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TREHS: An open-access software tool for investigating and evaluating temporary river regimes as a first step for their ecological status assessment

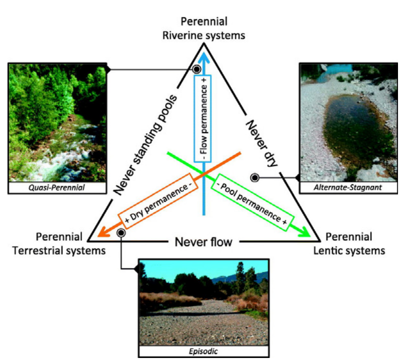
Francesc Gallart [a,*], Núria Cid [b,c], Jérôme Latron [a], Pilar Llorens [a], Núria Bonada [b,c], Justin Jeuffroy [d], Sara-María Jiménez-Argudo [e], Rosa-María Vega [e], Carolina Solà [f], Maria Soria [a], Mònica Bardina [f], Antoni-Josep Hernández-Casahuga [g], Aránzazu Fidalgo [e], Teodoro Estrela [e], Antoni Munné [f], Narcís Prat [b]

[a] Surface Hydrology and Erosion Group, IDAEA, CSIC, Jordi Girona 18, 08034 Barcelona, Catalonia,Spain
[b] Freshwater Ecology and Management (FEM) Research Group, Dept. Biologia Evolutiva, Ecologia i Ciències Ambientals, Universitat de Barcelona, Diagonal 643, 08028 Barcelona, Catalonia, Spain
[c] Institut de Recerca de la Biodiversitat (IRBio), Diagonal 643, 08028 Barcelona, Catalonia, Spain
[d] École Nationale du Génie de l'Eau et l'Environnement de Strasbourg (ENGEES), 1, Quai Koch, 67070 Strasbourg, France
[e] Júcar River Basin Authority, Av/Blasco Ibañez 48, 46010, Valencia, Spain
[f] Catalan Water Agency, c/Provença, 204, 08036 Barcelona, Spain
[g] Àngel Guimerà, 41, 3r., 08260, Súria, Barcelona, Spain

HIGHLIGHTS

- Determining a river's regime and its alteration is the first step for its management.
- TREHS gathers updated methods for investigating the hydrology of temporary rivers.
- Data input are flow records, interviews, observations and aerial photographs.
- A new regime classification reflects patterns of flow, isolated pools and dry bed.
- Concurrent aquatic states must be noted down when biological samples are taken.

GRAPHICAL ABSTRACT



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ABSTRACT

When the regime of a river is not perennial, there are four main difficulties with the use of hydrographs for assessing hydrological alteration: i) the main hydrological features relevant for biological communities are not quantitative (discharges) but qualitative (phases such as flowing water, stagnant pools or lack of surface water), ii) stream flow records do not inform on the temporal occurrence of stagnant pools, iii) as most of the temporary streams are ungauged, their regime has to be evaluated by alternative methods such as remote sensing or citizen science, and iv) the biological quality assessment of the ecological status of a temporary stream must follow a sampling schedule and references adapted to the flow- pool-dry regime.
To overcome these challenges within an operational approach, the freely available software tool TREHS has been developed within the EU LIFE TRIVERS project. This software permits the input of information from flow simulations obtained with any rainfall-runoff model (to set an unimpacted reference stream regime) and compares this

* Corresponding author.
E-mail addresses: Francesc.gallart@idaea.csic.es (F. Gallart), ncid@ub.edu (N. Cid), jerome.latron@idaea.csic.es (J. Latron), pilar.lorens@idaea.csic.es (P. Llorens), bonada@ub.edu (N. Bonada), jjeuffro@engees.eu (J. Jeuffroy), SaraMaria.Jimenez@chj.es (S.-M. Jiménez-Argudo), rvega@tragsa.es (R.-M. Vega), csolao@gencat.cat (C. Solà), maria.soria@idaea.csic.es (M. Soria), mbardinam@gencat.cat (M. Bardina), Arancha.Fidalgo@chj.es (A. Fidalgo), Teodoro.Estrela@chj.es (T. Estrela), anmunne@gencat.cat (A. Munné), nprat@ub.edu (N. Prat).

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Hydrological status
Ecological status
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with the information obtained from flow gauging records (if available) and interviews with local people, as well as instantaneous observations by individuals and interpretation of ground-level or aerial photographs. Up to six metrics defining the permanence of water flow, the presence of stagnant pools and their temporal patterns of occurrence are used to determine natural and observed river regimes and to assess the degree of hydrological alteration. A new regime classification specifically designed for temporary rivers was developed using the metrics that measure the relative permanence of the three main phases: flow, disconnected pools and dry stream bed. Finally, the software characterizes the differences between the natural and actual regimes, diagnoses the hydrological status (degree of hydrological alteration), assesses the significance and robustness of the diagnosis and recommends the best periods for biological quality samplings.

1. Introduction

Despite being largely ignored in the past, rivers that recurrently cease to flow at some point in time and/or space or may dry out completely (hereafter termed temporary, following Uys and O'Keeffe, 1997) are probably the most common fluvial ecosystems in the world (Fritz et al., 2006; Nadeau and Rains, 2007; Datry et al., 2014a). Recent decades have seen still more of them, due to climate change and pressures on water use, such as water abstraction (Jacobson et al., 2004; Larned et al., 2010). Flow regime shifts from perennial to temporary are predicted for many regions in the world under future climate change scenarios (Kirkby et al., 2011; Döll and Schmied, 2012). In fact, temporary rivers are already frequent in Mediterranean basins; for example, over 20% of river water bodies in Spain's Júcar River Basin are temporary (CHJ, 2016).

