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Accounting for flow intermittency in environmental flows design

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Abstract

1. River ecosystems worldwide are affected by altered flow regimes, and an advanced science and practice of environmental flows has 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.

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 *et al.* 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 *et al.* 2006; Poff *et al.* 2007).

Environmental flows (eflows) mitigate the deleterious effects of flow regime alterations (Arthington *et al.* 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 (Stanalker *et al.* 1995; Lamouroux & Jowett 2005), and those additionally considering socio-economic conditions (King & Louw 1998; King, Brown & Sabet 2003; Richter *et al.* 2006).

Around 30% of the global river network length is intermittent (Pekel *et al.* 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 recognising 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 *et al.* 2016a).

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

i) Socio-ecological effects of flow intermittency

Flow intermittency can be characterised 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 *et al.* 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, Boersma & Lytle 2015; Colls *et al.* 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; Jaeger, Olden & Pelland 2014; Garcia *et al.* 2017b). 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) (Döll & Schmied 2012; Acuña, Hunter & Ruhí 2017). 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 (Pumo *et al.* 2016; De Girolamo *et al.* 2017b; Garcia *et al.* 2017a), 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 favored (Múrria, Bonada & Prat 2008; Poznańska *et al.* 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 *et al.* 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 *et al.* 2004; Jacobson & Jacobson 2013; Shumilova *et al.* 2019).

We believe that although social perception of flow intermittency can be negative (Armstrong *et al.* 2012; Leigh *et al.* 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 wellbeing, from the local climate moderation to the generation of a pleasant waterscape (Gopal 2016), recent work has also recognised 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 *et al.* 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.

ii) 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* 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 undestanding of flow intermittency into environmental flow assessment methods, also judged as suitable for application in temporary waterways. In this section we provide such guidance.

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 *et al.* 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 et al. 2017b). 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 *et al.* 1996) provides a comprehensive statistical characterisation 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 the 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 *et al.* 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 (Williams 2006; Wissinger, Greig & McIntosch 2008; Gallart *et al.* 2012). 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 *et al.* 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 (Poff *et al.* 1997; Richter *et al.* 1998; García-Roger *et al.* 2011). 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 environmental flow regime should be established. Percentiles here are more suitable than using ±1 standard deviation 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 *et al.* 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 *et al.* 2017b; a). 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 (Fig. 1).

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 *et al.* 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 characterising habitats during flowing phases and for managing low flows by 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 *et al.* 2016a). 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 *et al.* 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 (Parasiewicz *et al.* 2013; Belletti *et al.* 2017). 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 (Fig. 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 characterisation of mesohabitats

(Fig. 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 (Fig. 3a), habitat suitability for key species (Fig. 3b), and connectivity (Fig. 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 *et al.* 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 *et al.* 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.

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 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, Brown & Sabet 2003; King *et al.* 2014) 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 *et al.* 2014; Seaman *et al.* 2016b). The first is a generic framework applied in the Säo 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 *et al.* 2016b). The DRIFT-ARID approach recognises 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 (i) improved knowledge of flow-ecology relationships in temporary waterways; (ii) delineation of different types of temporary waterways; (iii) 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); (iv) incorporation of examples of desiccation-resistant biota such as aestivating fish (Polacik & Podrabsky 2015), seed and egg banks (Brock *et al.* 2003; Rogers 2014) and terrestrial species that use the river bed during non-flow conditions (Steward *et al.* 2011); and (v) special emphasis on those non-flow ecological processes providing services with socioeconomic 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 emphasise the socioeconomic aspects of resource protection for environmental flow assessment. Developed to incorporate socioeconomic knowledge into environmental management, the ecosystem services concept may account for the value that a designed environmental flow regime provides to human wellbeing (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 *et al.* 2016), but also interrupts the service provision – temporally and spatially – and complicates its evaluation (Koundouri *et al.* 2017).

The ecosystem services concept may improve inter-stakeholder dialogue, as synergies and tradeoffs are easily identified (Pahl-Wostl *et al.* 2013; Jorda-Capdevila & Rodríguez-Labajos 2015). 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 (SUMHA) 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 (Nikolaidis *et al.* 2013; Acuña *et al.* 2014; Marshall *et al.* 2018) encourage holistic approaches to incorporate policy considerations in the design and implementation of eflows.

