Received: 11 July 2019 | Accepted: 21 December 2019
DOI: 10.1111/1365-2664.13590

REVIEW

Journal of Applied Ecology — BRITISH ECOLOGICAL SOCIETY

Accounting for flow intermittency in environmental flows design

Vicenç Acuña[1,2] | Dídac Jorda-Capdevila[1,2] | Paolo Vezza[3] | Anna Maria De Girolamo[4] | Michael E. McClain[5,6] | Rachel Stubbington[7] | Amandine V. Pastor[8] | Nicolas Lamouroux[9] | Daniel von Schiller[10] | Antoni Munné[11] | Thibault Datry[9]

[1]Catalan Institute for Water Research (ICRA), Girona, Spain; [2]Universitat de Girona (UdG), Girona, Spain; [3]Department of Environment, Land and Infrastructure Engineering (DIATI), Politecnico di Torino, Torino, Italy; [4]Water Research Institute, National Research Council (IRSA, CNR), Bari, Italy; [5]Department of Water Science and Engineering, IHE Delft Institute for Water Education, Delft, The Netherlands; [6]Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands; [7]School of Science and Technology, Nottingham Trent University, Nottingham, UK; [8]Centre for Ecology, Evolution and Environmental Changes (CE3C), Climate Change Impacts, Adaptation and Modelling (CCIAM), Faculdade de Ciências da Universidade de Lisboa, Lisbon, Portugal; [9]IRSTEA - Lyon, RiverLy Research Unit, Villeurbanne, France; [10]Professor Serra Húnter, Department of Evolutionary Biology, Ecology and Environmental Sciences, Faculty of Biology, University of Barcelona, Barcelona, Spain and [11]Catalan Water Agency (ACA), Barcelona, Spain

Correspondence
Dídac Jorda-Capdevila
Email: djorda@icra.cat

Funding information
European Cooperation in Science and Technology; Catalan Government, Grant/Award Number: ICRA- ENV 2017 SGR 1124; CERCA; La Agencia Estatal de Investigación del Ministerio de Ciencia Innovación y Universidades, Grant/Award Number: FJCI-2017-34977; Basque Government, Grant/Award Number: IT-951-16

Handling Editor: Vitor Paiva

Abstract

1. River ecosystems world-wide are affected by altered flow regimes, and advanced science and practice of environmental flows have been developed to understand and reduce these impacts. But most environmental flows approaches ignore flow intermittency, which is a natural feature of 30% of the global river network length. Ignoring flow intermittency when setting environmental flows in naturally intermittent rivers might lead to deleterious ecological effects.
2. We review evidence of the ecological effects of flow intermittency and provide guidance to incorporate intermittency (non-flow events) into existing methods judged as suitable for application in temporary waterways.
3. To better integrate non-flow events into hydrological methods, we propose a suite of new indicators to be used in the range of variability approach. These indicators reflect dry periods and the unpredictable nature of temporary waterways. We develop a predictability index for protecting those species adapted to temporary conditions.
4. For hydraulic-habitat models, we find that mesohabitat methods are particularly effective for describing complex habitat dynamics during dry phases. We present an example of the European eel to show the relationship between discharge and non-flow days and wet area, habitat suitability and connectivity.
5. We find that existing holistic approaches may be applied to temporary waterways without significant structural alteration to their stepwise frameworks, but new component methods are needed to address flow-related aspects across both flow and non-flow periods of the flow regime.
6. *Synthesis and applications*. Setting environmental flow requirements for temporary waterways requires modification and enhancement of existing approaches and methodologies, most notably the explicit consideration of non-flow events and

greater integration of specific geomorphic, hydrogeologic and hydraulic elements. Temporary waterways are among the freshwater ecosystems most vulnerable to alterations in flow regimes, and they are also under great pressure. The methodological modifications recommended in this paper will aid water managers in protecting key components of temporary flow regimes, thereby preserving their unique ecology and associated services.

KEYWORDS
ecological flows, environmental policy, flow regime, freshwater ecosystems, habitat modelling, socio-ecological systems, temporary waterways, water management

1 | INTRODUCTION

The natural flow regime of streams and rivers is commonly altered by anthropogenic activities, and will be further modified by the interacting effects of climate change and increasing human water demands (Schneider, Laizé, Acreman, & Flörke, 2013), especially in water scarce regions (Gerten et al., 2013; Kummu et al., 2016). Alterations to the flow regime are known to cause deleterious effects on freshwater ecosystem biodiversity, processes and services (Arthington, Bunn, Poff, & Naiman, 2006; Poff, Olden, Merritt, & Pepin, 2007).

Environmental flows (eflows) mitigate the deleterious effects of flow regime alterations (Arthington, Naiman, McClain, & Nilsson, 2010) and have been supported by national and international environmental policies, such as the European Water Framework Directive (Acreman & Ferguson, 2010; European Commission, 2016). Environmental flows describe the quantity, timing and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods and well-being (Arthington et al., 2018), while also taking into account sediment transport to preserve river geomorphology downstream and deltas in river mouths (Wohl et al., 2015). Existing methods to design eflows can be broadly differentiated in those based on only natural flow regime components (Acreman et al., 2014), those that also consider habitat conditions (Lamouroux & Jowett, 2005; Stanalker, Lamb, Henriksen, Bovee, & Bartholow, 1995) and those additionally considering socio-economic conditions (King, Brown, & Sabet, 2003; King & Louw, 1998; Richter, Warner, Meyer, & Lutz, 2006).

Around 30% of the global river network length is intermittent (Pekel, Cottam, Gorelick, & Belward, 2016; Schneider et al., 2017), and is also in need of eflows implementation. Intermittency is considered as an extreme flow event in the natural flow regime framework (Poff et al., 1997), and it is a key determinant of biodiversity and ecosystem function in temporary waterways (Acuña, Hunter, & Ruhí, 2017; Leigh & Datry, 2017). However, flow intermittency has been rarely considered in the design of eflows, often due to scarce available data on natural flows (gauging stations are rarely located in temporary waterways) and the complexity of recognizing how the effects of non-flow events on biological communities should be dealt with. Ignoring flow intermittency when setting eflows in these rivers might lead to deleterious ecological effects (Seaman, Watson, Avenant, Joubert, et al., 2016).

Here, we (a) review existing evidence of the ecological effects of flow intermittency on temporary waterways and discuss the likely consequences of its alteration; (b) review current methodological approaches to account for flow intermittency in the design of eflows for temporary waterways; and (c) discuss their limitations and propose modifications to properly account for flow intermittency.

1.1 | Socio-ecological effects of flow intermittency

Flow intermittency can be characterized by its spatial and temporal components; in space, the location and length of the non-flowing sections in the river network, and in time, the duration, frequency, timing and predictability of the non-flow events (Tonkin, Bogan, Bonada, Rios-Touma, & Lytle, 2017). Different combinations of these spatial and temporal components provide a high diversity of temporary waterways typologies (Eng, Wolock, & Dettinger, 2016), to which some species are specifically adapted (Bogan, Boersma, & Lytle, 2015). Beyond the spatial and temporal components, non-flowing sections might be mainly differentiated by the presence of permanent pools and by the severity of conditions in the river bed (temperature and humidity; Bogan et al., 2015; Colls, Timoner, Font, Sabater, & Acuña, 2019). The specific adaptations of species inhabiting temporary waterways mean that any significant change in, for example, the duration of non-flow events might alter biodiversity and thus ecosystem function (Datry, 2012; Garcia, Gibbins, Pardo, & Batalla, 2017; Jaeger, Olden, & Pelland, 2014). However, little research has explored the relationship between these spatial and temporal components. Only 4% of published studies in peer-reviewed journals on flow intermittency to date have analysed the effects of spatial or temporal components (Colls et al., 2019), restricting our ability to predict the ecological effects of changing flow intermittency patterns in temporary waterways.

Water resources management and climate change are the main drivers altering the spatial and temporal components of flow intermittency (Döll & Zhang, 2010). Management of water resources can even lead permanent watercourses to become temporary (artificial intermittency) or temporary to become permanent (artificial permanency; Acuña et al., 2017; Döll & Schmied, 2012). Land-use change also influences spatial and temporal variability in intermittency, for example the replacement of pasture by forest can cause shifts from permanent to intermittent flow (Gallart & Llorens, 2004). Observations over recent decades, as well as current global-scale climate change models, indicate changing precipitation and temperature patterns, with an overall increase in the temporal variability and a higher frequency of extreme events such as floods and supra-seasonal droughts (Döll & Schmied, 2012). These changes are leading to longer and more frequent non-flow events, to longer non-flowing river reaches (De Girolamo, Bouraoui, Buffagni, Pappagallo, & Lo Porto, 2017; Garcia, Amengual, Homar, & Zamora, 2017; Pumo, Caracciolo, Viola, & Noto, 2016) and to fundamental shifts from permanent to temporary river flow regimes (Döll & Schmied, 2012).

