sustaining aquatic life. Richter et al. (1997) developed 32 Indicators of Hydrological Alterations (IHAs), which describe all the flow regime components (duration, frequency, timing, rate of change, and predictability of flows), that have an important ecological function. The degree of hydrological alteration is computed by comparing IHAs before and after the impacts (Richter et al., 2012; Singh and Jain, 2021; Williams et al., 2019). The RVA does not recommend any E-Flow regime standard as it is suggested to conduct eco-hydrological research to correlate the hydrological alterations with the biological responses before setting an E-Flow. A limitation of the RVA is the lack of ecologically grounded procedures for defining how much a certain flow parameter may vary beyond the natural variability of the examined river (Arthington, 2012). Richter (2010) defined the Sustainability Boundary Approach as the extent to which the natural flow regime may change without negatively impacting the ecosystem functions and proposed a Presumptive Standard of limiting daily flow alterations to 20% or less (Richter et al., 2012; Richter, 2010). However, the authors pointed out that such a *presumptive standard* could be not sufficient to protect ecological values in intermittent streams and highlighted that in several case studies "hand-off" thresholds have been used to limit the impact on the low flow duration and frequency. The hydrological target must be reviewed over time to improve ecological outcomes (Richter et al., 1996, 1997). This method has been incorporated into some recent holistic methods (Acreman and Dunbar, 2004).

3.2. Hydraulic methods

Most of the HD_Ms have been developed to define E-Flow for economically important salmonid fisheries and they have been modified over time in sophisticated habitat simulations or adsorbed in H_Ms. HD_Ms are based on the concept that the river ecosystem depends on the quality of the aquatic environment. These methods are based on the relationship between hydraulic geometry, ecological function of the rivers, and streamflow (Acreman, 2016; Jowett, 1997; Książek et al., 2019). There are several ways to quantify the variation of the channel geometry with the flow rate (Bovee et al., 1978; Cochnauer, 1976; Dooley, 1976; Mosley, 1982) and this justifies the large number of HD_Ms. The need to have flow-dependent ecological data constitutes a limitation of the HD_Ms (Gopal, 2013) for which they are generally used on a local scale (Pastor et al., 2014). The wet perimeter method (WPM) is the most widely applied HD_M (Tharme, 2003). It is based on the empirical relationship between the wetted perimeter in a river cross section and the streamflow (Prakasam et al., 2021). The inflection point of this relationship is assumed to be the minimum flux required for the river habitat (Tharme, 2003; Linnansaari et al., 2012). The point inflection is determined for several river sections and for various streamflow rates including high and low flow. The critical point of the method is the fact that the inflection point determination may be subjective (Gippel and Stewardson, 1998).

3.3. Habitat methods

HB_Ms are based on the relationship between the hydraulic characteristics of the river reach (i.e., width, depth, and flow velocity at different flows) and the habitat suitability of the target species or aquatic communities (Bovee et al., 1998; Maddock, 2018). Once the relationships between habitat and flow have been identified, they can be used to define scenarios of E-Flow (Arthington, 2012; Dyson et al., 2003). HB_Ms such as Instream Flow Incremental Methodology (IFIM) (Bovee, 1982), Physical Habitat Simulation System (PHABSIM) (Bovee et al., 1998), and CASIMIR (Jorde et al., 2020) are the most commonly used HB_Ms. The theory behind PHABSIM, which is based on three modules (hydrological, hydraulic, and habitat; Nikghalb et al., 2016) is that the quality and quantity of physical habitats are related to the environmental needs of river ecosystems at each life stage (Grela and Madej, 2019; Jowett, 1989; Palau and Alcázar, 2012). The goal is to obtain relationships between discharge and habitat conditions for specific species (Acreman and Arthington, 2016). HB_Ms are species-specific and need to be recalibrated when they are applied to a different region. More recently, an advanced mesoscale habitat model has been developed such as MesoHABSIM model, which lays the foundations for the PHABSIM model (Parasiewicz, 2001, 2007; Vezza et al., 2012).

3.4. Holistic methods

H_Ms are a group of frameworks based on the need to maintain some similitude to the natural flow regime to sustain the riparian ecosystem and healthy rivers and try to merge human and ecosystem flow requirements (Tharme, 2003). H_Ms are expert panel approaches that include multidisciplinary experts and stakeholders. The natural pattern of seasonal flows must be the starting point for understanding how to protect aquatic ecosystems, anticipating what was subsequently defined as the "Natural flows paradigm" by Poff et al. (1997). The most widely used H_Ms are the Building Block Method (De Villiers et al., 2008; King and Louw, 1998; Tharme and King, 1999; Arthington, 2012) and the Ecological Limits of Hydrological Alteration (ELOHA) framework (Poff et al., 2010). The first is based on relationships between riverine species and flow regime components (blocks). Combining these blocks, a flow regime is obtained that guarantees ecological objectives. The E-Flow is assessed for the number of representatives reaches and it is the result of collaboration between experts (physicists, biologists, engineers), workshops, and scenario modelling (Arthington et al., 2006; Bunn and Arthington, 2002; Hughes and Rood, 2003; Poff et al., 2003). In the ELOHA approach, the E-Flow is defined in an adaptive context where stakeholders and decision-makers participate in the process of interpretation of the eco-hydrological relationships, cost analysis, and ecological goals (Arthington, 2012). It consists of 4 steps: (1) hydrological modelling to obtain the flow regime under natural and present conditions; (2) classification of river segments according to flow variability and different ecological characteristics (as defined by Arthington et al., 2006 the "uniqueness" of the flow regime of each river); (3) hydrological status assessment (deviation of the current flow regime from the un-impacted condition); (4) development of relationships between ecology and flow alterations.

4. Ecological flow in Europe

In the following paragraphs, the evolution over time of the legislation at the EU level and for the Mediterranean EU countries was analysed focusing on the E-Flow definition (Table 3, and Supplementary Material S1), on the recommendations concerning the methodologies to be used for setting an E-Flow (Table 4) and highlighting differences between perennial and non-perennial rivers.

4.1. Ecological flow in the European legislation

The WFD, which aims at achieving the good status (slight deviation in biology and water quality from natural conditions) in all water bodies, recognizes the importance of the hydro-morphological aspects as quality elements. However, hydro-morphological elements are fixed as determinants only for defining the High Ecological Status or the HMWBs. In addition, the WFD does not specify how water for E-Flow may be recovered where its over-use has been licensed (Acreman and Dunbar, 2004). In 2012, the E-Flow concept was officially introduced with the Water Blueprint Strategy (European Commission, 2012). The document highlighted that most of the EU MSs adopted E-Flow methods based on statistical hydrological evaluations (generally a minimum flow), without considering the flow-ecological and flow-morphological relationships. Many existing E-Flow assessment methodologies were adopted differently by the MSs. In 2015, the need to improve the knowledge on E-Flow and its implementation in River Basin Management Plants (RBMPs) led the EC to publish the CIS n.31. The report presents an overview of the topic, making available information on methodologies, monitoring, measurement, and evaluation related to E-Flow (Iglesias et al., 2011). In addition, the CIS n.31 stressed the existing linguistic lack of homogeneity of the MS's legislation referring to E-Flow, for instance as "ecological flow", or "ecological minimum flow", "minimum acceptable flow", "ecologically acceptable flow", "common low flow", "minimum allowable flow", "minimal residual flow", "minimum (balance) discharge", etc. The CIS n.31 does not define a standard protocol for setting an E-Flow, but it provides some recommendations such as: (i) to consider all the components of the natural flow regime, (ii) to adopt methods for classifying ecological status based on metrics sensitive to hydrological pressures, considering the link between hydrology, morphology, and biological impact. MSs are encouraged to "make best use of the shared understanding of E-Flows in all steps of the WFD process" and to adopt E-Flow site-specific methods considering national or regional legislation, specific environmental values, and other related EU Directives (i.e., WFD, Habitats Directive). The WFD provides for the updating of RBMPs that must be carried out for each River Basin District (RBD) and reviewed every six years (Article 13). MSs are expected to include the E-flow in the RBMPs along the 2nd and 3rd cycles based on the recommendations of the CIS n.31. Neither the WFD nor the CIS n.31 differentiated perennial and non-perennial rivers. The latter, represent the main waterways in the Mediterranean countries and several authors highlighted that this oversight is a critical issue of the WFD (Nikolaidis et al., 2013; Prat et al., 2014; Skoulikidis et al., 2017). Indeed, non-perennial rivers play a fundamental ecological and economic role in the Mediterranean Region and the alternation of natural flow regimes (i.e., dry, and wet conditions) may severely alter the biotic communities and the biogeochemical processes (Datry et al., 2014).