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 characterised to recognise 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.

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 (Hunt 1991; Frassl *et al.* 2018). 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 Acuña conceived the ideas, coordinated the co-authors and led the Socio-ecological effects of flow intermittency section; D Jorda-Capdevila also coordinated the co-authors, and led the submission process and the design of figures; P Vezza led the Hydraulic-habitat models section; AM De Girolamo led the Hydrological methods section; ME McClain led the Holistic methods section and made the English proofreading; R Stubbington also proofread the article and made multiple small contributions throughout the article, as well as AV Pastor, N Lamouroux, D von Schiller and A Munné. T Datry did an exhaustive revision of the article, pushed the work forward and organised the meeting in which this work started.

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Data availability statement

Data about the Celone River case study are available via Mendeley Data http://dx.doi.org/10.17632/ytsy2yck5g.1 (De Girolamo, 2020).

Data about the Gaià River case study are available via Mendeley Data http://dx.doi.org/10.17632/7svhmvpxrs.1 (Vezza, 2020).

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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, riparian cover.	(Arscott *et al.* 2010; Larned *et al.* 2010)
Predictability	Six-month seasonal predictability of non-flow period	Protects the development of specialist species.	(Williams 2006; Wissinger, Greig & McIntosch 2008; Gallart *et al.* 2012)
Magnitude of annual extreme flow condition	Annual 1-day mean maximum	Creates sites for colonisation and supports abundance of invertebrate assemblages.	(Richter *et al.* 1998; Poff & Zimmerman 2010)
	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.	(Richter *et al.* 1998; Bunn & Arthington 2002; Poff *et al.* 2010)
	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.	(Poff *et al.* 1997; Richter *et al.* 1998; García-Roger *et al.* 2011)
Magnitude of flow on monthly basis	Average monthly flow	Maintains species diversity and abundance and prevents establishment of non-native species.	(Konrad, Brasher & 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 & 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.	(Petts 1984; Richter *et al.* 1998; Baker *et al.* 2004; Konrad, Brasher & May 2008)