In consequence, significant basic and applied research on temporary rivers has increased since the late 1980′s (Sheldon, 2005; Leigh et al., 2016b). Much of this research has focused on understanding biodiversity patterns and trends, especially because global change is increasing flow temporariness in many parts of the world and threatening local biodiversity (Thoms and Sheldon, 2002; Blanchette and Pearson, 2012; García-Roger et al., 2011). Although hydrological and ecological assessment issues currently occupy much of the research into temporary rivers undertaken in many countries (Leigh et al., 2016a, 2016b), the lack of information and of new developments in hydrology are the main impediments to advancing in the science and management of temporary rivers (Acuña et al., 2014; Leigh et al., 2016a, 2016b; Seaman et al., 2016; Skoulikidis et al., 2017).

Ecological assessment of rivers has a long tradition in freshwater ecology (e.g. Bonada et al., 2006; Friberg et al., 2011). In most countries, ecological status is assessed by using biological quality indices to compare biological communities sampled at a site with its reference (benchmark or baseline) conditions (Hawkins et al., 2010). However, as reference conditions may vary over time due to wet or dry periods (Munné and Prat, 2011), changes in river regime should also be taken into account. In Europe, the Water Framework Directive (WFD, European Commission, 2000) requires that assessment of ecological status must also include information on the hydromorphological alterations that support biological elements, such as the hydrological regime, river continuity or the geomorphological conditions. However, this is still a challenging task in temporary rivers (Reyjol et al., 2014; Skoulikidis et al., 2017) because appropriate classification and assessment of the hydrological regime are required before it can be decided whether the current methods developed for perennial systems are still valid or new approaches need to be developed.

Hydrological alterations due to human activity are now one of the main causes of impairment of riverine ecosystems locally and globally. Determining them is the first step in river restoration and conservation (International River Foundation, 2007; Poff et al., 2010; European Commission, 2012; Seaman et al., 2106). Thus, distinguishing whether a water body has a natural or artificial hydrological regime is vital for the setting of environmental objectives and adequate assessment of ecological status (Skoulikidis et al., 2017; Stubbington et al., 2017a). In the case of temporary rivers, a proper assessment of these alterations is of even greater relevance (Leigh et al., 2016a, 2016b; Cid et al., 2017). For instance, perennial rivers can become temporary due to water abstractions, but in some particular cases, rivers that are naturally temporary may become artificially perennial, usually as a result of effluent inputs from waste-water treatment plants (Luthy et al., 2015). For example, this occurs in the intensively exploited aquifers of the Vinalopó river in Spain, whose aquifer water levels have decreased in recent years by between 65 m and 350 m due to groundwater abstractions, leading to the river drying (Custodio et al., 2016). Current streamflows are due mainly to effluent inputs from waste-water treatment plants (CHJ, 2016).

In perennial rivers, several software tools, such as IHA (Indicators of Hydrologic Alteration; Richter et al., 1996), IHARIS (Indicators of Hydrologic Alteration in RIverS; Martínez Santa-María and Fernández Yuste, 2010) or DRIFT (Downstream Response to Imposed Flow Transformations; Brown et al., 2013), are currently used to determine flow regimes and hydrological alterations by comparing impacted against reference (unimpacted) hydrographs. However, these tools usually fail when applied to temporary rivers because i) the main hydrological features relevant to biological communities in temporary rivers are not quantitative (i.e. discharges), but qualitative (i.e. the presence of flowing water, stagnant pools or the lack of surface water) (Boulton, 1989, Boulton et al., 2000; Uys and O'Keeffe, 1997; Buffagni et al., 2009; Seaman et al., 2016); ii) river flow records do not report the temporal occurrence of stagnant pools (Gallart et al., 2016), which act as refugees for many species during the cessation of flow (e.g. Bonada et al., 2006; Buffagni et al., 2009; Stubbington et al., 2017a); iii) as most temporary rivers are ungauged, hydrographs are often unavailable and those derived from models are of doubtful validity (Seaman et al., 2016); iv) those temporary rivers with a gauging station usually have only old data, which do not allow analysis of the current hydrological regime.

Furthermore, although the conceptual bases for identifying hydrological regimes of temporary rivers are established (Uys and O'Keeffe, 1997), in practice there are myriad terminologies and classifications based only on flow statistics. These classifications are usually difficult to implement or have unproven ecological significance (Poff and Ward, 1989; Poff, 1996; Uys and O'Keeffe, 1997; Rossouw et al., 2005; Mackay et al., 2012; Gallart et al., 2012; Arthington et al., 2014; Datry et al., 2016; Skoulikidis et al., 2017), to such an extent that classifications do not allow extrapolation of observations and do not help the comparison of regimes with reference conditions (Seaman et al., 2016). Thus, as temporary rivers are of great importance in some regions, particularly in the Mediterranean, Water Management Administrations in the European Union need specific tools for the implementation of the WFD in these cases.

Within this conceptual and methodological context, and with the explicit objective of implementing the WFD for temporary rivers, the hydrological part of the Temporary Rivers Ecological and Hydrological Status (TREHS) free software tool was developed. Although it was conceived for operational use, this does not prevent its being a useful research tool, since it includes some cutting-edge concepts and permits the gathering of information that is not compulsory under the current requirements of the WFD, but may help in the understanding of riverine ecosystems and contribute to their sound management.

The main aim of this paper is to propose updated methods for the operational monitoring, assessment and classification of the regime of temporary rivers, along with the evaluation of the degree of hydrological alteration. These targets are preconditions to setting environmental objectives and applying appropriate biomonitoring protocols in this type of water body. These methods are assembled in the TREHS software tool which makes the gathering, storing, analysis and evaluation of the information easier. A second but more ambitious aim is to propose the methods described below as a blueprint for monitoring and cataloguing temporary river regimes wherever they occur.

This is not, however, a TREHS user guide or a substitute for it. This guide can be downloaded at http://www.lifetrivers.eu. Examples of application of TREHS to real rivers are shown in Appendices B and C to this manuscript.

2. Hydrological features of the TREHS tool

The hydrological features of TREHS, in particular the classification of regimes and the assessment of the degree of hydrological alteration, were conceived as an instrument for the investigation of temporary river regimes, not focusing on water resources but rather on the ecological implications relevant to their knowledge and management.