Table 3
E-Flows in national legislation and its initial and current definition.

CNT	Initial definition	Law and reference year	Current definition	Law and reference year
SP	10% of mean annual flow	Unspecified law. 1981 from the Centro de Estudios Hidrograficos.	Flow that maintains, as a minimum, the fish life that would naturally live in the river, as well as riparian vegetation	Orden ARM 2656/2008 in Hydrological Planning Instructions
EL	Minimum Constant Flow (MCF): streamflow to balance human needs and aquatic ecosystem requirements. *NF information in English*	Ministerial Decree (MD) 12160/1999	NF	
IT	Minimum acceptable flow (DMV): minimum flow to ensure a balance between the availability of water resources and the needs for different uses and for aquatic life.	Legislative Decree no. 152/2006	Streamflow able to preserve morphological, chemical-physical characteristics of the waters, and for the maintenance of the biocoenosis typical of natural conditions.	Decree D.D. STA 30/2017 ((Decreto della Direzione generale per la salvaguardia del territorio e delle acque D.D,) MATTM, 2017)
PT	The E-Flows is the minimum volume of water capable of satisfying the needs of aquatic ecosystems.	Law 11/1987 (Lei de Bases do Ambiente)	A measure to mitigate the impacts on water and riparian ecosystems.	Law 186/90
FR	Minimum legal flow downstream to dams for sustaining aquatic ecosystems.	Fishing Law 1984	A minimum flow of water that ensures the life and reproduction of the aquatic species downstream of the structures. Max volume of water abstraction is based on the low flow objectives	Law n. 2004-338 of 21 April 2004 and the Law on Water and Aquatic Ecosystems (30 Dec. 2006) article L. 214-18 of the French Environmental Code.
CY	NF information in English			
MT	NP		NP	

CNT= Country; NF= Not Found; NP= Not Present. No proper definition has been found for France in the English language.

4.2. Ecological flow in Spain

The concept of E-Flow was introduced in Spain in 1981 and it was defined as 10% of the mean annual flow, but it remained purely

Table 4
Methodologies suggested by national legislations.

CNT	Present	Methodologies	Relevant factors	Law/national guidelines
SP	Y	Hydrological methods, Habitat-simulation methods	Habitat; biological communities; streamflow regime	Hydrological Planning Instruction (Orden ARM 2656/2008)
EL	Y	Hydrological method (a) 30% of the mean monthly flows of June, July, and August, or (b) 50% of the mean monthly flow of September, or (c) 0.03 m3/s when the previous values are lower)	Streamflow regime	Ministerial Decree 12160/1999
IT	Y	Hydrological methods, hydraulic-habitat methods, biological methods	Streamflow, similar to the natural one, for the maintenance of habitats and native species; biological or eco-hydraulic indicators	Decree D.D. STA 30/2017 ((Decreto della Direzione generale per la salvaguardia del territorio e delle acque D.D,) MATTM, 2017)
PT	Y	Hydrological methods (Portuguese Water Authority), habitat simulation method (IFIM)	Streamflow regime; biological, physicochemical and/or hydromorphological elements	2003 National Water Plan
FR	Y	Hydrological methods, hydraulic methods, habitat simulation methods.	Streamflow regime; hydraulic characteristics; biological aspects of species, life stages or species groups	Circular 5 July 2011 pursuant to L. 214-18 Article of French Environmental Code on instream flows
CY	Y	Hydrological methods (IHA method; Minimum Flow Threshold)	Streamflow regime	Annexed Report on Water Policy
MT	N		–	–

Y = yes, N = no, NF = not found.

theoretical for most of the cases (De Jalón, 1987). The Water Act (Ley 29/1985) and the Decree Law (Ley 14/1986) made mandatory the Environmental Impact Assessment (EIA) for hydraulic structures and the involvement of river ecology scientists for setting the minimum E-Flows (De Jalón, 1987). However, no methodologies were identified to calculate the E-Flow: it was set only for some newly built reservoirs which involved trout fishing (De Jalón, 1987). The WFD was transposed into the Spanish legislation with Article 129 of Law 62/2003 (Ley 62/2003), approved by Royal Legislative Decree 1/2001 (Real Decreto Legislativo 1/2001), and the RBDs were formally introduced with Real Decree (Real Decreto, RD) 125/2007. In the Commission's assessment (2015) of the RBMPs (1st cycle 2009–2015), it was emphasized that the E-Flow should not only consist of a fixed minimum flow throughout the year, but it should include a prescription for seasonal distribution. The definition of E-Flows in Spanish legislation is "flow that maintains, as a minimum, the fish life that would naturally live in the river, as well as riparian vegetation" (Table 3). This definition is reported in the Hydrological Planning Instructions (IPH), approved with Orden ARM 2656/2008. The Regulation of Hydrological Planning (RHP) (RD 907/2007) transposed the WFD by linking the concept of E-Flow to the ecological aspects only (RD 907/2007; RD 638/2016; Orden ARM 2656/2008). These documents are in Spanish language. The E-Flows methodologies mentioned in the text are the HL_Ms and the HB_Ms (Table 4). The E-Flows calculation involves the application of HL_Ms to calculate the maximum and minimum flow to consider the flow regime in natural conditions. The values obtained are modelled according to the habitat suitability by choosing specific target species. The obtained value should be adjusted to the flow corresponding to a range of 50–80% of the weighted useable area (WUA) of these target species (Mezger et al., 2019). The range drops to 30% of the minimum in dry periods and is between 30% and 80% in particularly hydrologically altered sites (Paredes-Arquiola et al., 2013). The IPH distinguishes the river types based on the flow permanence in the riverbed: temporary rivers with permanent water, flowing temporal rivers, temporary stagnant rivers, episodic rivers, and alternating temporal rivers (RD 1/2016). In addition, the document requires the characterization of the length, frequency, and seasonality of the periods of zero flow for non-perennial rivers to setting an E-Flow regime (Aguilar and Polo, 2016). No documentation has been found regarding laws regulating dam operations according to E-Flows.