Knowledge about the ecological consequences of flow intermittency alteration is fragmented (Datry, Larned, & Tockner, 2014). For example, artificial permanency will affect biodiversity, as specialists including rare species may be replaced by competitive generalists (Gehrke & Harris, 2001); lentic and terrestrial species associated with pool and dry phases may be lost; and desiccation-sensitive non-native invasive species may also be favoured (Múrria, Bonada, & Prat, 2008; Poznańska, Kakareko, Krzyżyński, & Kobak, 2013). Although local (alpha) biodiversity may increase with increasing permanence, spatial and temporal regional (gamma) diversity are likely to decline due to reduced hydrological habitat diversity (Larned, Datry, Arscott, & Tockner, 2010). In terms of ecosystem function, losing the characteristic alternation of wet and dry phases in temporary waterways will change their unique 'biogeochemical heartbeat', with pulsed temporal and spatial variations in nutrient and organic matter inputs, instream processing and downstream transport (Acuña, Giorgi, Muñoz, Uehlinger, & Sabater, 2004; Jacobson & Jacobson, 2013; Shumilova et al., 2019).

We believe that although social perception of flow intermittency can be negative (Armstrong, Stedman, Bishop, & Sullivan, 2012; Leigh, Boersma, Galatowitsch, Milner, & Stubbington, 2019), from an ecological perspective, artificial permanency should generally be avoided, in particular where a natural flow regime is a feasible management goal (Acreman et al., 2014). The changes in biodiversity and ecosystem function caused by the alteration of the temporal components of flow intermittency can change delivery of ecosystem services (Jorda-Capdevila & Rodríguez-Labajos, 2016). Although most studies have considered the influence of a minimum flow on human well-being, from the local climate moderation to the generation of a pleasant waterscape (Gopal, 2016), recent work has also recognized the importance of dry river beds, for example as walking trails, migration corridors for shepherds, as a source of medicinal plants and for capturing aestivating catfish (Steward, Schiller, Tockner, Marshall, & Bunn, 2012). Finally, the cultural values of temporary waterways are increasingly acknowledged (Dee et al., 2017), and should also be integrated into flow management practices whenever relevant.

2 | METHODOLOGICAL APPROACHES TO DESIGN EFLOWS IN TEMPORARY WATERWAYS

Due to the lack of approaches accounting for flow intermittency in eflows design, some river basin district authorities have prescribed a minimum flow in order to maintain at least connected pools that preserve refuges for biota during dry periods in overexploited rivers (e.g. Pla Sectorial de Cabals de Manteniment de les conques internes de Catalunya (ACA, 2005)). However, those preventive approaches are often not enough to restore and preserve essential ecosystem aspects in temporary waterways, and additional guidance is needed to incorporate current understanding of flow intermittency into environmental flow assessment methods, also judged as suitable for application in temporary waterways. In this section we provide such guidance.

2.1 | Hydrological methods

Hydrological methods for designing eflows constitute a first level of analysis and the only option when data and time are limited (Arthington, 2012). Hydrological methods have been developed for broad-scale planning (Pastor, Ludwig, Biemans, Hoff, & Kabat, 2013), because they are based on indicators whose reliability is not sensitive to river length. Indeed, they can be applied to any point on a river for which flow data are available. Specifically, and due to the typical absence of data, natural flow regime time series can be derived by combining hydrological impacts with measured flow (i.e. by adding the water abstractions or subtracting point sources discharges to measured flow) or simulated using hydrological models (De Girolamo, Bouraoui, et al., 2017). Widely applied methods include the Montana method (Tennant, 1976), which recommends various levels of eflows based on specified proportions of the mean flow, and flow duration curve analysis (Matthews & Bao, 1991; Petts, 2009), based on the probability that flow in a stream will equal or exceed a particular value. These methods propose a minimum level of streamflow to limit excessive water abstraction, which reduces and alters the aquatic habitat. However, they may not be appropriate for rivers where flow is highly unpredictable and sometimes ceases naturally, especially where habitat degradation comes from the artificial permanency.

The range of variability approach (RVA; Richter, Baumgartner, Powell, & Braun, 1996) provides a comprehensive statistical characterization of ecologically relevant hydrological indicators that represent the duration, frequency, timing and predictability of flows, but also non-flow events, i.e. dry periods. Thus, the RVA assumes that the full range of variability of the flow regime is necessary to preserve river ecosystems (Poff et al., 1997), hence making it more suitable for application in temporary waterways. Moreover, this method can be easily adapted by selecting those indicators that prove to be ecologically influential for temporary waterways (D'Ambrosio, Girolamo, Barca, Ielpo, & Rulli, 2017), and by excluding those with negligible effects.

Here we make a well-argued proposal of indicators, each of them suitable for enhancing a specific ecological function (Table 1), and we illustrate their use based on a study of the Celone River (Italian Peninsula). For many years, the environmental flow in the Celone has been fixed by the river basin district authority in a range defined by the $7Q_{10}$ (lowest flow that occurs for seven consecutive days in a 10-year return period) and the Q_{335} (quantile 335 of the flow duration curve). However, this method does not guarantee that flow variability mimics the natural regime, which is one of the fundamental principles of eflows. The goal of using the RVA method and including our modifications is the incorporation of natural dry periods in the simulated environmental flow regimes. Thus, we use a predictability index, as the six-month seasonal predictability of the dry period, designed to protect species adapted to temporary conditions (Gallart et al., 2012; Williams, 2006; Wissinger, Greig, & McIntosch, 2008). Indices based on the number of flow and non-flow months and days provide information about the non-flow phase and the duration required to maintain the structure of river morphology, riparian cover, habitat and communities (Arscott, Larned, Scarsbrook, & Lambert, 2010; Larned et al., 2010). The monthly flow and the annual minimum flow of 30 and 90 consecutive days are able to describe the transitions from a flowing river to connected pools, disconnected pools and dry river bed, which sustain the life cycle of native species (García-Roger et al., 2011; Poff et al., 1997; Richter, Baumgartner, Braun, & Powell, 1998). Finally, indicators of the magnitude, duration, frequency, timing and rate of change of high flows, already used in permanent rivers, are also included. All indicators are derived from historical daily flows and calculated annually for at least 20 years (considered as a representative time series). To calculate the timing of high flows, we define the previous and next month of the mode (i.e. the month with the highest number of yearly highest flows) as the limits of the suitable period of high flows. For other indicators, we fix the 25th and 75th percentiles as the minimum and maximum values of the range where the designed

TABLE 1 Adaptation of the range of variability approach (RVA) for temporary waterways: a selection of hydrological indicators that represent specific ecological functions

Flow components	Hydrological indicators	Example ecological functions	References
Flow permanence	Relative number of months with flow	Maintains structure of communities, habitat, river morphology and riparian cover	Arscott et al. (2010) and Larned et al. (2010)
Predictability	Six-month seasonal predictability of non-flow period	Protects the development of specialist species	Gallart et al. (2012), Williams (2006) and Wissinger et al. (2008)
Magnitude of annual extreme flow condition	Annual 1-day mean maximum	Creates sites for colonization and supports abundance of invertebrate assemblages	Poff and Zimmerman (2010) and Richter et al. (1998)
	Annual 3-day mean maximum	Structures river channel morphology and physical habitat condition	Richter et al. (1998)
	Annual 7-day mean maximum	Desiccates sensitive aquatic species	Richter et al. (1998)
	Annual 30-day mean minimum	Sustains the life cycle of native species, by causing anaerobic stress in plants and invertebrate assemblage richness, by ensuring transition from connected to disconnected pools	Bunn and Arthington (2002), Poff et al. (2010) and Richter et al. (1998)
	Annual 90-day mean minimum	Controls the duration of stressful conditions such as low oxygen and high chemical concentrations; promotes transition from riffle to connected pools, which enhances the abundance of aquatic fauna	García-Roger et al. (2011), Poff et al. (1997) and Richter et al. (1998)
Magnitude of flow on monthly basis	Average monthly flow	Maintains species diversity and abundance and prevents establishment of non-native species	Konrad, Brasher, and May (2008)
Duration and timing of extreme condition	Non-flow days duration, Julian date of maximum, high pulse duration	Prevents non-native species, which are less tolerant to the absence of flow, from becoming dominant	Poff and Ward (1989)
Frequency	High pulse count	Regulates community structure and promotes population persistency	Richter et al. (1998)
Rate of change	Flashiness index	Prevents non-native species, less tolerant to flash floods than tolerant and traps organisms in islands	Baker, Richards, Loftus, and Kramer (2004), Konrad et al. (2008), Petts (1984) and Richter et al. (1998)

environmental flow regime should be established. Percentiles here are more suitable than using ±1 *SD* from the mean because data may not be normally distributed and their covariance may be high.