TREHS is a user-friendly interface and a data base management instrument for the gathering of diverse types of hydrological-related data of temporary rivers. It calculates six temporary regime metrics from these data, offers a classification of the river regime on the basis of three metrics and has a graphical interface that facilitates river regime visualisation, classification and comparison between diverse river sites. In addition, if reference conditions are provided, TREHS assesses the hydrological regime (i.e. Hydrological Status), based on the evaluation of the degree of hydrological alteration. TREHS has the following functions, reported in a sequential order:

– Description of the test reach (station) with the adequate metadata; identification of the operator, date, location, River Basin District, water body and local name. The tool makes it possible to use interactive maps for the location of the reaches.

– Collection from different data sources: there are three kinds of data, flow records, interviews and observations. Flow records can be obtained from gauging stations or model-simulated flow series; diverse time periods of flow records or simulations from different models can be separately analysed. Observations may consist of in situ observations from the field and observations from aerial or ground-level photographs.

– Calculation of six temporary river metrics and their variability, using all the diverse data sources stated above.

– Analysis of the long-term monthly or seasonal relative frequencies of the *aquatic states* of the water body by drawing the *Aquatic States Frequency Graph*. This function can also be obtained from various data sources.

– Drawing two types of graphs for showing and comparing the metrics results obtained from the diverse data for a single river reach or a group of them.

– Classification of the river *aquatic phases regime*, taking into account the metrics that represent the relative occurrence of the main three aquatic phases: flow, disconnected pools and dry channel.

– Advice on the best sampling calendar to be used for collecting samples and assessing the *Ecological Status* of the water body by including the hydrological constraints of aquatic life.

– Comparison between the actual and the reference (non-impacted) river regime metrics for assessing the degree of hydrological alteration in terms of the implications for the development of macroinvertebrate aquatic fauna. Determination of *Hydrological Status* as a measurement or diagnosis of hydrological alteration due to human pressures on river regime (water quantity).

– Listing metrics and reporting results for a selected river reach or a group of them.

3. Principles used in TREHS

TREHS follows the conceptual framework of hydrological alteration and its ecological limits (Richter et al., 1996; Poff et al., 2010; Seaman et al., 2016) and the description of the hydrological phases in temporary rivers (Boulton, 2003; Fritz et al., 2006). TREHS also implements the concepts and applications for investigating and managing temporary rivers formulated during the European Community's Seventh Framework Programme “Mediterranean Intermittent River Management” (MIRAGE) research project (Gallart et al., 2012; Prat et al., 2014; De Girolamo et al., 2015; Cid et al., 2016; Nikolaidis et al., 2013) and uses alternative data-gathering methods (Turner and Richter, 2011; Buytaert et al., 2014; Datry et al., 2016; Gallart et al., 2016). Table 1 shows the main acronyms and terms used in TREHS that were defined in Gallart et al. (2016) or are newly defined in this work.

In particular, TREHS is based on the working hypothesis that the hydrological regime features that are most relevant to the development of aquatic life in a temporary river are not the temporal patterns of water discharges but of the occurrence of mesohabitats (e.g. Larned et al., 2010; Gallart et al., 2012; Schriever et al., 2015). This is consistent with the idea that temporary rivers should be seen as a distinct class of systems, instead of just hydrologically challenged permanent rivers (Larned et al., 2010).

All questions of data gathering, analysis and evaluation turn on these premises, with the advantage that qualitative states are much more easily obtained through non-instrumental methods than water discharges are (Fritz et al., 2006; Turner and Richter, 2011; Datry et al., 2016; Gallart et al., 2016).

3.1. Spatial and temporal units

The spatial unit for the management of river systems under the regulations of the WFD is the *water body* (European Commission, 2000), which may comprise several kilometre-long river sections where regime may spatially vary. This is why TREHS software focuses mainly on a part of a water body, a hundred meter-long river reach called “*station*”. Several *stations* may be defined and separately analysed by TREHS within each *water body* according to their spatial regime variation or data availability. Results are not mapped in TREHS, but it provides suitable outcomes that can be implemented in a GIS.

TREHS uses several temporal units. The basic time unit used is the month, as community composition of many aquatic organisms change among months and recovery from water quantity disturbances (i.e. floods and drying periods) usually occur in few weeks (Robinson et al., 2003; Leigh et al., 2016a, 2016b; Dolédec et al., 2017). Nevertheless, when interviews or either in situ or photographic observations are used, the month becomes a too short unit because it is not feasible to get sufficiently time-detailed information; in these cases, for practical reasons, the season is taken as the operational time unit. The metrics described below in Section 5.1 use diverse time units, from the month to the semester, whereas the year is the time period used to complete the river regime. Some issues arisen with the use of time units, such as the role of short events and the loss of information when flows are aggregated from a daily scale to a monthly one are analysed in the discussion (Section 7).

3.2. Aquatic states and aquatic phases

The units for describing the immediate hydrological state at the moment of inspection are the *aquatic states*, defined as the transient sets of

Table 1
Acronyms, terms and concepts used in the paper.