4.3. Ecological flow in Greece

In Greece, to cope with the increase in water demand for irrigation and industries and to protect aquatic ecosystems, Law 1739/87 on the management of water resources was promulgated in 1987 (Demetropoulou et al., 2010). The primary objective of the Law was to guarantee adequate water supply, giving to the competent authority the power to limit water use, and to define a minimum flow of water in rivers and a minimum level in lakes (Papalimmeou, 1995). The application of E-Flows was introduced with the Ministerial Decree (MD) 12160/1999 (Patsialis et al., 2014). It was defined as Minimum Constant Flow (MCF): streamflow to balance human needs and aquatic ecosystem requirements (Table 3). The method used to define the E-Flows was empirical and mainly oriented to protect rivers from overexploitation by hydroelectric plants. The E-Flow regime was calculated as 30% of the summer flow, or 50% of the flow recorded in September, or 0.03 m3/s when the previous values are lower (Patsialis et al., 2014) (Table 4). For large rivers, the E-Flows were defined as a constant value during the year, meanwhile, for small basins, it was defined by MD 196978/2011 (FEK 518/B/5/04/2011) (Papadaki et al., 2014). In the mid-1990s, a seasonally constant minimum flow downstream from the Stratos dam was defined through the statistical analysis of the average monthly naturalized discharges of the driest month (August) (Hydroexygiantiki, 1995; Efstratiadis, 2014), and in 1996 a constant value (1 $m^3 s^{-1}$) was assumed downstream from the Evinos dam according to the water resources management plan (Zarris, 2010). For large dams, some studies related to E-Flows have been developed, for example for the Gadouras dam for which E-Flows have been defined and applied, but neither an overall plan nor a guideline for practical applications have been defined (Stoumboudi et al., 2019). The National Law 3199/2003 is the first attempt to transpose the WFD into Greek legislation (Farmaki and Tranoulidis, 2020). The HL_Ms are the most used methods, where the minimum acceptable E-Flow regimes are based on the recorded flows (Papadaki et al., 2014).

4.4. Ecological flow in Italy

The concept of E-Flow regime has gone through an evolution in Italian regulations. The first concept was associated with a minimum residual flow to assure fish life (1978). For several years a minimum constant flow (MCF) has been guaranteed to balance human needs and aquatic ecosystem requirements (Law no. 183 of 18 May 1989). Legislative Decree 152/2006 (D. Lgs. 152/2006) implemented the WFD and changed the MCF to minimum acceptable flow (DMV) (Table 3). The

DMV guarantees the equilibrium between the water resources availability and the needs for the different uses and aquatic life. The criteria and the rules were defined in the Water Protection Plans and approved by each Region by the general objectives proposed by the local River Basin Authority. Different methods were adopted in the country and the DMV was defined on a hydrological basis, proportional to the mean annual discharge, corrected using coefficients to include river morphology, functional uses, and biological factors. In 2017, the Decree D.D. STA 30/2017 (Decreto della Direzione generale per la salvaguardia del territorio e delle acque D.D,)(MATTM, 2017) updated the DMV, and the methodologies for setting an E-Flow regime in line with CIS n. 31 (hydrological regime that complies with the achievement of the environmental objectives defined under Article 4(1) of the WFD). A transition period (2018–2021) was identified by the Decree to identify some site-specific situations and the definitive transition to the E-Flows was fixed for 2022. The methods identified in the guidelines are grouped into three classes: HL_Ms, HB_Ms, and biological methods (ecological status-oriented). Each RBD is in charge of defining in the RBMPs the method based on data availability, environmental needs (species, habitat, environmental values), water uses, and hydraulic conditions (i.e., hydropeaking). The HL_Ms (E-IARI, Flow Duration Curve method, Aquatic States for non-Perennial streams) assume that the maintenance of a certain degree of the natural variability of the hydrological regime is fundamental for river ecosystems. The HB_Ms (E-IH method based on the MesoHABSIM) assume that biotic communities in rivers are limited by habitat availability. Hydraulic-habitat models are able to simulate the spatial and temporal variations of physical habitat characteristics (water depth, flow velocity, and substrate composition) that are linked to the species' presence and abundances. The biological methods, ecological status-oriented, are based on the existing link between biological metrics and hydrological/habitat components (i.e., the river lentic-lotic character as the proportion between lentic and lotic areas) (Table 4). The Ministerial Decree n. 131 (MATTM, DM 16 June 2008, n. 131) provided the definition of the typology of Italian surface watercourses dividing them into: temporary (river with dry periods all over the water body or in parts of it, recorded either every year or at least twice in five years) and perennial. In turn, temporary rivers are divided into intermittent (temporary rivers with flow during more than eight months per year), ephemeral (temporary rivers with flow during less than eight months per year but continuative), episodic (temporary rivers usually dry with flow only after intense rainfall). The river classification in different typologies is a fundamental step in assessing ecological status since the reference conditions may vary across river types.

4.5. *Ecological flow in Portugal*

In Portugal, the concept of E-Flows, with a view to the conservation of aquatic ecosystems, dates to 1987 with the Law 11/1987 (Lei de Bases do Ambiente), which recalls the need to include the protection and conservation of the environment in the planning, administration, and use of the water (Alves and Bernardo, 2002; in Portuguese language). E-Flow regime was defined as the minimum volume of water capable of satisfying the needs of aquatic ecosystems (Alves and Bernardo, 2002). Law 186/90 introduced an advancement of the concept of the E-Flows in Portugal by defining it as a measure to mitigate the impacts on water and riparian ecosystems (CIS n° 31) (Table 3). Decree-Law 46/94 defined the objectives of the National Water Plan (PNA) and aquatic ecosystems and made it compulsory to install the devices necessary to set the E-Flows (Ferreira et al., 2010). Water Law (Lei n. 58/2005) transposed the WFD in the Portugal environmental legislation, and the successive Decree--Law 226-A/2007 and Ordinance 1450/2007 regulated the uses of water resources. The latter established that the request for authorization for hydroelectric production must be supported by the definition of an E-Flow regime and dam operations have to integrate E-Flow to support downstream ecosystems. It also states that E-Flows must be adapted to fish life cycles to maintain ecosystem integrity. Furthermore, Law n. 7/2008, which has not yet been implemented, establishes that the owner must set an E-Flow regime that protects the ecosystem and aquatic species (CIS n° 31). The first method used to calculate E-Flows, intended as a constant minimum flow to maintain the minimum health of the river, was based on the natural flow regime. The E-Flows were set in the range of 3%–5% of the average annual flow (Godinho et al., 2014). In the past, ad hoc HL_Ms have been developed for the Iberian Peninsula such as the "base flow method" (Palau and Alcázar, 1996) and the "Portuguese Water Authority method" (Alves and Bernardo, 2002). The first method involved the use of a statistical approach to determine the baseflow (Alcázar et al., 2008; Palau and Alcázar, 1996). The Portuguese Authority's method, valid since 2002, included distinct percentiles on the duration of the flow for different periods of the year (Alves and Bernardo, 2002). These methods have been recommended since 2003 in the PNA. In Portugal, currently, HL_Ms remain the most used methods (Ramos et al., 2017). However, HB_Ms such as the IFIM (Bovee, 1982) and HD_Ms such as the WPM have also been applied in the Iberian Peninsula (Oliveira et al., 2004) (Table 4). Portela (2006) proposed a method, based on both hydrological and hydraulic criteria, which will be identified as HH_M from now on, to calculate E-Flows in southern Portugal. Bernardo and Alves (1999) defined a methodology for the Iberian rivers which considers the conditions of low summer discharge as the main environmental constraint. The result is an E-Flow regime that should allow the persistence of the summer conditions streamflow (i.e., presence of pools) considered favourable for the fish fauna. According to CIS n.31, for particularly dry years, the calculation of the E-Flows must take into account the value of the rainfall accumulated since the beginning of the hydrological year (October). The first and second cycles of the RBMPs required by the WFD contained little information on the definition of E-Flows in Portugal (Martínez-Fernández et al., 2020).