Once all indicators are calculated, and as in the current RVA method, the procedure is monitored and revised based on biological data, such as those describing bioindicators used to assess ecological status in the Water Framework Directive (i.e. macroinvertebrates, fish, diatoms and macrophytes; Belmar, Vila-Martínez, Ibáñez, & Caiola, 2018). This is done in a process of successive approximations able to identify relationships between biota and flow regime. At this stage, reference values need to be carefully defined in temporary waterways according to the hydrological regimes. Then, the environmental flow designers select a range of ecologically acceptable variability of each indicator, such as is done in the Ecological Limits of Hydrological Alteration (ELOHA) framework (Poff et al., 2010).

The particular assessment in the Celone River was performed downstream of a reservoir, and each indicator was calculated by using simulated streamflow data obtained from a hydrological model, and measured streamflow under current conditions in the impacted reach (De Girolamo, Barca, Pappagallo, & Lo Porto, 2017; De Girolamo, Bouraoui, et al., 2017). Results from our adapted methodology show that a new environmental flow regime for the Celone River should include a non-flow period from June to October and 2–5 high flow pulses between February and April (Figure 1).

2.2 | Hydraulic-habitat models

Hydraulic-habitat models complement hydrological methods by incorporating flow-dependent ecological data, such as the occurrence of wetted areas and the connectivity between them, the local hydraulic-habitat conditions of water depth and flow velocity, the presence of ecological refuges. The premise underlying hydraulic-habitat models is that biotic communities in rivers are limited by hydraulic-habitat availability. Thus, these models simulate spatial and temporal variability in physical habitat characteristics, such as depth, velocity and substrate composition, which in turn are used to predict taxonomic occurrence and abundance (Ahmadi-Nedushan et al., 2006; Heggenes & Wollebaek, 2013). The most commonly used hydraulic-habitat models, such as PHABSIM (Bovee, 1982) and CASiMiR (Jorde, Chneider, Peter, & Zöllner, 2001), work at the microhabitat scale, referring to a single point (or river element) that is evaluated to determine its suitability as hydraulic habitat.

Although hydraulic models have been used for characterizing habitats during flowing phases and for managing low flows by

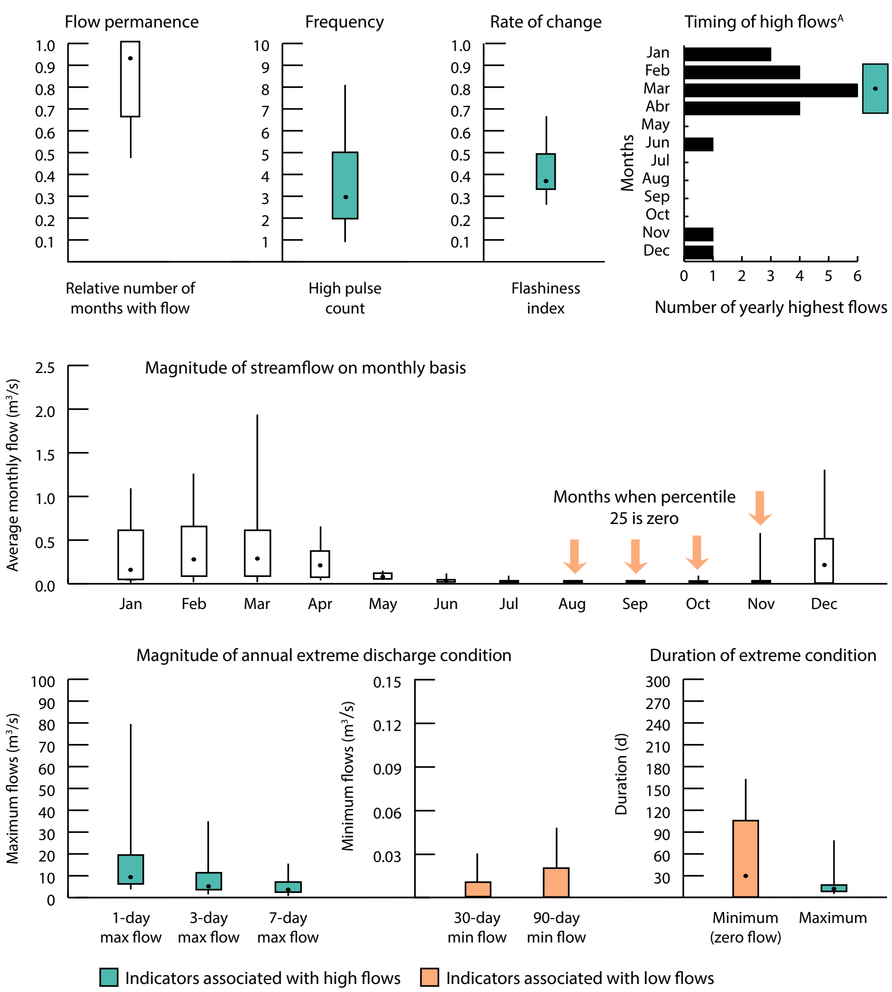

FIGURE 1 Indicator selection for the adaptation of the range of variability approach method to temporary waterways applied in the Celone River (Italian Peninsula). Lines show 5th and 95th percentiles, boxes show 25th and 75th percentiles and dots show the median values higher than zero. For the timing of high flows, the dot corresponds to the mode and the box includes the previous and upcoming months and shows the period in which high flows should be released

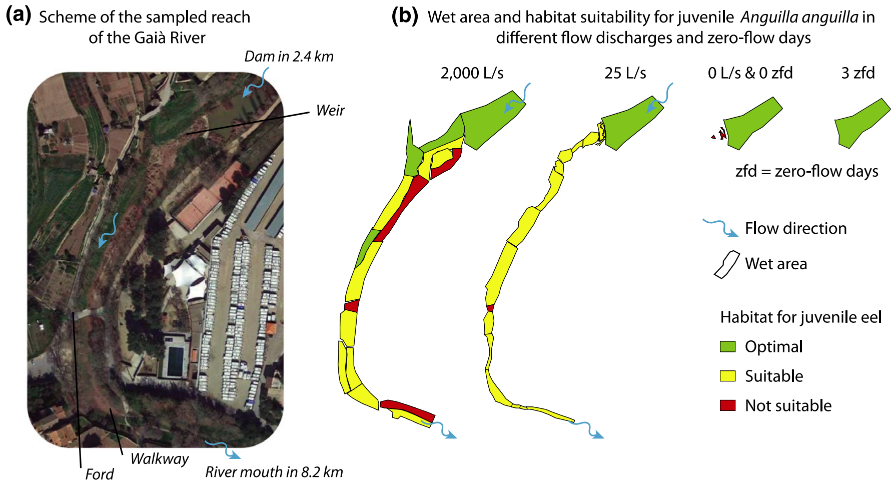

FIGURE 2 Application of the meso-scale hydraulic-habitat model (MesoHABSIM) to the Gaià River (Iberian Peninsula). We show here basic information for the studied reach (a) and the wet area and habitat suitability for the key specie European eel *Anguilla anguilla* in its juvenile life stage under different levels of flow discharge and non-flow days (b)

maintaining isolated pools in temporary waterways (Theodoropoulos et al., 2019), they are unreliable for flow rates near zero and evidently do not describe non-flow periods. Coupled groundwater-surface water physical models are more appropriate but are still uncertain when flow is near zero (Seaman, Watson, Avenant, Joubert, et al., 2016). During non-flow periods, habitat characteristics other than local hydraulics are more important for biota, such as the connectivity and distance among wetted areas, river planforms and morphology and water temperature and quality in disconnected pools (Gordon, McMahon, Finlayson, Gippel, & Nathan, 2004). Therefore, dynamics of these habitats are particularly important to describe. When flow decreases to zero, the aquatic habitat is reduced not instantly but gradually. This implies that, despite the non-flow conditions, water can remain stagnant in pools for a few days or for a longer period of time. The wetted area of the river, as well as the habitat availability in non-flow conditions, is then reduced according to the time since flow ceased at a rate that depends on the geomorphology of the river stretch, the groundwater level, the soil humidity and the weather conditions.

Mesohabitat methods, based on field surveys of habitat configurations on various occasions, are particularly effective for describing complex habitat dynamics during non-flow periods (Belletti et al., 2017; Parasiewicz et al., 2013). A first attempt to explore how habitat changes when water flows cease was carried out in the Gaià River (Iberian Peninsula) during both flow and non-flow phases (Figure 2a). This provided detailed data on morphological (planforms, surface and connectivity of wetted areas), hydrological (streamflow time series, water depth and flow velocity patterns), vegetation (distribution and type), cover (refuges availability for biota) and sediment (size, patches, embeddedness) properties of the river (Belletti et al., 2017). After segmenting the river into homogeneous hydromorphological reaches, multiple, stage-dependent surveys of geomorphological units provided basic maps for the characterization of mesohabitats (Figure 2b), which were used to calculate spatio-temporal variation in habitat availability. These data were used to draw curves that represent the relationship between discharge and zero-flow days and wet area (Figure 3a), habitat suitability for key species (Figure 3b) and connectivity (Figure 3c). The level of each variable can also be represented as a percentage of its maximum level.