Acronym	Concept	Definition
AF	Alternate-Fluent[1]	Aquatic phases regime from FPD plot; alternation between the three aquatic phases, but flowing for longer periods ($Mf > 0.40$ and $Md \geq 0.10$).
Al	Alternate[1]	Aquatic phases regime from FPD plot; alternation between the three aquatic phases ($Mf \leq 0.40$, $Mp < 0.40$ and $Md < 0.60$).
Aquatic phase	Aquatic phase[1]	Simplified transient stage of temporary water condition occurring in a reach and moment (flow, standing pools, dry stream bed)
Aquatic state	Aquatic state[2]	Transient set of mesohabitats occurring in a reach and moment, controlled by water stage (*Hyperrheic*, *Eurheic*, *Oligorheic*, *Arheic*, *Hyporheic*, *Edaphic*)
Arheic	*Arheic*[2]	Aquatic state; zero surface flow but isolated water pools are present.
AS	Alternate-Stagnant[1]	Aquatic phases regime from FPD plot; alternates between the three aquatic phases, but remains stagnant for longer periods ($Mf \leq 0.40$, $Mp \geq 0.40$ and $Md \geq 0.10$).
ASFG	Aquatic States Frequency Graph[2]	River regime graph; relative frequency of the aquatic states during months or seasons throughout the year.
Edaphic	*Edaphic*[2]	Aquatic state; waterless river bed and alluvium, involving the disappearance of any active aquatic habitat.
Ep	Episodic[1]	Aquatic phases regime from FPD plot; usually dry river with either flowing or stagnant water at infrequent intervals ($Md \geq 0.80$).
ESs	Equinox-solstice seasonality[1]	Metric; temporal arrangement of no flow periods: the relative frequency of 0-flow months in equinoxes minus the one in solstices.
Eurheic	*Eurheic*[2]	Aquatic state; water discharge is high enough to allow the occurrence and connectivity of all the feasible aquatic habitats in the reach.
FPD	Flow-Pool-Dry plot[1]	Aquatic phases regime graph; triangle showing the complementary metrics on the permanence of the three aquatic phases in the river reach (*Mf*, *Mp* and *Md*).
FS	Fluent-Stagnant[1]	Aquatic phases regime from FPD plot; usually flowing but otherwise with isolated pools ($0.40 < Mf \leq 0.90$ and $Md < 0.10$).
Hyperrheic	*Hyperrheic*[2]	Aquatic state; infrequent high water (flood) conditions
Hyporheic	*Hyporheic*[2]	Aquatic state; most of the stream bed is devoid of surface water in the reach, although alluvium may remain wet enough to allow hyporheic life.
Md	Dry channel permanence[1]	Metric; long-term mean annual relative number of months without surface water in the channel.
Mf	Flow permanence[2]	Metric; long-term mean annual relative number of months with flowing water.
Mp	Pools permanence[1]	Metric; long-term mean annual relative number of months with isolated pools.
Oc	Occasional[1]	Aquatic phases regime from FPD plot; river usually dry that sometimes, but not often, has flowing or stagnant water ($0.60 \leq Md < 0.80$).
Oligorheic	*Oligorheic*[2]	Aquatic state; surface water discharge is scarce but sufficient to connect most pools in the reach through water threads.
Pe	Perennial[1]	Aquatic phases regime from FPD plot; permanently flowing ($Mf > 0.99$).
Qp	Quasi-Perennial[1]	Aquatic phases regime from FPD plot; usually flowing, except on infrequent occasions ($0.90 < Mf \leq 0.99$).
Sd_6	Six-month predictability of zero-flow periods[2]	Metric; temporal arrangement of no flow periods: the unity minus the relative frequency of the zero-flow months in the wetter 6-month period divided by the relative frequency in the complementary (drier) 6-month period.
St	Stagnant[1]	Aquatic phases regime from FPD plot; river usually in the form of isolated water pools ($Mf \leq 0.40$ and $Md < 0.10$).
SWs	Summer-winter seasonality[1]	Metric; temporal arrangement of no flow periods: the relative frequency of 0-flow months in summer minus the one in winter.
TRP	Temporary Regime Plot[2]	Temporary regime graph; X-Y plot of flow permanence *Mf* (X) versus Six-month predictability of zero-flow periods Sd_6 (Y).
WDF	Water Framework Directive	Water regulation: European framework for water policy (European Commission, 2000)

[1] Defined in this work.
[2] Defined in Gallart et al., 2012.

aquatic mesohabitats occurring on a given river reach at a particular moment, depending on the hydrological conditions (Gallart et al., 2012). Six aquatic states were there defined, from wet to dry: flooding conditions (*Hyperrheic*), full prevalence of all the possible mesohabitats (*Eurheic*), sequence of pools connected by flowing water threads (*Oligorheic*), occurrence of isolated pools (*Arheic*), disappearance of surface water, with the wet alluvium still allowing underground aquatic life (*Hyporheic*) and the desiccation of the river bed and alluvium, involving the disappearance of any active aquatic habitat (*Edaphic*).

The aquatic states occurring at the moment of sampling are identified for better evaluation of the biological assemblages (Prat et al., 2014) and are recorded in the TREHS data base. Nevertheless, as it is not currently possible to obtain this detailed information for the past, to obtain the metrics and classification of the river regime the six aquatic states have been simplified to three *aquatic phases* (flowing water, isolated pools and dry river bed). The identification of the temporal patterns of occurrence of these three phases is consistent with the conceptual 'continuum' defining the behaviour of temporary river regimes (Uys and O'Keeffe, 1997), may be successfully obtained with various non-instrumental methods and characterizes the river regime sufficiently for most purposes (Datry et al., 2016; Gallart et al., 2016). The relationships between the three aquatic phases and the biological communities using communities as predictors of hydrological conditions have been explored in Cid et al. (2016).

4. Data gathering and management

Input to TREHS may come from three data sources: i) flow discharge sequences (measured or simulated), ii) interviews and iii) in situ observations from field visits or through aerial or ground-level photographs. These data are stored and analysed by the software in order to obtain different outputs (see Section 5).

4.1. Flow discharges

Monthly flow data from a gauging station or model simulations are used to obtain the statistics of the occurrence of diverse aquatic states, following the method described in Gallart et al. (2012, 2016). This kind of information allows only the appropriate determination of the aquatic states that correspond to the flowing water phase (*Hyperrheic*, *Eurheic* and *Oligorheic*), separated from the remaining ones that correspond to zero flows, once flow thresholds between these states are assessed. To identify these thresholds correctly, field observations on the aquatic states synchronous with discharge measurements would be needed. However, in the absence of these observations, thresholds can be provisionally assessed with the help of the shape of the flow duration curve (distribution function of flow discharges), as proposed by TREHS.