4.6. *Ecological flow in France*

In France, since 1984 (Fishing Law n. 84–512 of June 29, 1984), a minimum E-Flow regime downstream from dams for sustaining aquatic ecosystems has been required (Table 3). The law provided a guidance on the management of freshwater systems by seeking a balance between protection and use (CIS n. 31; Souchon, 2004). In 1992, the Water Law (Law n. 92-3 of January 3, 1992) significantly changed the French water management system with the introduction of the RBMPs (SDAGE-Schémas Directeurs d'Aménagement et de Gestion des Eaux) that provided the guidelines for river basin planning and management over a 10–15-year period. One of the goals of the SDAGE was the conservation of aquatic ecosystems and wetlands (Nion, 2009). Law n. 2004-338 of 21 April 2004 transposed the WFD into French legislation (Nion, 2009) and with the Law on Water and Aquatic Ecosystems (30 December 2006) the achievement of the GES was set by 2015 (Nion, 2009). The French Environmental Code (art. L. 214-18) imposes on every hydraulic structure, regardless of the purpose, to set E-Flows defined "a minimum flow of water that ensures the life and reproduction of the aquatic species downstream from the structures" (CIS n°31). To cope with the accentuation of low flow periods due to intensive withdrawals for irrigation, the Prefects (a local government body) have established maximum volumes of withdrawal regardless of use for all French basins (CIS n ° 31). This volume is estimated in compliance with the low flow objectives ("Débits Objectifs d'Etiage – DOEs"). The DOEs are established in the RBMPs, they represent the average monthly streamflow above which it is assumed that all uses can be in balance with the life, circulation, and reproduction of aquatic species. Since the early 1980s, methods for determining the minimum legal flow have been based on empirical hydraulic and morphological data such as mean flow velocity and water depth of the river without considering the biological factors (Belaud et al., 1989). Subsequently, Dumont and Rivier (Dumont and Rivier, 1978)(1978) expanded the calculation of the minimum legal flows, obtained quantitatively on the Tennant minimum flow objectives, including the biological aspects downstream from the water extraction river section (Belaud et al., 1989; Lamb et al., 2004). In the late 1980s, the IFIM was adapted to the French context. This method is still widely used in France better known as the "microhabitat" methodology (Acreman and Ferguson, 2010; Sabaton et al., 2004). More recently, two methods have been developed in France based on HL_Ms, HD_Ms, and HB_Ms (CIS n°31). The methods are EVHA method (Evaluation of Habitat) ((Ginot et al., 1998)Ginot et al., 1998) and ESTIMHAB method ((Souchon et al., 2003)Souchon et al., 2003). The first is based on the use of a hydraulic model for different values of the velocity and corresponding water level. The second is based on the results of the aforementioned model where the evolution of the habitat is a function of the streamflow and is directly correlated to the geometry of the channel.

4.7. Ecological flow in Cyprus

In Cyprus, the WFD was transposed into national legislation with the Integrated Water Management Act (Law N. 79 (I)/2010). It does not explicitly mention E-Flows but provides tools to enforce its determination (Table 3).

The island's rivers have been classified into four types based on two hydrological indicators: the "*flow permanence*" (mean annual number of months with discharge) and the "*six-month predictability of zero-flow periods*" (one minus the ratio between the multi-annual frequency of occurrence of the zero-flow months in the wet semester and the frequency of the zero-flow months in the dry semester). In Cyprus, 87% of water bodies were classified as intermittent rivers and ephemeral streams (Stubbington et al., 2018). The withdrawal of water for irrigation purposes is the main form of pressure on water resources. The 2nd cycle of RBMP was adopted by the Council of Ministers on 7 October 2016. The analysis of this Plan shows that E-Flows was considered only for the river sections downstream from the dam. According to what is reported by Ramos et al. (2018), the approaches used in Cyprus to set E-Flows are the HL_Ms (such as Sustainable Diversion Limits, Minimum Flow Threshold, Maximum Extraction Rate). However, most of the country's dams were built in the late 1940s and therefore were not designed to release E-Flows. Hence, a specific analysis was carried out for defining E-Flows in HMWBs downstream from the dams with the aim of reaching the GEP. The IHA method was applied in 21 river basins with the aim of characterizing flow regime (Table 4). The results of this analysis are used to formulate the determination of E-Flows downstream from the dams and in selected sites of significant ecological importance. Furthermore, a specific measure has been inserted in order to monitor the outcomes of E-Flows considering the biological, physic-chemical, and hydro-morphological elements in order to its re-examine in the next management cycle. Indeed, some rivers are still subject to hydro-morphological pressures, resulting in poor ecological status (Stubbington et al., 2018; Ramos et al., 2018).

4.8. Ecological flow in Malta

The WFD is transposed into national legislation as Legal Notice 194 of 2004 entitled 'The Water Policy Framework Regulations 2004'. This regulation defined the Sustainable Energy and Water Conservation Unit as a competent authority for groundwater and inland waters. In line with the WFD objectives, the "Second Water Catchment Management Plan (WCMP) for the Malta Water Catchment District 2015–2021" was drawn up to develop measures necessary to achieve the environmental objectives set for 2021. According to this document, the criterion for characterizing watercourses is the hydrological regime. Based on monitoring of the watercourses (data covered only 2012 and 2013), non-perennial rivers were classified in agreement with the definition provided by Williams (1996) (stream showing a dry phase along the river course which can often be predicted in space and time).

Quoting the CIS n.31, "The concept of E-flows is completely new to the Maltese Islands. No data exist and therefore none of the methods can be applied for now. Malta is constructing its information base as a first step in this lengthy process". Therefore, since the hydro-morphological elements (flow regime and longitudinal continuity) play a fundamental role for the sustenance of biological quality elements, as expressed in the 2nd WCMP, Malta is undertaking to monitor these elements on a bimonthly basis. In the first WCMP, Malta defined the baseline flow regime of three rivers by monitoring the flow of surface waters. The monitoring program (chapter 5- 2nd WCMP) and Natura 2000 management plans will contribute to understanding the contribution of natural flow to water-dependent habitats and species and to understanding habitat requirements and the selection of indicator species with the final goal of defining the E-Flows.

5. Ecological flow in non-perennial rivers: case studies

The bibliographic search in Elsevier's Scopus database resulted in 133 articles potentially reporting studies on E-Flows in arid and semi-arid environments. With a subsequent revision, only case studies falling within the selected Mediterranean MSs, which were 60 (445.11% of the total), were selected. The further cut concerned those articles whose studies referred to future implementation of the E-Flows (e.g., Belmar et al., 2011; Benejam et al., 2010). Finally, the articles taken into consideration were 20 (33.33% of the 60 articles) (Table 5), one of which was in Spanish (Sanz and Garcia de Jalon, 1997) and another is not available (Perales, 2010) and therefore not useable by the scientific community. Although non-perennial rivers have been studied within EU-funded projects (e.g., TempQsim, MIRAGE, SMIRES), this study shows that there are a few case studies in the literature reporting E-Flows development and applications.