Figures

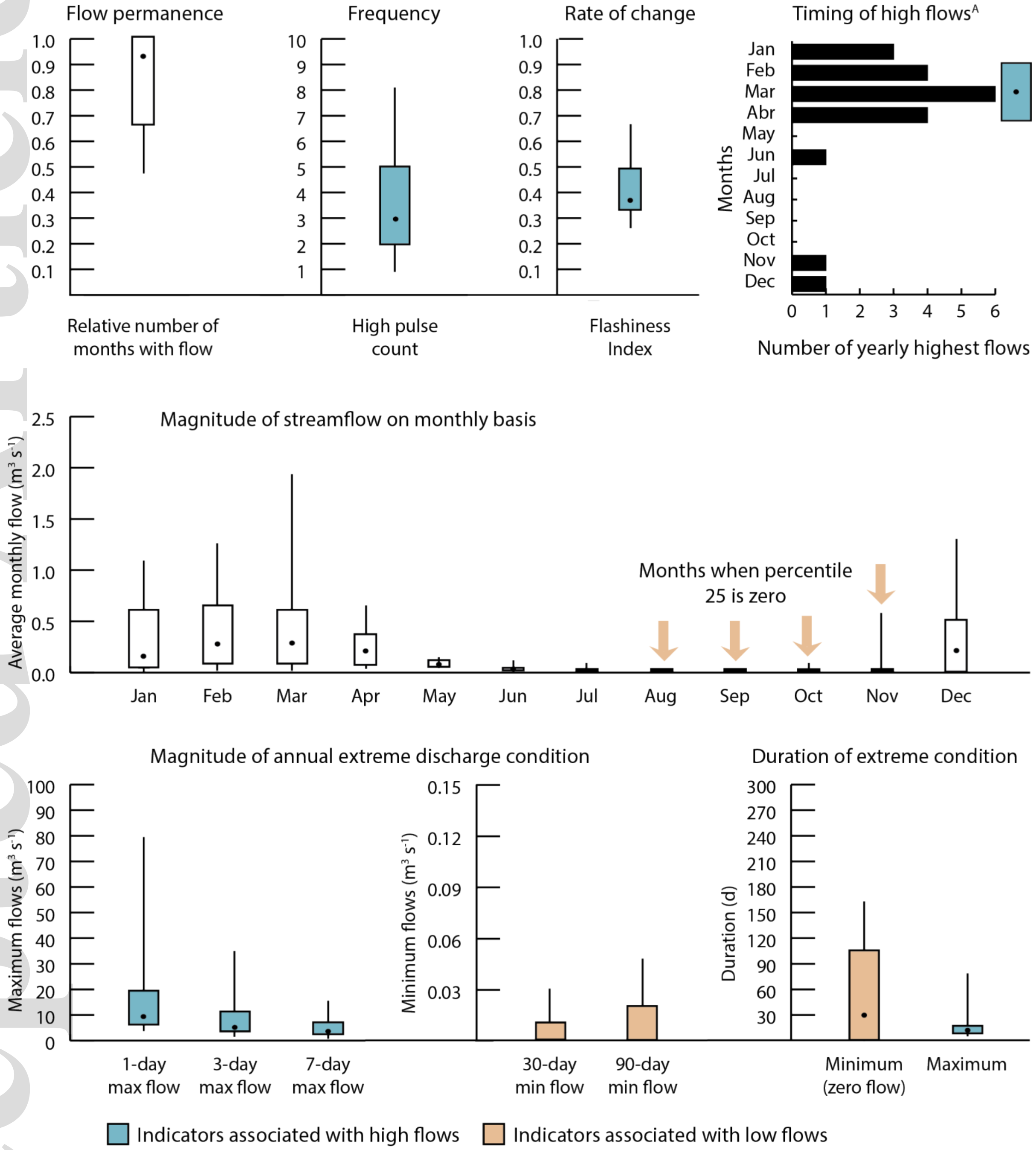

Figure 1. Indicator selection for the adaptation of the Range of Variability Approach (RVA) method to temporary waterways applied in the Celone River (Italian Peninsula). Lines show 5th and 95th percentiles, boxes 25th and 75th percentiles, and dots the median values higher than zero. For the timing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

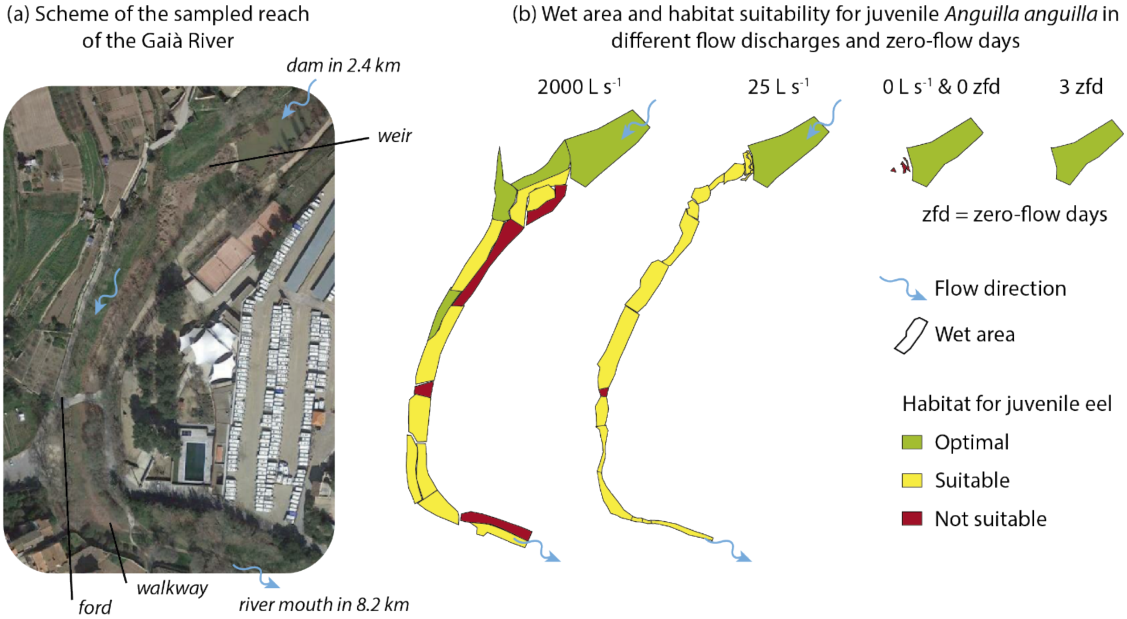

Figure 2. Application of the meso-scale hydraulic-habitat model (MesoHABSIM) to the Gaià River (Iberian Peninsula). We show here basic information for the studied reach (a) and the wet area and habitat suitability for the key specie European eel (*Anguilla anguilla*) in its juvenile life stage under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