Accurate determination of the discharge reading corresponding to real zero flow is usually not straightforward for several reasons: gauging stations are not normally designed to measure zero flows and small changes due to erosion/deposition of sediments in the gauging section or inadequate maintenance of the artificial control can modify the zero flow value. In addition, some gauging stations may not measure water flow through the alluvium, whereas other stations are designed to intercept subsurface flow within the alluvium in order to measure it as surface flow. Therefore, low flow values may correspond to either the *Arheic* (isolated pools) or *Hyporheic* (no surface water) states (an example is shown in Appendix C). Furthermore, low flow values on the monthly scale may actually mean a month with a few days with flow among many days without flow, but with or without pools.

When flow simulations obtained with a rainfall-runoff model are used, it must not be forgotten that, apart from the role of the above issues in the flow data used for model calibration, most current models are not designed to simulate zero water discharges.

In practice, the user can decide the value corresponding to actual zero flow and can assign the smaller values to either the *Arheic* or *Hyporheic* states. TREHS states a warning message that the frequency of the *Arheic* state (pools phase) is usually underestimated by flow measurements.

Several flow records of diverse origin or period and selected thresholds between aquatic states may be stored in TREHS and alternatively selected to compare results. The reference (unimpacted) conditions are usually taken from flow values simulated with a rainfall-runoff model assuming natural conditions, but flow records measured in the past before hydrological alteration in the same or another location can also be used.

4.2. Interviews

Interviews are designed to assess the current regime of the river reach in the last 10 years period. They follow the method described in Gallart et al. (2016) and are designed to be answered by neighbours of the fluvial system, i.e. people living near the rivers or working in vegetable gardens beside the river, selected haphazardly from people met near the river and willing to answer the questions. Alternatively, interviews can be conducted with key informants who have a more expert professional or leisure relationship with the river regime.

Given the impracticality of obtaining information by means of these methods for each month and for all the aquatic states described above, the months are grouped in seasons and the six aquatic states are reduced to the three aquatic phases. Thus, after some preliminary questions, the core of the questionnaire consists of a template with four columns corresponding to the four seasons and three rows corresponding to three aquatic phases (flow, disconnected pools and dry river bed). As each box represents the number of months of occurrence of the corresponding state in the corresponding season, every column must cover 3 months and every row 12 months.

Interviewees are also asked about the occurrence of wet/saturated alluvium after the disappearance of surface water (pools). Yet, for the driest rivers, when the interviewee indicates that the river flow 'ceases for long periods', the question is reformulated in reverse as 'How many days per year does the river carry water?'. This question was included in order to document low-flow frequency.

Any interview may be selected or discarded for the analysis, depending on the user's confidence in its reliability.

4.3. In situ observations and aerial or ground-level photographs

The primary purpose of this data source input to TREHS is the documentation of the aquatic state of the reach at the date when it is visited for water and biological sampling. The entry was also adapted to include interpretations of past aerial photographs or surface photographs such as those taken by the Google Maps Street View multitemporal facility. For the last cases, as it is not possible to identify the six aquatic states in photographs, these have to be simplified into the three aquatic phases. In the current version of TREHS, the data from both in situ and photographic observations are merged for obtaining metrics and graphs, so the recorded aquatic states are simplified to aquatic phases when analysed.

Flow and pool frequency statistics are calculated from observations only when at least five observations are available and then, as a measurement of dispersion, the resolution of the statistics is calculated as the inverse of the number of observations. As in the case of interviews, the temporal scale for observations is simplified to the season scale. Statistics and graphs on the temporal pattern of features are derived only when there are at least three observations per season. In this case, permanence statistics are first calculated for each season and subsequently averaged, in order to prevent any bias due to different numbers of observations in the various seasons. This prevention cannot be made when there are less than three observations per season, so in these cases the resulting permanence statistics may be subject to some seasonal bias.

Aerial or ground-level photographs may be taken at some distance from the station point, in which cases operators are advised to state the coordinates of the observation point. The capture date of aerial photographs may be unknown, as many orthophotographs are composed from photograph mosaics without a specific capture date; in these cases the seasonal information is lost and only the capture year may be recorded.

5. Data analyses and outputs

5.1. Temporary regime metrics

Six metrics, exclusive to temporary rivers and obtainable with the above-mentioned methods, were defined. Three metrics describe the time-compressed occurrence of the corresponding three aquatic phases, whereas the other three metrics try to describe the temporal arrangement of these phases. We decided not to use metrics on the six aquatic states because there is not yet sufficient information. The metrics selected are as follows:

Mf; flow permanence, defined as the long-term mean annual relative number of months with flow, with values between 0 (always dry) and 1 (always flowing, i.e. perennial river systems). This metric was defined in Gallart et al. (2012) from former studies (e.g. Poff, 1996; Arscott et al., 2010).

Mp; pool permanence, defined as the long-term mean annual relative number of months when isolated pools occur, with values between 0 (pools never occur in the system) and 1 (always with pools, i.e. perennial still-water/lentic systems).

Md; dry channel permanence, defined as the long-term mean annual relative number of months when the channel has no surface water. It is a metric complementary to the two metrics above, so $Md = 1 - (Mf + Mp)$.

Sd_6; six-month predictability of zero-flow periods, defined in Gallart et al. (2012) and calculated by Eq. 1:

$$Sd_6 = 1 - \left(\sum_{1}^{6} Fd_i / \sum_{1}^{6} Fd_j \right) \tag{1}$$

where *Fdi* represents the multi-annual frequencies of 0-flow months for the contiguous 6 wetter months of the year and *Fdj* represents the multi-annual frequencies of 0-flow months for the remaining 6 drier months. Wet and dry 6-month periods mean here those with fewer and more zero-flow frequencies in the long term, respectively. This variable is dimensionless and takes the value of 0 when zero flows occur equally throughout the year in the long run and 1 when all the zero flows occur in the same 6-month period every year. When the regime is fully permanent, this metric cannot be computed, so the value of 1 is set to indicate full predictability.

SWs; summer-winter seasonality, defined as the difference in the relative frequencies of 0-flow months between summer and winter. It takes a value of 1 when there is no flow during summer versus continuous flow in winter and −1 when the contrary occurs. Summer and winter are calculated in TREHS as for the Northern Hemisphere; this metric would take the contrary sign in the Southern Hemisphere.