Based on the criteria of this review, in Scopus, no case studies were found in France, Malta and Cyprus. Fig. 2 shows the location of the river basin analysed in this study. Based on the information reported in the papers, rivers were differentiated into intermittent (I), temporary (T), and non-perennial (N–P) (Fig. 3). However, in some cases, the river type was unspecified (Not Mentioned NM) (Fig. 3).

HL_Ms resulted the most commonly used approaches in the selected case studies (Fig. 4) (Acuña et al., 2020; Aguilar and Polo, 2016; Belmar et al., 2010; Godinho et al., 2014; Leone et al., 2023; Palau and Alcázar, 2012; Papadaki et al., 2014, 2017; Portela, 2008; Sanz and Atienzar, 2018; Sanz and Garcia de Jalon, 1997; Theodoropoulos et al., 2018a, 2018b). This is due to the fact that HL_Ms are easy to apply because they are based only on the analysis of the flow time series, and they don't require biological data. In addition, as mentioned by most of the authors, the main problem when setting E-Flows in non-perennial rivers is the paucity of hydrological and biological data (De Girolamo et al., 2022b). When hydrological data are not available, continuous models are generally used to reconstruct long-term daily flow. In the analysed case studies, the hydrological models such as Soil and Water Assessment Tool (SWAT) (Acuña et al., 2020; Leone et al., 2023; Papadaki et al. 2017, 2020), Water Integrated Management for Mediterranean Watersheds model (WiMMED) (Aguilar and Polo, 2016), MIKE SHE hydrological model (Patsialis et al., 2014; Stamou et al., 2018) and Integrated System for Rainfall-Runoff Modelling (SIMPA) (Sanz and Atienzar, 2018) were used (Table 3). H_M was applied to a non-perennial river only in a case study (Bernardo and Alves, 1999), meanwhile two applications of a C_M were found (Papadaki et al., 2020; Stamou et al., 2018).

5.1. Portugal

Portela (2008) applied and compared HL_Ms to the Guadiana River (Basic Flow Method, the Portuguese Authority's method -INAG-, and the wet perimeter method), and the HH_M (Portela, 2006). The wet perimeter method is an HL_M based on the monthly flow series, which considers the temporal variability of the flow regime throughout the year, discarding part of the maximum average daily flows when

Table 5
Summary of case studies analysed: Authors and year of publication; country/River; applied methodology for setting E-Flows; hydrological model used in case of absence of streamflow data.

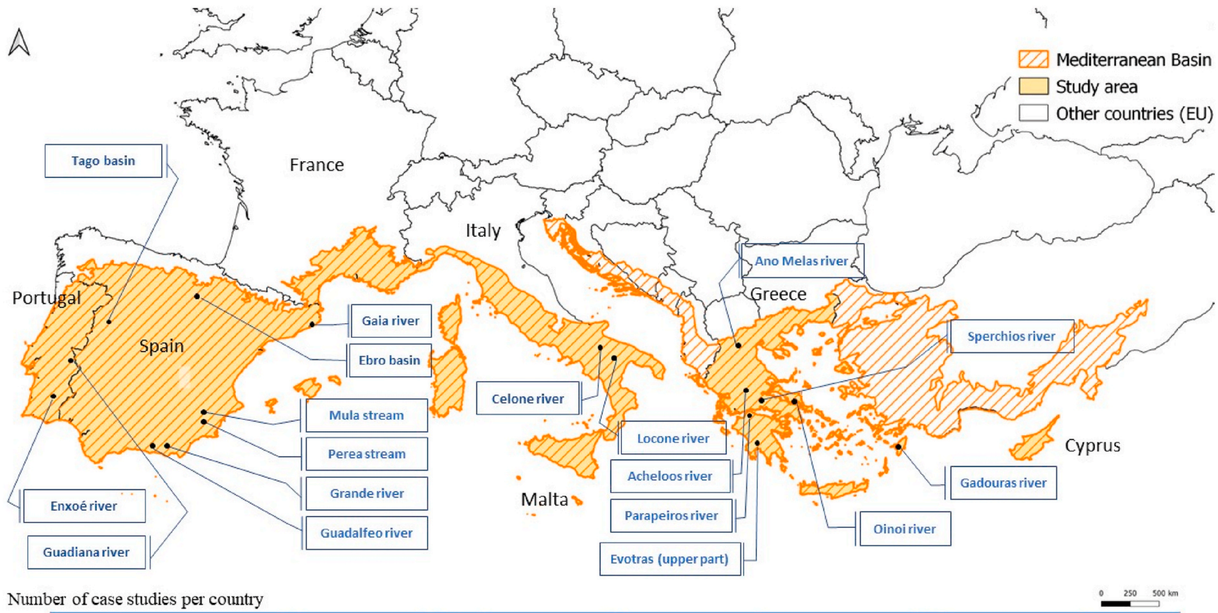
Authors/Year	Country/River	Method	Hydrological model
Acuña et al. (2020)	IT/Celone River SP/Gaia River	HL_M: RVA; HB_M: MesoHabsim.	SWAT
Aguilar and Polo (2016)	SP/Guadalfeo river	HL_M: IHAs to contemplate Environmental Flow Components.	WiMMED
Alcázar and Palau (2010)	SP/Ebro River basin	HL_M: Basic Flow Method.	–
Leone M. et al. (2023)	IT/Locone River basin	HL_M: RVA	SWAT+
Sanz and Atienzar (2018)	SP/Ebro basin (Banuelos, Farasdues, and Clamor)	HL_M calculation of a statistical parameter based on the moving averages of different intervals of the daily flow.	SIMPA
Sanz and Garcia de Jalon (1997)	SP/Rivers in Tagus basin	HL_M: Q25d as the minimum ecological flow.	–
Belmar et al. (2010)	SP/Mula stream and Perea stream	HL_M: 25th and 75th percentile boundaries for the annual runoffs.	–
Bernardo and Alves (1999)	PT/Enxoé river	H_M.	–
de Jalón (2003)	SP/River Grande	HB_M: IFIM.	–
Dimitriou et al. (2015)	EL/Gadouras stream	Fully dynamic model.	–
Godinho et al. (2014)	PT/Guadiana River. São Pedro, Brenhas and Amoreiras rivers.	HL_Ms: Baseflow method; Portuguese Water Authority. HH_M. HD_M: WPM.	–
Papadaki et al. (2017)	EL/upper part of Acheloos river (Mesochora and Tripotamo streams)	HL_M: EMC with Global Environmental Flow Calculator (GEFC, 2016). HB_M: modified physical habitat simulation system (Bovee et al., 1998).	SWAT
Papadaki et al. (2020)	EL/upper part of Acheloos river (Mesochora stream)	C_M: SRD (hydrological analysis of streamflow + habitat requirement quantification).	SWAT
Patsialis et al. (2014)	EL/Ano Melas Stream	HL_M: IHA (RVA) and Tennant; empirical method based on Greek legislation.	MIKE SHE
Perales (2010)	SP/Guadalfeo river	HB_M: PHABSIM + 1-D hydraulic model.	–
Portela (2008)	PT/Guadiana River	HH_M. HL_M: Wet Perimeter Method, Basic Flow Method, INAG.	–
Stamou et al. (2018)	EL/Sperchios river	C_M: 3H-EMC (Hydrological, Hydrodynamic and Habitat Modelling).	MIKE SHE
Theodoropoulos et al. (2018b)	EL/river Parapeiros	HL_M: Tennant; Lyons; Basic Maintenance Flow. HB_M: hydraulic-hydrodynamic habitat models.	rainfall-runoff models
Theodoropoulos et al. (2018a)	EL/Oinoi stream	HL_M: Tennant; Lyons; Basic Maintenance Flow; HB_M: Hydraulic-Hydrodynamic Habitat Model.	Athens Water Supply and Sewerage C.
Theodoropoulos et al. (2019)	EL/upper half of the Evrotas River	HB_M: combination of indicators-variables.	–