As an example, a native fish species (European eel) was used as an ecological target, although macroinvertebrates could be also targeted (Parasiewicz et al., 2013; Vezza, Ghia, & Fea, 2015). Rating curves were developed between flow and habitat, allowing to estimate habitat availability for fish species in space (% of channel area) during both flow and non-flow phases. Lastly, habitat time series (Milhous, Bartholow, Updike, & Moss, 1990) represented how physical habitat changes through time to identify deviation in habitat availability between reference and altered conditions. Increasing duration and frequency of flow events below minimum habitat thresholds may create catastrophically low habitat quantity for aquatic organisms. Several examples have been reported on frequency analysis of habitat (under-threshold) events, investigating current and future stress conditions that are created by persistent limitations in habitat availability (Parasiewicz et al., 2013; Vezza, Muñoz-Mas, Martinez-Capel, & Mouton, 2015).

Environmental flows design should avoid these habitat bottlenecks and meso-scale habitat models can be used to simulate possible future scenarios and select the most appropriate one. This approach represents a feasible solution for different river morphological types (Belletti et al., 2017) and has been proven robust and quite universal (Parasiewicz et al., 2013). The combination of habitat-flow rating curve, habitat-time rating curve and habitat time series is an extension of meso-scale habitat models for application in temporary waterways, and can simulate habitat availability in current and future river flow and morphological conditions. Results from hydraulic-habitat models may then be used to calibrate hydrological methods by providing ecologically meaningful data.

2.3 | Holistic methods

Holistic approaches use stepwise structured frameworks that collect, analyse and integrate data and knowledge to recommend flow levels to meet specific objectives (Acreman & Dunbar, 2004). By

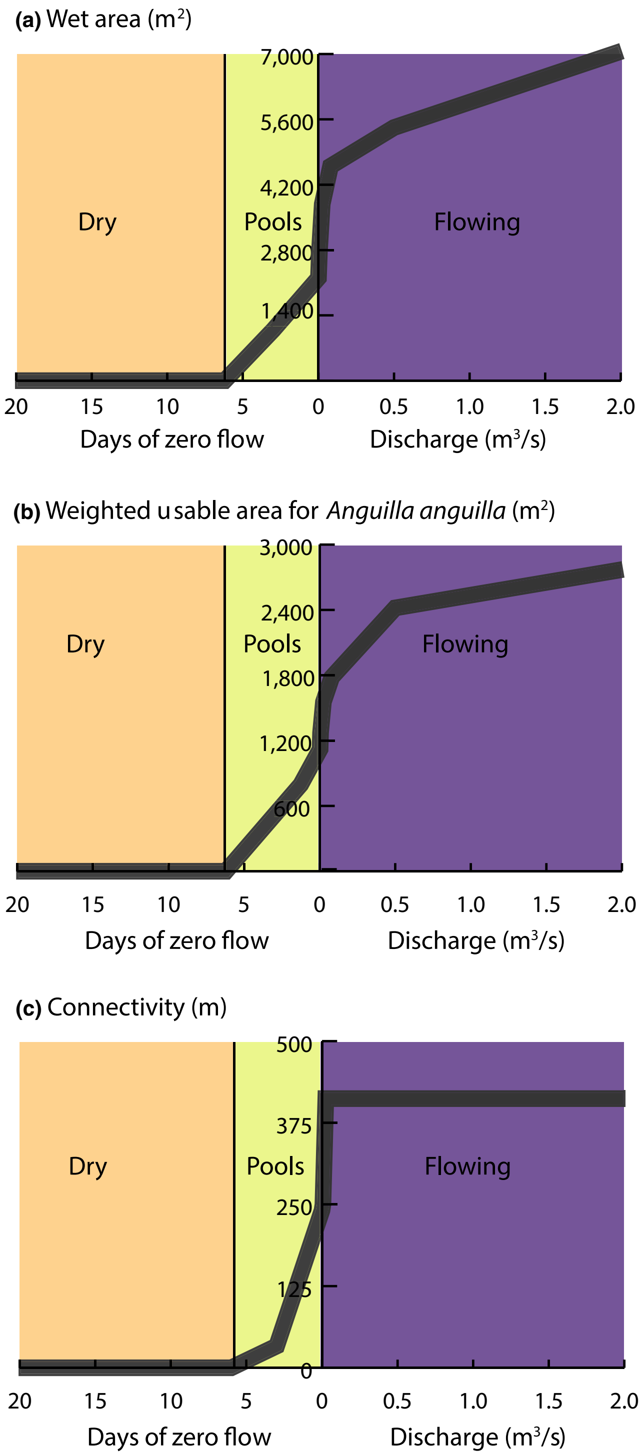

FIGURE 3 Adaptation of the hydraulic-mesohabitat models to temporary waterways by including the zero-flow-days axis in the graphs relating wet area (a), weighted usable area for key species (b) and connectivity (c) to flow discharge. Results shown are from the Gaià River (Iberian Peninsula), where the selected key species is European eel *Anguilla anguilla*

design, they include stakeholder engagement and adjustment of results through negotiation and consensus building, and thus require considerable time to overcome difficulties in their implementation. Widely applied basin-scale approaches like the Downstream Response to Imposed Flow Transformation (DRIFT; King, Beuster, Brown, & Joubert, 2014; King et al., 2003) and ELOHA (Poff et al., 2010) produce results showing the response of river systems to varying degrees of flow regime alteration, through plausible resource development scenarios. By including stepwise guidance on data and knowledge needs, they generally do not prescribe specific analytical methods to fill each data requirement. This makes holistic approaches flexible enough to be applied across a wide range of socio-ecological and biophysical conditions. Holistic approaches may thus incorporate the modified hydrological and hydraulic-habitat methods described above, or expert knowledge in the absence of empirical data.

To date, at least two published studies have applied holistic approaches in temporary waterways (Godinho, Costa, Pinheiro, Reis, & Pinheiro, 2014; Seaman, Watson, Avenant, King, et al., 2016). The first is a generic framework applied in the São Pedro, Brenhas and Amoreiras Rivers (Iberian Peninsula; Godinho et al., 2014). It lays out a series of steps that enable the integration of hydrological, hydraulic rating, habitat simulation and other methods in the formulation of environmental flow regimes to meet the biotic, hydromorphological and water quality criteria of the European Water Framework Directive. The second was applied to the Mokolo River (Southern Africa), which flows for 72%–87% of the year (Seaman, Watson, Avenant, King, et al., 2016). The DRIFT-ARID approach recognizes the need to represent periods of unmeasurable surface flow when groundwater dynamics become controlling. An integrated groundwater-surface water model simulates daily groundwater depth, groundwater flow beneath the river and net groundwater baseflow to the river (Prucha et al., 2016). Onset dates of non-flow and flowing periods are also new indicators that quantify the duration of unmeasurable surface flows.

As these examples demonstrate, existing holistic approaches may be applied to temporary waterways without significant structural alteration to their stepwise frameworks, but new component methods are needed to address flow-related aspects across both flow and non-flow periods of the flow regime. Key lessons learned from these experiences include the need for (a) improved knowledge of flow-ecology relationships in temporary waterways; (b) delineation of different types of temporary waterways; (c) increased terrestrial (e.g. soil science) and socio-economic knowledge in assessment teams to properly consider processes and interactions distinct from those in perennial rivers (Arce et al., 2019); (d) incorporation of examples of desiccation-resistant biota such as aestivating fish (Polacik & Podrabsky, 2015), seed and egg banks (Brock, Nielsen, Shiel, Green, & Langley, 2003; Rogers, 2014) and terrestrial species that use the river bed during non-flow conditions (Steward et al., 2011); and (e) special emphasis on those non-flow ecological processes providing services with socio-economic value to human communities. Regarding the first point, knowledge has grown considerably in recent years (Datry, Bonada, & Boulton, 2017), thus facilitating the implementation of holistic approaches in temporary waterways whenever planned.

Holistic approaches also emphasize the socio-economic aspects of resource protection for environmental flow assessment.

Developed to incorporate socio-economic knowledge into environmental management, the ecosystem services concept may account for the value that a designed environmental flow regime provides to human well-being (Jorda-Capdevila & Rodríguez-Labajos, 2016). The unpredictable character of temporary waterways and the distinction among phases provide additional values not accounted for in permanent rivers (Steward et al., 2012), such as the use of the dry river bed for cultural activities or the corridor for mammals appreciated by hunters (Sánchez-Montoya, Moleón, Sánchez-Zapata, & Tockner, 2016), but also interrupts the service provision—temporally and spatially—and complicates its evaluation (Koundouri, Boulton, Datry, & Souliotis, 2017).