ESs; equinox-solstice seasonality, defined as the difference in the relative frequencies of 0-flow months between equinoxes and solstices. It takes a value of 1 when there is no flow during equinoxes versus continuous flow in solstices and −1 when the contrary occurs.

5.2. Temporary regime graphs

Three graphs can be obtained by TREHS: the Aquatic States Frequency Graph (ASFG) and Temporary Regime Plot (TRP), both defined in Gallart et al. (2012), and the new Flow-Pool-Dry plot (FPD).

The ASFG summarizes the relative frequency of the wetter aquatic states throughout the year, using a monthly temporal scale when it employs flow records or simulations or the three aquatic phases with a seasonal temporal scale when it employs interviews or observations (see Fig. A.1 in the Appendix A). The purpose of this graph is to show the relative importance of the diverse states or phases throughout the year and the degree of seasonality of the regime at a glance. It also gives a first impression of how the sampling calendar should be defined in the station. Nevertheless, it does not allow the quantitative assessment of the river regime required for comparisons between rivers or reaches.

The TRP (see Fig. A.2 in the Appendix A) was designed to compare the two main metrics relevant to the occurrence of flow obtained for diverse rivers. Thus, flow permanence (*Mf*) and seasonal (Sd_6) predictability are represented in this plot. The grey triangle represents an area where the values of the two metrics are incompatible and the bars represent the standard error of the metrics. This plot can be used to compare the regimes of diverse rivers or the metrics obtained for the same river when diverse sources of information are used. Four sectors in this plot represent the temporary *aquatic regime types* defined by Gallart et al. (2012): Perennial (P), Intermittent-pools (I-P), Intermittent-dry (I-P) and Ephemeral (E). These types are shown in this graph for comparison but not used below, because a more ambitious classification was developed for TREHS on the basis of the plot subsequently described. The main drawback of the TRP plot shown above is the lack of information on the occurrence of surface water in the form of stagnant pools when flow is interrupted.

As both interviews and observations may provide relevant information on the frequency of pools that cannot be plotted in the TRP graph, a flow-pools-dry (FPD) plot was designed in order to show the metrics associated with the three aquatic phases relevant to aquatic life development (flow, disconnected pools and dry river bed) and observable in the river reaches with these methods. The design of the plot is triangular, the classic format when three complementary components are analysed, such as for sand, silt and clay components in soil texture (Soil Survey Division Staff, 1993). In the FPD plot (Fig. 1 and Fig. A.3 in the Appendix A), the axis on the left represents flow permanence (*Mf*), with the percentage of *Mf* increasing from the triangle bottom ($Mf = 0\%$) to the top ($Mf = 100\%$). The axis on the right represents pool permanence (*Mp*), increasing from the left axis ($Mp = 0\%$) to the bottom right vertex ($Mp = 100\%$). Finally, the axis on the bottom

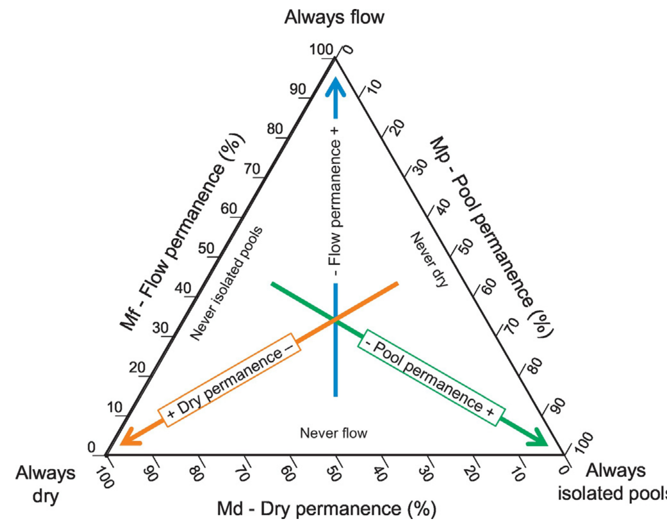

Fig. 1. Arrangement of the three main metrics that correspond to the three aquatic phases; flow permanence (*Mf*), Isolated pools permanence (*Mp*) and dry river permanence (*Md*), in the FPD (Flow – Pools – Dry) graph. The arrows show the progression of every one of the three metrics whereas the axes show the values of every one of them. The central point represents a river that undergoes the three aquatic phases with the same frequency.

represents dry channel permanence (*Md*), complementary to the others ($Md = 1 - (Mf + Mp)$), with the lowest value in the right axis ($Md = 0\%$) and the highest value in the bottom left vertex ($Md = 100\%$).

Therefore, the upper, right and left vertexes of the FPD plot represent perennial riverine systems (i.e. perennial rivers), perennial lentic systems (i.e. perennial ponds or wetlands) and terrestrial systems, respectively. Points along the lower axis, with $Mf = 0\%$ and different values of *Mp* and *Md*, represent temporary ponds or wetlands. Points along the left axis represent temporary rivers without a pool phase, whereas points on the right axis represent temporary rivers without any dry phase. Finally, the inside of the triangle represents temporary rivers that alternate between the three phases, with a wide range of different *Mf*, *Mp* and *Md* values (see Section 5.1 for details).

5.3. River regime terminology and classification

The five metrics described in Section 5.1 and the graphs shown in Section 5.2 may be used to characterize and compare the regimes of diverse rivers, but an operational and ecologically relevant classification of the regimes was considered necessary for clearer communication in this multidisciplinary field (Uys and O'Keeffe, 1997), extrapolation of observations and progress in the sound management of rivers (Poff et al., 2010; Seaman et al., 2016). As argued in the Introduction, there is consensus among authors that aquatic life in temporary rivers depends not only on the occurrence of flow but also on the presence of surface water in the form of stagnant pools when flow is interrupted (e.g. Robson et al., 2013; Davis et al., 2013). Some pools may persist through months of no rainfall whilst others may change in size or disappear, for reasons difficult to be identified (Seaman et al., 2016). Consequently, there are some terminologies and classifications of the regime of temporary rivers that mention the occurrence of pools, but fail to operationally include their frequency in the identification of regime classes due to the lack of adequate statistics (e.g. Uys and O'Keeffe, 1997; Rossouw et al., 2005; Gallart et al., 2012).