Table 5 (*continued*)

evaluating monthly streamflow. The mean monthly E-Flows were expressed in dimensionless form, as a percentage of the module called Qmod. The Portela HH_M leads to mean monthly E-Flow values that are lower than the other methods. Godinho et al. (2014) proposed a holistic 7-step methodology that can be applied to both permanent and non-perennial rivers (i.e. São Pedro, Brenhas, and Amoreiras rivers, which are tributaries of the Guadiana River). The procedure was a generic framework that allows to obtain the E-Flows by integrating the HL_Ms, HD_Ms, and HB_Ms to achieve the biotic, hydro-morphological, and water quality criteria imposed by the WFD. Bernardo and Alves (1999) defined the lowest possible flow regime to allow the persistence of summer pools in conditions deemed favourable for fish fauna by applying a H_M. The proposed methodology was based on the characterization of fish assemblages along the river, and on the analysis of aerial photography from several different hydrological years to identify persistent summer pools in distinct hydrological conditions, and rainfall-runoff models. However, the result of this modelling gave different results from those observed, indicating that a great uncertainty affected the output of the rainfall-runoff model used in that study.

5.2. Greece

Patsialis et al. (2014) applied the Tennant method and the RVA based on the IHAs to estimate the E-Flows in a small mountainous sub-basin (N Greece). The values obtained with the Tennant method were lower than the other, and both methods provided values lower than those obtained with the empirical legislative method. Papadaki et al. (2017) compare monthly E-Flows obtained with an HL_M and an HB_M (modified IFIM proposed by Bovee et al., 1998) in the upper Acheelos River. The simulated monthly hydrological flows were introduced in the GEFC obtaining EMC E-Flows scenarios based on purely hydrological criteria. The authors state that these HL_Ms are useful as a first analysis to contemplate the variability of the hydrological regime, especially in the Mediterranean environment, but they must be supported by biological knowledge. Therefore, in line with the WFD, Papadaki et al. (2017) combined a HL_M and HB_M methods to calculate monthly E-Flow values, including low flow periods. The different results obtained with the two methods lead the authors to promote the need for further eco-hydrological methodologies contemplating river-type and site-specific assessment for more holistic evaluations of the E-Flows. Papadaki et al., (2020) use a C_M based on the calculation of the Suitable Range Discharge (SRD) of the upper part of the Acheloos River during the dry period obtained by combining statistical analyses of hydrological data and habitat suitability models. To quantify habitat availability, they calculate the WUA (Bovee et al., 1998). The comparison between the SRD and the minimum E-Flows of the legislative framework was expressed in terms of WUA: the E-Flows of the legislation would provide a greater WUA. Theodoropoulos et al. (2018a) compared different scenarios of E-Flows downstream of the Marathon dam (Attica Region-Central Greece). They used a two-dimensional hydrodynamic habitat model (HB_M) targeting a benthic macroinvertebrate aquatic community. They compared the lowest E-Flow values (0.17 $m^3\ s^{-1}$ and 1.5 $m^3\ s^{-1}$) obtained by using this method with those obtained with three HL_Ms: Tennant, Lyons, and Basic Maintenance Flow (E-Flows variable between 0.0006 $m^3\ s^{-1}$ and 0.18 $m^3\ s^{-1}$) and with the E-Flows calculated on the basis of national guidelines. From the results obtained,



Number of case studies per country

Greece	Spain	Portugal	Italy	France	Malta	Cyprus
8	8	3	2	0	0	0

Fig. 2. Study area: Mediterranean EU Member States (France, Italy, Portugal, Spain, Portugal, Greece, Malta, and Cyprus) and case studies; the table below shows the number of articles by study area. Acuña et al. (2020) was counted twice since it described two different case studies (Italy, Spain) and methodologies.

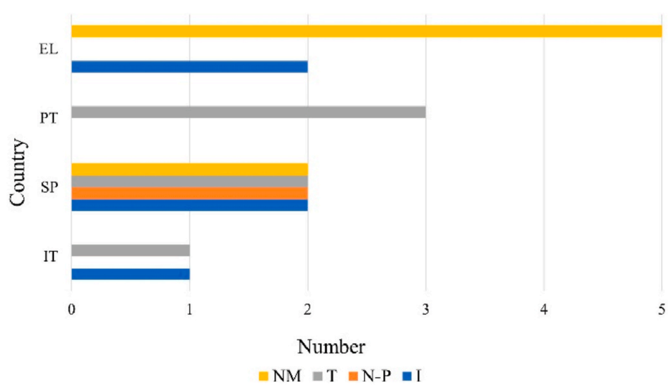


Fig. 3. Characterization of watercourses. NM: Not Mentioned; T: Temporary; N–P: Non-Perennial; I: Intermittent.

the authors concluded that HL_Ms lead to an underestimation of the E-Flows except for a flow scenario, which considering 30% of the average value for the whole period of the study calculated with the Tennant method. According to the authors, although HL_Ms involve less cost and time, they should not be applied as stand-alone methods, but supported by other methods when biological data are available. Stamou et al., (2018) proposed the novel integrated modelling procedure 3H-EMC, which combined HL_Ms, Hydrodynamic and HB_Ms with the use of the EMCs (C_M). The authors collected microhabitat data given by Evinos River as the "best-available" reference river. They demonstrated that the E-Flows values obtained with the C_M was greater than those imposed by the Greek legislation: equal to 1 $m^3 s^{-1}$ against values ranging between 0.4 $m^3 s^{-1}$ and 0.5 $m^3 s^{-1}$. Theodoropoulos et al. (2018b) applied a benthic-invertebrate, two-dimensional, fuzzy rule-based E-Flows Assessment (HB_M) to calculate the E-Flow downstream route of the river Parapeiros. They show that the E-Flows established by legislation (0.2 $m^3 s^{-1}$) is below that obtained with HB_M (between 0.6 $m^3 s^{-1}$ and 2 $m^3 s^{-1}$). Theodoropoulos et al., (2019) aimed at calculating specific aquatic states of intermittent rivers. The authors emphasized the importance of adapting the methodologies used for permanent rivers to intermittent rivers considering the different aquatic states that can occur in the latter. The authors distinguish the aquatic states (between dry and wet periods) within which to calculate the E-Flows: they determine the baseflow necessary to ensure adequate habitat conditions (abundant-riffles). In addition, they determined the timing and duration of each aquatic states (and consequently the timing and duration of the E-Flows) based on a combination of hydrodynamic simulation and hydrological data. They used the outputs to get the streamflow above which isolated pools occurred; beyond which the pools were connected; beyond which the riverbed was completely