The ecosystem services concept may improve inter-stakeholder dialogue, as synergies and trade-offs are easily identified (Jorda-Capdevila & Rodríguez-Labajos, 2015; Pahl-Wostl et al., 2013). Considering ecosystem services is especially recommended when flow regimes need to be designed for modified and managed rivers (Acreman et al., 2014). Thus, new frameworks that incorporate service provision within environmental flow assessment should not only account for their values but also for power asymmetries to foster environmental justice (Gopal, 2016; Jorda-Capdevila & Rodríguez-Labajos, 2017). The Sustainable Management of Hydrological Alteration framework (Pahl-Wostl et al., 2013), built on ELOHA, incorporates desirable ecosystem service goals that require negotiation in participatory settings. However, example applications of holistic methods that incorporate ecosystem services valuation are still missing. Finally, although not yet widely classified as water bodies protected by water policies, calls for greater attention to temporary waterways (Acuña et al., 2014; Marshall et al., 2018; Nikolaidis et al., 2013) encourage holistic approaches to incorporate policy considerations in the design and implementation of eflows.

3 | CONCLUSIONS

First, the main obstacle in the assessment and implementation of eflows in temporary waterways is the lack of hydrological data as well as of knowledge on the ecological effects of hydrological variability. Moreover, the study of flow intermittency by social and economic disciplines remains in its infancy.

Second, as revealed by actual applications, the habitat description of temporary waterways needs to combine specific hydrological variables (e.g. duration and timing of flow intermittency) and specific geomorphic/hydrogeologic/hydraulic elements (e.g. pool persistence and connectivity dynamics). In fact, the hydrology of temporary waterways should be precisely characterized to recognize their spatial and temporal variability. Hydrological methods can easily adapt to such variability and be implemented in any reservoir throughout a basin. However, hydrological data are typically unavailable, so models can rarely by applied to simulate both non-regulated and regulated conditions. This difficulty reinforces other approaches based on scenario comparisons, which focus on social and ecological objectives beyond natural conditions, and hence need to encompass elements other than hydrology.

Third, geomorphic and hydraulic elements (e.g. pool persistence and connectivity dynamics) describe the habitats that environmental flow designers aim to protect. Thus, hydraulic-habitat models relate geomorphic and hydraulic features in specific reaches to the flow regime and pursue flow objectives that target specific aquatic species, including those that have a terrestrial stage. However, for temporary waterways, such elements depend not only on the flow regime, but also on the time after the stream dries out, a variable that we identified as vital to incorporate for any eflows assessment. The analysis can be easily extended to life stages of various species that can be used as Indicators within hydraulic-habitat models developed for temporary waterways. Additionally, knowledge of groundwater levels and their influence on the maintenance of locally connected or disconnected pools in surface waters becomes key to correctly manage suitable eflows in temporary waterways.

Fourth, management objectives for the implementation of eflows should also include socio-economic perspectives (e.g. an ecosystem services-based approach). This means that managers should engage local stakeholders and balance a range of perspectives to adequately address eflows in temporary waterways. In this sense, holistic approaches are appropriate, since they include multiple type of variables and recall expert knowledge in situations with high uncertainty.

ACKNOWLEDGEMENTS

This paper is based upon work from COST Action CA15113 (SMIRES, Science and Management of Intermittent Rivers and Ephemeral Streams; www.smires.eu) supported by COST (European Cooperation in Science and Technology). V Acuña and D Jorda-Capdevila also acknowledge the support from the Economy and Knowledge Department of the Catalan Government through Consolidated Research Group (ICRA-ENV 2017 SGR 1124) and from the CERCA. The Juan de la Cierva contract of D Jorda-Capdevila (FJCI-2017-34977) is funded by La Agencia Estatal de Investigación del Ministerio de Ciencia Innovación y Universidades. The participation of D von Schiller was additionally supported by a Grant for Research Groups of the Basque University System (IT-951-16), funded by the Basque Government. Field work in the Gaià case study was supported by Mònica Bardina, Evelyn Garcia and Carolina Solà.

AUTHORS' CONTRIBUTIONS

All authors approved the final version to be published, and all questions related to the accuracy or integrity of any part of the authors' work have been appropriately investigated and resolved. Note that we followed the CrediT system (https://casrai.org/credit/) and key references on the topic (Frassl et al., 2018; Hunt, 1991). The CrediT has been used as system to evaluate individual contributions to the paper (see details in Table S1), which identified those meeting authorship criteria, as well as the order of the listed authors. In sum, V.A. conceived the ideas, coordinated the co-authors and led the Socio-ecological effects of flow intermittency section; D.J.-C. also coordinated the co-authors, and led the submission process and the design of figures; P.V. led the

Hydraulic-habitat models section; A.M.D.G. led the Hydrological methods section; M.E.M. led the Holistic methods section and did the English proofreading; R.S. also proofread the article and made multiple small contributions throughout the article, as well as A.V.P., N.L., D.v.S. and A.M.; T.D. did an exhaustive revision of the article, pushed the work forward and organized the meeting in which this work started.

DATA AVAILABILITY STATEMENT

Data about the Celone River case study are available via Mendeley Data https://doi.org/10.17632/ytsy2yck5g.1 (De Girolamo, 2020). Data about the Gaià River case study are available via Mendeley Data https://doi.org/10.17632/7svhmvpxrs.1 (Vezza, 2020).

ORCID

Vicenç Acuña https://orcid.org/0000-0002-4485-6703
Dídac Jorda-Capdevila https://orcid.org/0000-0002-5670-829X
Paolo Vezza https://orcid.org/0000-0002-6784-8036
Anna Maria De Girolamo https://orcid.org/0000-0001-5605-6239
Michael E. McClain https://orcid.org/0000-0003-2956-9818
Rachel Stubbington https://orcid.org/0000-0001-8475-5109
Amandine V. Pastor https://orcid.org/0000-0003-4526-7705
Daniel von Schiller https://orcid.org/0000-0002-9493-3244
Thibault Datry https://orcid.org/0000-0003-1390-6736

REFERENCES

ACA. (2005). *Pla Sectorial de Cabals de Manteniment de Les Conques Internes de Catalunya*. Barcelona, Spain: Agència Catalana de l'Aigua.

Acreman, M., Arthington, A. H., Colloff, M. J., Couch, C., Crossman, N. D., Dyer, F., … Young, W. (2014). Environmental flows for natural, hybrid, and novel riverine ecosystems in a changing world. *Frontiers in Ecology and the Environment*, *12*, 466–473. https://doi.org/10.1890/130134

Acreman, M. C., & Dunbar, M. J. (2004). Defining environmental river flow requirements–A review. *Hydrology and Earth System Sciences*, *8*, 861–876. https://doi.org/10.5194/hess-8-861-2004

Acreman, M. C., & Ferguson, A. J. D. (2010). Environmental flows and the European water framework directive. *Freshwater Biology*, *55*, 32–48. https://doi.org/10.1111/j.1365-2427.2009.02181.x

Acuña, V., Datry, T., Marshall, J., Barceló, D., Dahm, C. N., Ginebreda, A., … Palmer, M. A. (2014). Why should we care about temporary waterways? *Science*, *343*, 1080–1081. https://doi.org/10.1126/science.1246666

Acuña, V., Giorgi, A., Muñoz, I., Uehlinger, U., & Sabater, S. (2004). Flow extremes and benthic organic matter shape the metabolism of a headwater Mediterranean stream. *Freshwater Biology*, *49*, 960–971. https://doi.org/10.1111/j.1365-2427.2004.01239.x

Acuña, V., Hunter, M., & Ruhí, A. (2017). Managing temporary streams and rivers as unique rather than second-class ecosystems. *Biological Conservation*, *211*, 12–19. https://doi.org/10.1016/j.biocon.2016.12.025

Ahmadi-Nedushan, B., St-Hilaire, A., Bérubé, M., Robichaud, É., Thiémonge, N., & Bobée, B. (2006). A review of statistical methods for the evaluation of aquatic habitat suitability for instream flow assessment. *River Research and Applications*, *22*, 503–523. https://doi.org/10.1002/rra.918

Arce, M. I., Mendoza-Lera, C., Almagro, M., Catalán, N., Romaní, A. M., Martí, E., … von Schiller, D. (2019). A conceptual framework for understanding the biogeochemistry of dry riverbeds through the lens of soil science. *Earth-Science Reviews*, *188*, 441–453. https://doi.org/10.1016/j.earscirev.2018.12.001

Armstrong, A., Stedman, R. C., Bishop, J. A., & Sullivan, P. J. (2012). What's a stream without water? Disproportionality in headwater regions impacting water quality. *Environmental Management*, *50*, 849–860. https://doi.org/10.1007/s00267-012-9928-0

Arscott, D. B., Larned, S. T., Scarsbrook, M. R., & Lambert, P. (2010). Aquatic invertebrate community structure along an intermittence gradient: Selwyn River, New Zealand. *Journal of the North American Benthological Society*, *29*, 530–545. https://doi.org/10.1899/08-124.1

Arthington, A. (2012). *Environmental flows. Saving rivers in the Third Millenium*. Berkeley, CA: University of California Press.