The new *aquatic phases regime* classification implemented in TREHS was designed as i) fully applicable from available information, ii) taking into account the statistics of the three aquatic phases, iii) able to be represented in a single graph, iv) conflict-free from the most usual terminologies, and v) defined from hydrological features assumed to have biological implications, though these are not yet proved. However, practical reasons made it appropriate to discard the representation of the temporal structure of the aquatic phases. Therefore, it is to be expected that the biological significance of the classes designed will have different biological implications in distinct climate settings. Moreover, since both the terminology and the classification are coded in a spreadsheet auxiliary to the TREHS application, they can be updated by an advanced user using different threshold values for the metrics or even adding other TREHS metrics to the procedure. The approach selected for regime classification was based on the FPD plot (Fig. 2), using the following attributes:

– *Perennial*: Permanently flowing, except on rare occasions. The term 'temporary', following Uys and O'Keeffe (1997), is used as a blanket opposite term for the remaining rivers that occasionally or recurrently cease to flow.
– *Fluent*: Usually flowing.
– *Stagnant*: Usually takes the form of isolated pools.
– *Alternate*: Rotates between the three aquatic phases.
– *Occasional*: River usually dry that sometimes, but not often, has flowing or stagnant water.
– *Episodic*: Dry river with either flowing or stagnant water at infrequent intervals.

These terms are combined to identify nine types of regime, as shown in Table 2 and Fig. 2, where the threshold values defined for the three metrics are indicated. Two of these boundaries are assumed as the most relevant for aquatic life: *Mf* smaller than 0.4 is assumed as a practical boundary where usual WFD methods cannot be used to assess biological status; and *Md* smaller than 0.1 represents conditions with quasi-perennial surface water, either flowing or stagnant.

The results of this classification are displayed in TREHS for all the diverse types of information. Furthermore, as some European Member States included classifications of the rivers according to their natural flow regimes in the respective transpositions of the WFD ("ORDEN ARM/2656/2008" in Spain and "DECRETO 16 giugno 2008, n. 131" in Italy), these classifications are also offered by TREHS for the natural (reference) conditions, as the 'prescribed regime', as well as for each and every kind of information available.

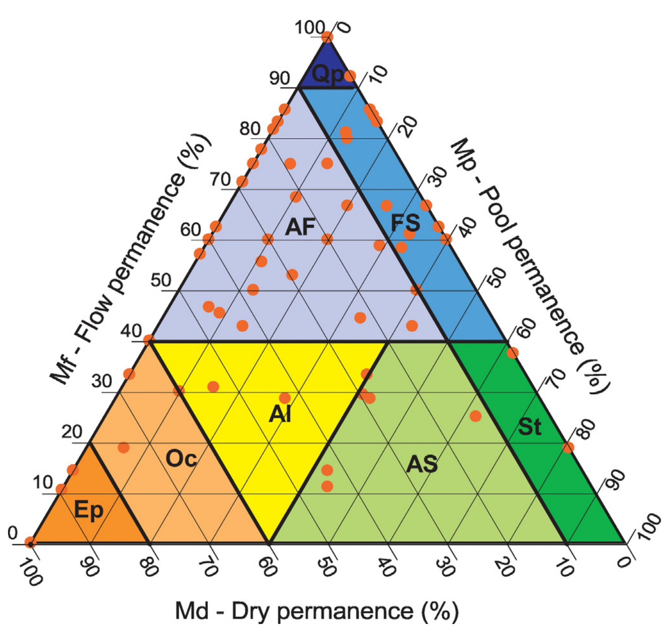

Fig. 2. Distribution of the TREHS aquatic phases regimes in the FPD plot. Qp: Quasi-perennial; AF: Alternate-Fluent; FS: Fluent-Stagnant; St: Stagnant; AS: Alternate-Stagnant; Al: Alternate; Oc: Occasional; EP: Episodic. *Mf*: flow permanence; *Mp*: pool permanence; *Md*: dry channel permanence. The orange dots represent river stations were the metrics were obtained from in situ or photographic observations (73 points).

Table 2
Nomenclature and metrics boundaries of aquatic phases regimes as used in TREHS. *Mf*: flow permanence, *Mp*: pool permanence; *Md*: dry channel permanence. The characteristic metric boundaries used for defining the regimes in Fig. 2 are shown in **bold**.

Regime	*Mf*	*Mp*	*Md*
Perennial (Pe)	**0.99** < ***Mf*** ≤ 1.00	0.00 ≤ *Mp* < 0.01	0.00 ≤ *Md* < 0.01
Quasi-perennial (Qp)	**0.90** < ***Mf*** **≤ 0.99**	0.00 ≤ *Mp* ≤ 0.10	0.00 ≤ *Md* ≤ 0.10
Fluent-Stagnant (FS)	**0.40** < ***Mf*** **≤ 0.90**	0.00 ≤ *Mp* < 0.60	0.00 ≤ ***Md*** < **0.10**
Alternate-Fluent (AF)	**0.40** < ***Mf*** ≤ 0.90	0.00 ≤ *Mp* < 0.50	**0.10 ≤ *Md*** < 0.60
Stagnant (St)	0.00 < ***Mf*** **≤ 0.40**	0.50 ≤ *Mp* < 1.00	0.00 ≤ ***Md*** < **0.10**
Alternate-Stagnant (AS)	0.00 < ***Mf*** **≤ 0.40**	**0.40 ≤ *Mp*** < 0.90	**0.10 ≤ *Md*** < 0.60
Alternate (Al)	0.00 < ***Mf*** **≤ 0.40**	0.00 ≤ ***Mp*** < **0.40**	0.20 ≤ ***Md*** < **0.60**
Occasional (Oc)	0.00 < *Mf* ≤ 0.40	0.00 ≤ *Mp* < 0.40	**0.60 ≤ *Md*** < **0.80**
Episodic (Ep)	0.00 < *Mf* ≤ 0.20	0.00 ≤ *Mp* < 0.20	**0.80 ≤ *Md*** < 1.00