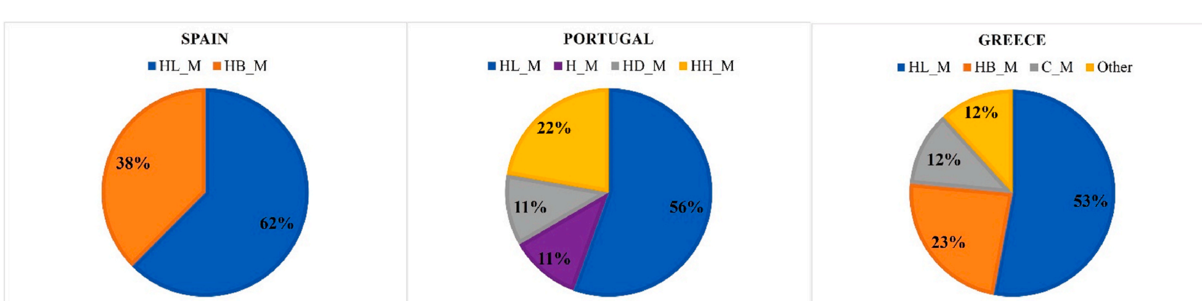


Fig. 4. Methodological approach applied in Spain, Portugal, Greece for setting E-Flows and their percentage as produced by the present review.

covered with water. The authors develop an annual E-Flow regime adapted to the intermittence of rivers. It is worth mentioning Dimitriou et al. (2015) reported the results of a fully dynamic model applied to the Gadouras River Dam which is the only case of effective application of the E-Flows. This experiment made it possible to identify the release period and volumes downstream from the dam to protect the aquatic species identified for wet and dry years and dry and wet seasons.

5.3. Spain

In Spain, the Ebro River basin has been extensively studied although it includes unmonitored subbasins. Palau and Alcázar (2012) applied the Basic Flow method at the basin scale in 46 river reaches of Ebro River Basin. Diverse models were applied in the different study areas to calculate a parameter that was useful for setting an E-Flow regime. The variables identified are all hydrological (e.g., flow equalled or exceeded 347 days per year). The E-Flows for the unmonitored areas of the basin was calculated by interpolating the Basic Flow value of the monitored areas. Basic Flow is defined as "the absolute minimum flow that should be circulating within the river anytime". However, such patterns require a daily flow under natural conditions, which are not readily available for most water bodies in the Ebro basin. Therefore, Sanz and Atienzar (2018) developed a model to calculate the E-Flows of 55 river reaches of the Ebro, some of which are temporary rivers (Banuelos, Farasdues, and Clamor). In the work by Sanz and Garcia de Jalon (1997), several hydrological parameters that have influence on river ecology were calculated for several rivers of the Tagus basin. In particular, the Q25d parameter (minimum flow recorded over 25 consecutive days) was considered as a representative flow. However, this article is in Spanish. Aguilar and Polo (2016) calculate the monthly minimum E-Flows upstream of the Rules Dam (Guadalfeo River). In the study, they implement 4 regimes: minimum E-Flows for dry and wet periods obtained from a previous work by Perales (2010) who applied HB_M (PHABSIM) at this non-permanent river, and two obtained through the calculation of IHAs therefore on a purely hydrological basis. The work of Perales (2010) is not downloadable but has been well described by the authors Aguilar and Polo (2016). Perales (2010) applied the PHABSIM methodology identifying two sets of minimum E-Flow values for WUA thresholds pre-established by IPH. In the Mula river basin (downstream from the La Cierva reservoir), and in the Perea river basin (southern Segura River basin), a HL_M was used by Belmar et al. (2010). The method was based on the approach developed by Martinez and Fernandez (2006; not present in any database but cited by Belmar et al., 2010). For wet, average, and dry years the authors used the 25th and 75th percentile boundaries for the annual runoffs. The output was the E-Flow regime requirements. According to the authors, this method has numerous advantages because, for example, it involves the typical interannual variability of the flow of Mediterranean torrents and considers flows and droughts, the key flow regime elements of intermittent streams. However, it provides the minimum requirements of stream ecosystems without consideration of the environmental requirements of natural species and their habitats (Magdaleno, 2009). There are only two HB_Ms applications in literature for intermittent rivers in Spain: de Jalón (2003) and Acuña et al. (2020). The first author applied the IFIM method showing the results for several Spanish rivers. The procedure consists of using the mean monthly flows of the natural regime as the pattern of flow fluctuation and the minimum monthly flow is identified as the basic flow. For the other months, the E-Flows are adjusted according to the natural regime. Acuña et al. (2020) applied an HB_M to describe the complex nature of the habitat dynamics of a non-perennial river. They investigated how the habitat changed with the reduction of flow in the Gaia River (Iberian Peninsula) and used a native species of fish as an ecological target. The authors found that the increase in duration and frequency of flow events below the minimum habitat thresholds can create a reduced habitat availability for aquatic organisms. This approach is an extension of the mesoHABSIM model as it introduces the combination of habitat-flow rating curve, habitat-time rating curve, and habitat time series to contemplate the temporality of rivers. Acuña et al. (2020) pointed out that existing H_Ms could be applied to non-perennial rivers without significantly changing them compared to application to permanent rivers. However, the authors also argue the importance of integrating new components of the methods to consider the non-flow events and geomorphological, hydraulic, and hydrological elements of non-perennial rivers.

5.4. Italy

Acuña et al. (2020) modified the RVA method (HL_M) for setting an E-Flow regime in the Celone River basin. The authors excluded the IHAs that were not relevant for non-perennial rivers (i.e., min flow over 3-, 7-, 30 consecutive days) and included two representative hydrological indices: the "flow permanence" and the "six-month predictability of zero-flow periods" identified by (Gallart et al., 2012)Gallart et al., (2012) as relevant eco-hydrological indicators for non-perennial rivers. Among the other, the result of this study showed a no-flow period from June to October and a number of flow pulses (i.e., 2–5) between February and April. However, the authors concluded that the method needs to be verified after having monitored the biological status. Finally, following the holistic ELOHA method, E-Flows should be set by choosing an ecologically acceptable range of variability of each indicator. Leone et al. (2023) apply the same HL_M, based on the most representative IHAs of the temporary river Locone (i.e., zero-days, 90-day min). In both Italian case studies, the variability of each IHA was set between the 25th and 75th percentiles. The natural dry condition, which occurs from July to September, should be maintained in the Locone river. Acuña et al. (2020) and Leone et al. (2023) strongly suggested that natural dry conditions should be safeguarded and considered when setting the E-Flows based on the Paradigm of natural flows (Poff et al., 1997), as suggested by the Italian legislation (Decree D.D. STA 30/2017(Decreto della Direzione generale per la salvaguardia del territorio e delle acque D.D,) (MATTM, 2017)).

6. Discussion and conclusions

This study reports the results of the scientific literature review concerning the E-flows (ecological flows and/or environmental Flows) in non-perennial rivers in the EU MSs of southern Europe. To this aim, legislation was examined regarding E-Flows at the EU level and of the Mediterranean MSs (Fig. 5). Starting from the definition of the E-Flows provided at the EU level, the questions covered by the present paper were (i) Did MSs implement the WFD? (ii) How did the concept of E-Flows change over time? (iii) Which methods did MSs propose for setting an E-Flow regime?