Arthington, A. H., Bhaduri, A., Bunn, S. E., Jackson, S. E., Tharme, R. E., Tickner, D., … Ward, S. (2018). The Brisbane declaration and global action agenda on environmental flows (2018). *Frontiers in Environmental Science*, *6*, 1–15. https://doi.org/10.3389/fenvs.2018.00045

Arthington, A. H., Bunn, S. E., Poff, L. N., & Naiman, R. J. (2006). The challenge of providing environmental flow rules to sustian river ecosystems. *Ecological Applications*, *16*, 1311–1318.

Arthington, A. H., Naiman, R. J., McClain, M. E., & Nilsson, C. (2010). Preserving the biodiversity and ecological services of rivers: New challenges and research opportunities. *Freshwater Biology*, *55*, 1–16. https://doi.org/10.1111/j.1365-2427.2009.02340.x

Baker, D. B., Richards, R. P., Loftus, T. T., & Kramer, J. W. (2004). A new flashiness index: Characteristics and applications to midwestern rivers and streams. *Journal of the American Water Resources Association*, *40*, 503–522. https://doi.org/10.1111/j.1752-1688.2004.tb01046.x

Belletti, B., Rinaldi, M., Bussettini, M., Comiti, F., Gurnell, A. M., Mao, L., … Vezza, P. (2017). Characterising physical habitats and fluvial hydromorphology: A new system for the survey and classification of river geomorphic units. *Geomorphology*, *283*, 143–157. https://doi.org/10.1016/j.geomorph.2017.01.032

Belmar, O., Vila-Martínez, N., Ibáñez, C., & Caiola, N. (2018). Linking fish-based biological indicators with hydrological dynamics in a Mediterranean river: Relevance for environmental flow regimes. *Ecological Indicators*, *95*, 492–501. https://doi.org/10.1016/j.ecolind.2018.06.073

Bogan, M. T., Boersma, K. S., & Lytle, D. A. (2015). Resistance and resilience of invertebrate communities to seasonal and supraseasonal drought in arid-land headwater streams. *Freshwater Biology*, *60*, 2547–2558. https://doi.org/10.1111/fwb.12522

Bovee, K. D. (1982). *A guide to stream habitat analysis using the instream flow incremental methodology*. Fort Collins, CO: U.S. Fish and Wildlife Service.

Brock, M. A., Nielsen, D. L., Shiel, R. J., Green, J. D., & Langley, J. D. (2003). Drought and aquatic community resilience: The role of eggs and seeds in sediments of temporary wetlands. *Freshwater Biology*, *48*, 1207–1218. https://doi.org/10.1046/j.1365-2427.2003.01083.x

Bunn, S. E., & Arthington, A. H. (2002). Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management*, *30*, 492–507. https://doi.org/10.1007/s00267-002-2737-0

Colls, M., Timoner, X., Font, C., Sabater, S., & Acuña, V. (2019). Effects of duration, frequency, and severity of the non-flow period on stream biofilm metabolism. *Ecosystems*, *22*, 1393–1405. https://doi.org/10.1007%2Fs10021-019-00345-1

D'Ambrosio, E., De Girolamo, A. M., Barca, E., Ielpo, P., & Rulli, M. C. (2017). Characterising the hydrological regime of an ungauged temporary river system: A case study. *Environmental Science and Pollution Research*, *24*, 13950–13966. https://doi.org/10.1007/s11356-016-7169-0

Datry, T. (2012). Benthic and hyporheic invertebrate assemblages along a flow intermittence gradient: Effects of duration of dry events. *Freshwater Biology*, *57*, 563–574. https://doi.org/10.1111/j.1365-2427.2011.02725.x

Datry, T., Bonada, N., & Boulton, A. (Eds.). (2017). *Intermittent rivers and ephemeral streams* (1st ed.). Cambridge, MA: Academic Press.

Datry, T., Larned, S. T., & Tockner, K. (2014). Intermittent rivers: A challenge for freshwater ecology. *BioScience*, *64*, 229–235. https://doi.org/10.1093/biosci/bit027

De Girolamo, A. M. (2020). Data from: Natural streamflow and IHAs. Celone River case study. *Mendeley Data*, *V1*, https://doi.org/10.17632/ytsy2yck5g.1

De Girolamo, A. M., Barca, E., Pappagallo, G., & Lo Porto, A. (2017). Simulating ecologically relevant hydrological indicators in a temporary river system. *Agricultural Water Management*, *180*, 194–204. https://doi.org/10.1016/j.agwat.2016.05.034

De Girolamo, A. M., Bouraoui, F., Buffagni, A., Pappagallo, G., & Lo Porto, A. (2017). Hydrology under climate change in a temporary river system: Potential impact on water balance and flow regime. *River Research and Applications*, *33*, 1219–1232. https://doi.org/10.1002/rra.3165

Dee, L. E., Allesina, S., Bonn, A., Eklöf, A., Gaines, S. D., Hines, J., … Thompson, R. M. (2017). Operationalizing network theory for ecosystem service assessments. *Trends in Ecology & Evolution*, *32*, 118–130. https://doi.org/10.1016/j.tree.2016.10.011

Döll, P., & Schmied, H. M. (2012). How is the impact of climate change on river flow regimes related to the impact on mean annual runoff? A global-scale analysis. *Environmental Research Letters*, *7*, 014037. https://doi.org/10.1088/1748-9326/7/1/014037

Döll, P., & Zhang, J. (2010). Impact of climate change on freshwater ecosystems: A global-scale analysis of ecologically relevant river flow alterations. *Hydrology and Earth System Sciences*, *14*, 783–799. https://doi.org/10.5194/hess-14-783-2010

Eng, K., Wolock, D. M., & Dettinger, M. D. (2016). Sensitivity of intermittent streams to climate variations in the USA. *River Research and Applications*, *32*, 885–895. https://doi.org/10.1002/rra.2939

European Commission. (2016). *Ecological flows in the implementation of the water framework directive: Guidance document No 31*. Luxembourg: Office for Official Publications of the European Communities. https://doi.org/10.2779/775712

Frassl, M. A., Hamilton, D. P., Denfeld, B. A., de Eyto, E., Hampton, S. E., Keller, P. S., … Catalán, N. (2018). Ten simple rules for collaboratively writing a multi-authored paper. *PLOS Computational Biology*, *14*, e1006508. https://doi.org/10.1371/journal.pcbi.1006508

Gallart, F., & Llorens, P. (2004). Observations on land cover changes and water resources in the headwaters of the Ebro catchment, Iberian Peninsula. *Physics and Chemistry of the Earth*, *29*, 769–773. https://doi.org/10.1016/j.pce.2004.05.004

Gallart, F., Prat, N., García-Roger, E. M., Latron, J., Rieradevall, M., Llorens, P., … Froebrich, J. (2012). A novel approach to analyzing the regimes of temporary streams in relation to their controls on the composition and structure of aquatic biota. *Hydrology and Earth System Sciences*, *16*, 1–18.

Garcia, C., Amengual, A., Homar, V., & Zamora, A. (2017). Losing water in temporary streams on a Mediterranean island: Effects of climate and land-cover changes. *Global and Planetary Change*, *148*, 139–152. https://doi.org/10.1016/j.gloplacha.2016.11.010

Garcia, C., Gibbins, C. N., Pardo, I., & Batalla, R. J. (2017). Long term flow change threates invertebrate diversity in temporary streams: Evidence from an island. *Science of the Total Environment*, *580*, 1453–1549.