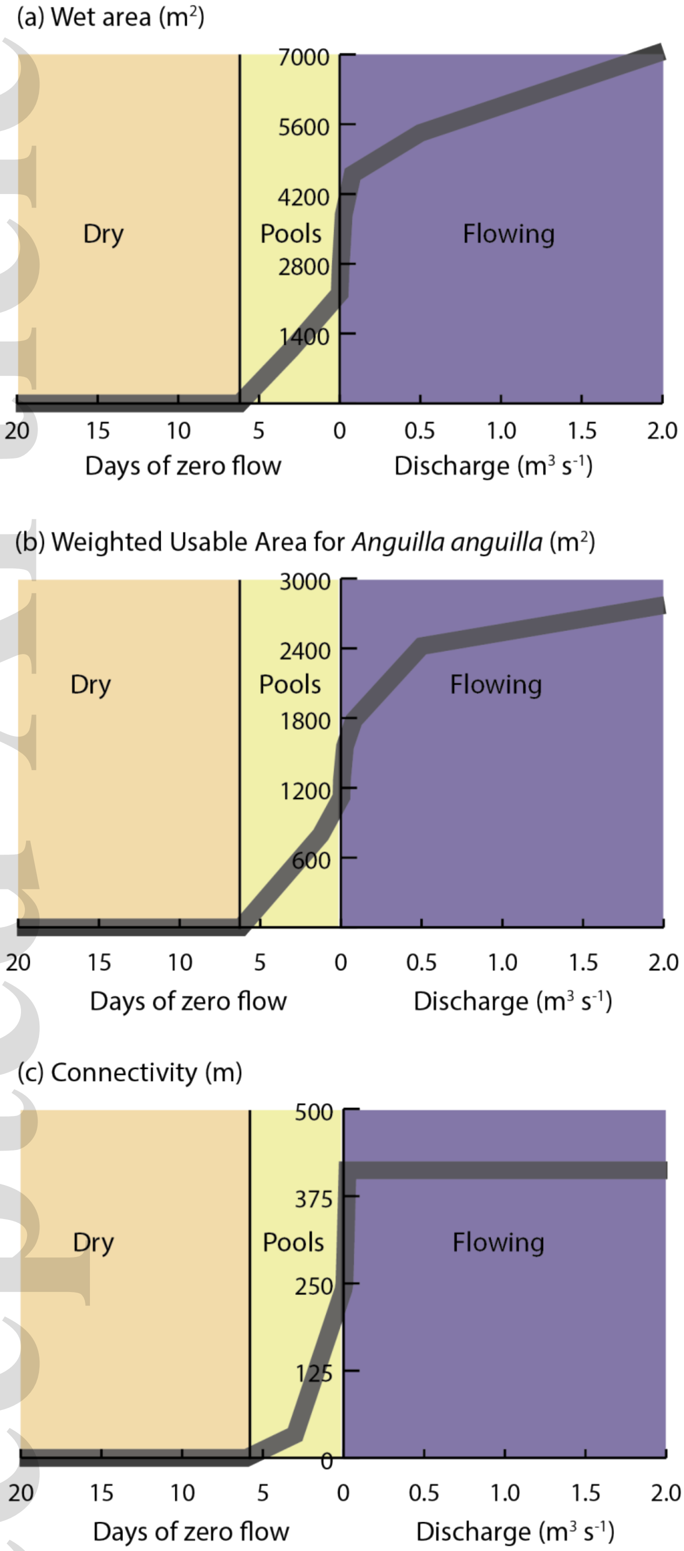

Figure 3. Adaptation of the hydraulic-mesohabitat models to temporary waterways by including the zero-flow-days axis in the graphs relating wet area (a), weighted usable area for key species (b) and connectivity (c) to flow discharge. Results shown are from the Gaià River (Iberian Peninsula), where the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