The results of the present work showed that MSs investigated in the study have incorporated the WFD into their legislation and drafted the RBMs. The EU Commission has provided guidelines to MSs for including the E-Flows in the RBMPs, where it is strongly suggested to consider all the components of the natural, and the link between hydrology, morphology, and biological aspects when setting an E-Flow regime. However, no recommendations about the methods were provided. The analysis of national legislation showed that an important step forward toward regulatory unification at the European level has been done in the last two decades in the field of E-Flows and more generally toward the protection of aquatic ecosystems. For most of the analysed countries, the definition of E-Flow regime has abandoned the idea of a regime of constant or minimal flow, but it recognizes the importance of the biological, and chemical-physical aspects connected to the flow regime. Most of the MSs have embraced a more holistic view of the E-Flows concept by integrating the key aspect relating to ecology in line with European legislation (Table 4; Supplementary Material S1). This study highlights that several differences in legislation, monitoring, and E-Flows approaches still exist among Mediterranean MSs. The national

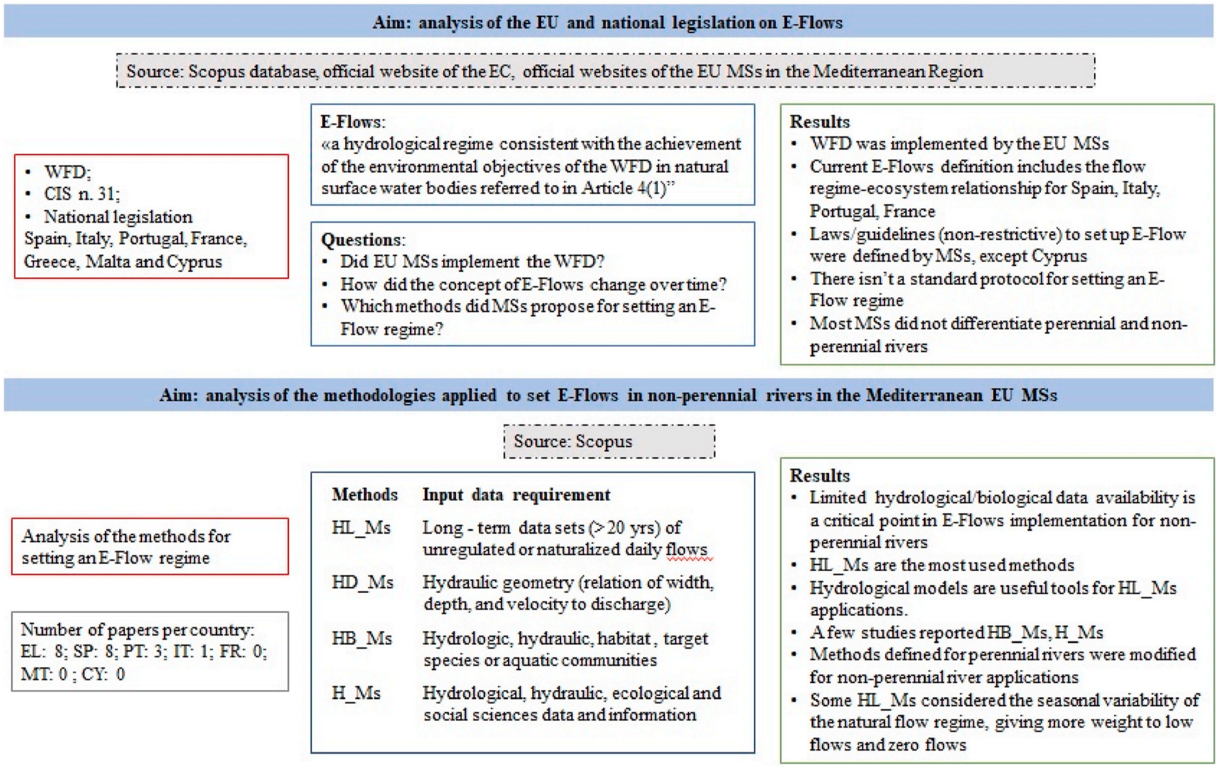


Fig. 5. Flow chart of the paper: concept, aims, methods, main results.

legislation of the MSs analysed in this study does not provide restrictive or specific indications concerning the methodologies for setting an E-Flow regime. Spain, Italy, France, and Portugal have identified several methodological approaches that can be valid for setting an E-Flow regime (HL_Ms; HB_Ms, HD_Ms), meanwhile, Greece and Malta did not report recommendations about the methodologies. In addition, this study clearly shows that most of the MSs do not differentiate between perennial and non-perennial rivers. In spite of this, recent studies suggested for non-perennial rivers an E-Flow regime that contemplates the typical seasonality of the natural flow regime (e.g., Acuña et al., 2020; Aguilar and Polo, 2016; Portela, 2008; Sanz and Atienzar, 2018) since the low flow and the zero-flow are fundamental to avoid non-native species, less tolerant to the absence of flow, to become dominant (Arthington, 2012). The lack of a clear differentiation between perennial and non-perennial in the EU guidelines resulted in differences between the methods adopted at the national level and in a general delay in the implementation of the E-Flow. The guidelines at the national level are not restrictive to ensure their applicability in districts that are very dissimilar from each other in environmental characteristics and economic resource availability. As described in the paper, the complexity and comprehensiveness vary according to the method, as well as the required resources in terms of data, time, and funds. The economic aspects are not mentioned in the guidelines although they are a determining factor in the choice of the methodological approach. Specifically, E-Flows assessments with easy hydrological methods (e.g. Tennant method; Tennant, 1976) requires up to five months and funds for about $ 10000, meanwhile, assessment with a complex holistic approach (expert panel, field studies, and modelling) may require from 2 to 5 years and more than $ 1000000 (The Nature Conservancy2008).

From the analysis of the case studies concerning the E-Flows implementation, one can surmise that in non-perennial rivers the E-Flows science is still an emerging discipline. The limited availability of data (i.e., hydrological, hydraulic, and biological), and the restricted economic resources allocated for managing non-perennial rivers are the main causes of the delay in the E-Flows implementation in MSs. HL_M are the most commonly used because they require only flow data and, in case of absence, hydrological modelling makes up for the shortcoming. According to the CIS, HL_Ms are applicable, but the report stresses the importance of linking the flow regime and biological information. HL_Ms are economically advantageous and certainly faster than the other methods, but it would be appropriate to apply an additional methodology (for instance in a cascade mode) to contemplate other aspects such as the hydraulic or biological. Indeed, only in a few case studies, the availability of biological data allowed the authors to connect HL_M and HB_M or HD_M (Papadaki et al., 2017; Papadaki et al., 2020; Stamou et al., 2018; Theodoropoulos et al., 2018a, b; Theodoropoulos et al., 2019). H_Ms, which are considered by several authors as more comprehensive methods since they include multidisciplinary experts and stakeholders (Arthington, 2012), are limited to a few case studies. On the one hand, this is due to the data scarcity that characterizes the non-perennial rivers, and on the other hand, this is because H_Ms are time-consuming and expensive. Several authors pointed out that existing methodologies for perennial rivers could be implemented to set the E-Flows in non-perennial rivers with appropriate modifications and evaluations (Godinho et al., 2014; Acuña et al., 2020). In this sense, the experience and deep knowledge of these rivers become fundamental. Furthermore, from the analysis of the case studies, it emerged that the E-Flows setting is restricted to the definition of the water release from the reservoir without considering a larger scale.

Although this study cannot be considered exhaustive since many technical reports on E-Flows and laws that regulate water releases from reservoirs are available in the native language and, therefore, were not included in this study, it highlights some critical issues, which represent a starting point to improve approaches for setting an E-Flow regime in non-perennial river systems. The next challenges in E-Flows science in non-perennial rivers should define the relationships between hydrology and river ecology. To do this, an enhancement of the monitoring of the ecological and hydrological status of the rivers is critical. All the quality aspects should be included in the E-Flows assessment. Finally, the local stakeholders' involvement is also essential, as would be a better integration of the social and economic disciplines.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Data availability

Supplementary data are attached as Supplementary Material

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.118097.

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