García-Roger, E. M., del Mar Sánchez-Montoya, M., Gómez, R., Suárez, M. L., Vidal-Abarca, M. R., Latron, J., … Prat, N. (2011). Do seasonal changes in habitat features influence aquatic macroinvertebrate assemblages in perennial versus temporary Mediterranean streams? *Aquatic Sciences*, *73*, 567–579. https://doi.org/10.1007/s00027-011-0218-3

Gehrke, P. C., & Harris, J. H. (2001). Regional-scale effects of flow regulation on lowland riverine fish communities in New South Wales, Australia. *Regulated Rivers: Research & Management*, *17*, 369–391. https://doi.org/10.1002/rrr.648

Gerten, D., Hoff, H., Rockström, J., Jägermeyr, J., Kummu, M., & Pastor, A. V. (2013). Towards a revised planetary boundary for consumptive freshwater use: Role of environmental flow requirements. *Current Opinion in Environmental Sustainability*, *5*, 551–558. https://doi.org/10.1016/j.cosust.2013.11.001

Godinho, F., Costa, S., Pinheiro, P., Reis, F., & Pinheiro, A. (2014). Integrated procedure for environmental flow assessment in rivers. *Environmental Processes*, *1*, 137–147. https://doi.org/10.1007/s40710-014-0012-z

Gopal, B. (2016). A conceptual framework for environmental flows assessment based on ecosystem services and their economic valuation. *Ecosystem Services*, *21*, 53–58. https://doi.org/10.1016/j.ecoser.2016.07.013

Gordon, N., McMahon, T., Finlayson, B., Gippel, C., & Nathan, R. (2004). *Stream hydrology: An introduction for ecologists*. Hoboken, NJ: Wiley.

Heggenes, J., & Wollebaek, J. (2013). Habitat use and selection by brown trout in streams. I. Maddock, A. Harby, P. Kemp, & P. J. Wood (Eds.), *Ecohydraulics: An integrated approach* (p. 462). Chichester, UK: John Wiley & Sons Ltd.

Hunt, R. (1991). Trying an authorship index. *Nature*, *352*, 187. https://doi.org/10.1038/352187a0

Jacobson, P. J., & Jacobson, K. M. (2013). Hydrologic controls of physical and ecological processes in Namib Desert ephemeral rivers: Implications for conservation and management. *Journal of Arid Environments*, *93*, 80–93. https://doi.org/10.1016/j.jaridenv.2012.01.010

Jaeger, K. L., Olden, J. D., & Pelland, N. A. (2014). Climate change poised to threaten hydrologic connectivity and endemic fishes in dryland streams. *Proceedings of the National Academy of Sciences of the United States of America*, *111*, 13894–13899. https://doi.org/10.1073/pnas.1320890111

Jorda-Capdevila, D., & Rodríguez-Labajos, B. (2015). An ecosystem service approach to understand conflicts on river flows: Local views on the Ter River (Catalonia). *Sustainability Science*, *10*, 463–477. https://doi.org/10.1007/s11625-014-0286-0

Jorda-Capdevila, D., & Rodríguez-Labajos, B. (2016). Socioeconomic value(s) of restoring environmental flows: Systematic review and guidance for assessment. *River Research and Applications*. https://doi.org/10.1002/rra.3074

Jorda-Capdevila, D., & Rodríguez-Labajos, B. (2017). Embracing complexity improves the assessment of environmental flows – One step beyond Gopal's (2016) framework. *Ecosystem Services*, *25*, 79–81. https://doi.org/10.1016/j.ecoser.2017.03.018

Jorde, K., Schneider, M., Peter, A., & Zoellner, F. (2001). Fuzzy based models for the evaluation of fish habitat quality and instream flow assessment. In *Proceedings of the 3rd international symposium on environmental hydraulics*, *3*, 27–28.

King, J., Beuster, H., Brown, C., & Joubert, A. (2014). Pro-active management: The role of environmental flows in transboundary cooperative planning for the Okavango River system. *Hydrological Sciences Journal*, *59*, 786–800. https://doi.org/10.1080/02626667.2014.888069

King, J., Brown, C., & Sabet, H. (2003). A scenario-based holistic approach to environmental flow assessments for rivers. *River Research and Applications*, *19*, 619–639. https://doi.org/10.1002/rra.709

King, J., & Louw, D. (1998). Instream flow assessments for regulated rivers in South Africa using the building block methodology. *Aquatic Ecosystem Health and Management*, *1*, 109–124. https://doi.org/10.1016/S1463-4988(98)00018-9

Konrad, C. P., Brasher, A. M. D., & May, J. T. (2008). Assessing streamflow characteristics as limiting factors on benthic invertebrate assemblages in streams across the western United States. *Freshwater Biology*, *53*, 1983–1998. https://doi.org/10.1111/j.1365-2427.2008.02024.x

Koundouri, P., Boulton, A. J., Datry, T., & Souliotis, I. (2017). Ecosystem services, values, and societal perceptions of intermittent rivers and ephemeral streams. In T. Datry, N. Bonada, & A. J. Boulton (Eds.), *Intermittent rivers and ephemeral streams: Ecology and management* (pp. 455–476). London, UK: Academic Press.

Kummu, M., Guillaume, J. H. A., de Moel, H., Eisner, S., Flörke, M., Porkka, M., … Ward, P. J. (2016). The world's road to water scarcity: Shortage and stress in the 20th century and pathways towards sustainability. *Scientific Reports*, *6*, 38495. https://doi.org/10.1038/srep38495

Lamouroux, N., & Jowett, I. G. (2005). Generalized instream habitat models. *Canadian Journal of Fisheries and Aquatic Sciences*, *62*, 7–14. https://doi.org/10.1139/f04-163

Larned, S. T., Datry, T., Arscott, D. B., & Tockner, K. (2010). Emerging concepts in temporary-river ecology. *Freshwater Biology*, *55*, 717–738. https://doi.org/10.1111/j.1365-2427.2009.02322.x

Leigh, C., Boersma, K. S., Galatowitsch, M. L., Milner, V. S., & Stubbington, R. (2019). Are all rivers equal? The role of education in attitudes towards temporary and perennial rivers. *People and Nature*, 181–190. https://doi.org/10.1002/pan3.22

Leigh, C., & Datry, T. (2017). Drying as a primary hydrological determinant of biodiversity in river systems: A broad-scale analysis. *Ecography*, *40*, 487–499. https://doi.org/10.1111/ecog.02230

Marshall, J. C., Acuña, V., Allen, D. C., Bonada, N., Boulton, A. J., Carlson, S. M., … Vander Vorste, R. (2018). Protecting US river health by maintaining the legal status of their temporary waterways. *Science*, *361*, 857.

Matthews, R. C., & Bao, Y. (1991). The Texas method of preliminary instream flow determination. *Rivers*, *2*, 295–310.

Milhous, R. T., Bartholow, J. M., Updike, M. A., & Moss, A. R. (1990). *Reference manual for generation and analysis of habitat time series: Version II*. Fort Collins, CO: US Department of the Interior, Fish and Wildlife Service.

Múrria, C., Bonada, N., & Prat, N. (2008). Effects of the invasive species *Potamopyrgus antipodarum* (Hydrobiidae, Mollusca) on community structure in a small Mediterranean stream. *Fundamental and Applied Limnology*, *171*, 131–143. https://doi.org/10.1127/1863-9135/2008/0171-0131

Nikolaidis, N. P., Demetropoulou, L., Froebrich, J., Jacobs, C., Gallart, F., Prat, N., … Perrin, J.-L. (2013). Towards sustainable management of Mediterranean river basins: Policy recommendations on management aspects of temporary streams. *Water Policy*, *15*, 830–849. https://doi.org/10.2166/wp.2013.158

Pahl-Wostl, C., Arthington, A., Bogardi, J., Bunn, S. E., Hoff, H., Lebel, L., … Tsegai, D. (2013). Environmental flows and water governance: Managing sustainable water uses. *Current Opinion in Environmental Sustainability*, *5*, 341–351. https://doi.org/10.1016/j.cosust.2013.06.009

Parasiewicz, P., Rogers, J. N., Vezza, P., Gortázar, J., Seager, T., Pegg, M., … Comoglio, C. (2013). Applications of the MesoHABSIM simulation model. In I. Maddock, A. Harby, P. Kemp, & P. J. Wood (Eds.), *Ecohydraulics: An integrated approach* (pp. 109–124). Chichester, UK: John Wiley & Sons Ltd.

Pastor, A. V., Ludwig, F., Biemans, H., Hoff, H., & Kabat, P. (2013). Accounting for environmental flow requirements in global water assessments. *Hydrology and Earth System Sciences*, *10*, 14987–15032. https://doi.org/10.5194/hessd-10-14987-2013

Pekel, J.-F., Cottam, A., Gorelick, N., & Belward, A. S. (2016). High-resolution mapping of global surface water and its long-term changes. *Nature*, *540*, 418–422. https://doi.org/10.1038/nature20584

Petts, G. E. (1984). *Impounded rivers: Perspectives for ecological management*. Chichester, UK: John Wiley & Sons Ltd.

Petts, G. E. (2009). Instream flow science for sustainable river management. *Journal of the American Water Resources Association*, *45*, 1071–1086. https://doi.org/10.1111/j.1752-1688.2009.00360.x

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B. D., … Stromberg, J. C. (1997). The natural flow regime. *BioScience*, *47*, 769–784. https://doi.org/10.2307/1313099

Poff, N. L., Olden, J. D., Merritt, D. M., & Pepin, D. M. (2007). Homogenization of regional river dynamics by dams and global biodiversity implications. *Proceedings of the National Academy of Sciences of the United States of America*, *104*, 5732–5737. https://doi.org/10.1073/pnas.0609812104

Poff, N. L., Richter, B. D., Arthington, A. H., Bunn, S. E., Naiman, R. J., Kendy, E., … Warner, A. (2010). The ecological limits of hydrologic alteration (ELOHA): A new framework for developing regional environmental flow standards. *Freshwater Biology*, *55*, 147–170. https://doi.org/10.1111/j.1365-2427.2009.02204.x

Poff, N. L., & Ward, J. V. (1989). Implications of streamflow variability and predictability for lotic community structure: A regional analysis of streamflow patterns. *Canadian Journal of Fisheries and Aquatic Sciences*, *46*, 1805–1818. https://doi.org/10.1139/f89-228

Poff, N. L., & Zimmerman, J. K. H. (2010). Ecological responses to altered flow regimes: A literature review to inform the science and management of environmental flows. *Freshwater Biology*, *55*, 194–205. https://doi.org/10.1111/j.1365-2427.2009.02272.x

Polacik, M., & Podrabsky, J. E. (2015). Temporary environments. In R. Riesch, M. Tobler, & M. Plath (Eds.), *Extremophile fishes* (pp. 217–245). Berlin, Germany: Springer International Publishing.

Poznańska, M., Kakareko, T., Krzyżyński, M., & Kobak, J. (2013). Effect of substratum drying on the survival and migrations of Ponto-Caspian and native gammarids (Crustacea: Amphipoda). *Hydrobiologia*, *700*, 47–59. https://doi.org/10.1007/s10750-012-1218-6

Prucha, B., Graham, D., Watson, M., Avenant, M., Esterhuyse, S., Joubert, A., … Vos, T. (2016). MIKE-SHE integrated groundwater and surface water model used to simulate scenario hydrology for input to DRIFT-ARID: The Mokolo River case study. *Water SA*, *42*, 384–398. https://doi.org/10.4314/wsa.v42i3.03

Pumo, D., Caracciolo, D., Viola, F., & Noto, L. V. (2016). Climate change effects on the hydrological regime of small non-perennial river basins. *Science of the Total Environment*, *542*, 76–92. https://doi.org/10.1016/j.scitotenv.2015.10.109

Richter, B. D., Baumgartner, J. V., Braun, D. P., & Powell, J. (1998). A spatial assessment of hydrologic alteration within a river network. *Regulated Rivers: Research & Management*, *14*, 329–340. https://doi.org/10.1002/(SICI)1099-1646(199807/08)14:4<329:AID-RRR505>3.0.CO;2-E

Richter, B. D., Baumgartner, J. V., Powell, J., & Braun, D. P. (1996). A method for assessing hydrologic alteration within ecosystems. *Conservation Biology*, *10*, 1163–1174. https://doi.org/10.1046/j.1523-1739.1996.10041163.x

Richter, B. D., Warner, A. T., Meyer, J. L., & Lutz, K. (2006). A collaborative and adaptive process for developing environmental flow recommendations. *River Research and Applications*, *22*, 297–318. https://doi.org/10.1002/rra.892

Rogers, D. C. (2014). Hatching response to temperature along a latitudinal gradient by the fairy shrimp *Branchinecta lindahli* (Crustacea; Branchiopoda; Anostraca) in culture conditions. *Journal of Limnology*, *74*, 85–94. https://doi.org/10.4081/jlimnol.2014.1036

Sánchez-Montoya, M. M., Moleón, M., Sánchez-Zapata, J. A., & Tockner, K. (2016). Dry riverbeds: Corridors for terrestrial vertebrates. *Ecosphere*, *7*, 1–10. https://doi.org/10.1002/ecs2.1508

Schneider, A., Jost, A., Coulon, C., Silvestre, M., Théry, S., & Ducharne, A. (2017). Global-scale river network extraction based on high-resolution topography and constrained by lithology, climate, slope, and observed drainage density. *Geophysical Research Letters*, *44*, 2773–2781. https://doi.org/10.1002/2016GL071844

Schneider, C., Laizé, C. L. R., Acreman, M. C., & Flörke, M. (2013). How will climate change modify river flow regimes in Europe? *Hydrology and Earth System Sciences*, *17*, 325–339. https://doi.org/10.5194/hess-17-325-2013

Seaman, M., Watson, M., Avenant, M., Joubert, A., King, J., Barker, C., … Vos, T. (2016). DRIFT-ARID: Application of a method for environmental water requirements (EWRs) in a non-perennial river (Mokolo River) in South Africa. *Water SA*, *42*, 368–383. https://doi.org/10.4314/wsa.v42i3.02

Seaman, M., Watson, M., Avenant, M., King, J., Joubert, A., Barker, C., … Vos, T. (2016). DRIFT-ARID: A method for assessing environmental water requirements (EWRs) for non-perennial rivers. *Water SA*, *42*, 356–367. https://doi.org/10.4314/wsa.v42i3.01

Shumilova, O., Zak, D., Datry, T., von Schiller, D., Corti, R., Foulquier, A., … Zarfl, C. (2019). Simulating rewetting events in intermittent rivers and ephemeral streams: A global analysis of leached nutrients and organic matter. *Global Change Biology*, *25*, 1591–1611. https://doi.org/10.1111/gcb.14537

Stanalker, C., Lamb, B. L., Henriksen, J., Bovee, K., & Bartholow, J. (1995). The instream flow incremental methodology. A primer for IFIM. *Biological Report*, *29*, 53.

Steward, A. L., Marshall, J. C., Sheldon, F., Harch, B., Choy, S., Bunn, S. E., & Tockner, K. (2011). Terrestrial invertebrates of dry river beds are not simply subsets of riparian assemblages. *Aquatic Sciences*, *73*, 551–566. https://doi.org/10.1007/s00027-011-0217-4

Steward, A. L., von Schiller, D., Tockner, K., Marshall, J. C., & Bunn, S. E. (2012). When the river runs dry: Human and ecological values of dry riverbeds. *Frontiers in Ecology and the Environment*, *10*, 202–209. https://doi.org/10.1890/110136

Tennant, D. L. (1976). Instream flow regimens for fish, wildlife, recreation and related environmental resources. *Fisheries*, *1*, 6–10. https://doi.org/10.1577/1548-8446(1976)001<0006:IFRFFW>2.0.CO;2

Theodoropoulos, C., Papadaki, C., Vardakas, L., Dimitriou, E., Kalogianni, E., & Skoulikidis, N. (2019). Conceptualization and pilot application of a model-based environmental flow assessment adapted for intermittent rivers. *Aquatic Sciences*, *81*, 10. https://doi.org/10.1007/s00027-018-0605-0

Tonkin, J. D., Bogan, M. T., Bonada, N., Rios-Touma, B., & Lytle, D. A. (2017). Seasonality and predictability shape temporal species diversity. *Ecology*, *98*, 1201–1216. https://doi.org/10.1002/ecy.1761

Vezza, P. (2020). Data from: Meso-scale habitat description in the Gaià River (Tarragona, Spain). *Mendeley Data*, *V1*, https://doi.org/10.17632/7svhmvpxrs.1

Vezza, P., Ghia, D., & Fea, G. (2015). Quantitative habitat models for the conservation of the endangered European crayfish *Austropotamobius pallipes* complex. In T. Kawai & N. Cumberlidge (Eds.), *A global overview of the conservation of freshwater decapod crustaceans* (pp. 339–358). Berlin, Germany: Springer International Publishing.

Vezza, P., Muñoz-Mas, R., Martinez-Capel, F., & Mouton, A. (2015). Random forests to evaluate biotic interactions in fish distribution models. *Environmental Modelling and Software*, *67*, 173–183. https://doi.org/10.1016/j.envsoft.2015.01.005

Williams, D. D. (2006). *The biology of temporary waters*. Oxford, UK: Oxford University Press.

Wissinger, S. A., Greig, H. S., & McIntosch, A. (2008). Absence of species replacements between permanent and temporary lentic communities in New Zealand. *Journal of the North American Benthological Society*, *28*, 12–23. https://doi.org/10.1899/08-007.1

Wohl, E., Bledsoe, B. P., Jacobson, R. B., Poff, N. L., Rathburn, S. L., Walters, D. M., & Wilcox, A. C. (2015). The natural sediment regime in rivers: Broadening the foundation for ecosystem management. *BioScience*, *65*, 358–371. https://doi.org/10.1093/biosci/biv002

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Acuña V, Jorda-Capdevila D, Vezza P, et al. Accounting for flow intermittency in environmental flows design. *J Appl Ecol*. 2020;57:742–753. https://doi.org/10.1111/1365-2664.13590