5.4. Assessing hydrological alteration

After Article 4(1) of the WFD, the regime of a fluvial water body must be assessed for its ability to reach a good status of biological indicators (European Commission, 2000; CIS, 2015). Unfortunately, the ecology of temporary rivers is not yet sufficiently understood to make a sound evaluation of the ecological implications of regime alterations. Indeed, following the recommendations of the Ecological Limits of Hydrologic Alteration (ELOHA) framework (Poff et al., 2010), it is necessary i) to find 'baseline' or reference unimpacted regime characteristics for the water body under study, ii) to classify the river regime using ecologically relevant variables, iii) to determine the deviation of the current regime from the baseline-condition one and iv) to develop regime alteration-ecological response relationships.

TREHS was designed to help cope operationally with the first three steps of the ELOHA framework and to determine Hydrological Status (HS) as an assessment of the ecological relevance of hydrological alteration, on the basis of expert criteria that can be easily updated when new information is made available. In the following subsections, the way the metrics described in 5.1 are used for assessing the degree of hydrological alteration and determining its ecological relevance (HS) is summarized.

5.4.1. Reference regime conditions

The default method for determining the baseline or reference regime for a station in TREHS is the use of a flow-discharge series simulated with a rainfall-runoff model, assuming natural conditions. This kind of simulation for every water body is usually available for the implementation of the WFD (for instance, in Spain according to the "Instrucción de Planificación Hidrológica", ORDEN ARM/2656/2008). Alternatively, historical flow records from gauging stations obtained before hydrological alteration can also be used to determine the reference regimes.

In these cases, simulated or recorded flow series are handled as described in Section 4.1 to obtain the corresponding metrics and are selected as the reference ones. It is important to remember that the occurrence of isolated pools and therefore the determination of the *Mp* metrics are not straightforward when water flow data are used for calculating the metrics. The permanence of pools *Mp* obtained with these data is expected to be usually underestimated.

If reference regime metrics can be obtained from any other source (flow records from another gauging station in the area, interviews for this purpose), the corresponding metrics can be directly entered into TREHS. Finally, if diverse sources of reference regimes are available, such as from different rainfall-runoff models, their use in TREHS can be switched on and off in order to compare the results.

5.4.2. Hydrological status

TREHS calculates the degree of hydrological alteration with an expert scoring method from the differences between the metrics obtained for the reference regime and the actual one. These calculations are made on a separate auxiliary spreadsheet that can be inspected by the user in order to monitor the process and, if need be, update some of the expert criteria. To avoid a long description, an example of this spreadsheet is offered as supplementary material to this paper.

First, for every metric, the average and standard deviation of the values obtained from the diverse types of information on the reference and actual regime are obtained. The TREHS user can switch off any of the types of information if bias is suspected.

Then, the differences between the reference and the available actual metrics are compared with threshold values that depend on the reference *Mf* value, to decide whether the divergences are unacceptable; the more permanent the regime is, the lower divergences of the metrics are permitted. These threshold values are calculated in the auxiliary spreadsheet from tables of benchmark values that can be updated by an expert user.

The criteria used for assessing the hydrological alteration are as follows:

– Decrease of flow permanence *Mf*, two levels of severity (gentle and harsh).
– Decrease of surface water permanence ($Mf + Mp$), two levels of severity.
– Increase of flow permanence *Mf*, two levels of severity.
– Change of seasonal predictability Sd_6.
– Change of seasonal patterns *SWs* or *ESs*.

Note that an increase in flow permanence or a change in the temporal pattern is also taken as hydrological alteration because they may facilitate the advent of generalist invasive species, particularly fishes and crayfishes (e.g. Riley et al., 2005).

Every criterion is penalised with one negative score that is subtracted from a value of 4; then the HS is determined as 'not altered', 'lightly altered', 'moderately altered' or 'highly altered' for total values from 4 to 1 respectively.

TREHS also displays the criteria used for this determination, in order to inform the manager of the measures to be taken for regime reclamation. Finally, it also calculates the degree of confidence of the diagnosis issued, based on the ratio between the metric differences and their standard deviations, as well as its robustness, based on the number of different kinds of information used.

6. Application of TREHS in ecological status assessments

The hydrological information provided by TREHS is intended to guide managers on the establishment of environmental objectives and selection of the most appropriate methods for ecological status assessment of temporary rivers.

On the one hand, hydrological status (i.e. distinguishing whether a water body has a natural or altered hydrological regime) contributes to defining specific environmental targets according to the river's natural regime and thereby to proposing adequate restoration or conservation measures. The WFD requires assessment of the ecological status of a river by means of groups of aquatic organisms, namely biological quality elements (i.e. macroinvertebrates, algae, macrophytes and fish). The combination of several indicators provides contrasting but complementary information on how they might respond differently to each stressor (Mykrä et al., 2012). Each taxonomic group is affected in a different way by regime alteration because each one has different traits as ways of coping with drying or floods, etc. For example, fish communities have limited traits to cope with interruption of flow or drying riverbeds (Kerezsy et al., 2017), whereas macroinvertebrates and even algae have more resistant and resilient strategies (Sabater et al., 2017; Stubbington et al., 2017b). Thus, alteration of natural regimes that imply habitat loss, such as disconnected pools during the scarce or zero-flow period (e.g. alteration from a natural FS to Oc due to water abstraction), lead to stronger implications for the maintenance of native fish communities, which negatively affect the achievement of ecological status. In such examples, in which poor hydrological status is evident, biomonitoring of macroinvertebrate communities would not ensure a correct ecological status assessment and fish communities should be included (Benejam et al., 2010). Suitable knowledge of the natural presence of fish communities for each river site is essential prior to ecological status assessment with this biological quality element. Thus, TRESH software can provide useful information on the natural river regime that can later be compared with measured data, which shows whether fish fauna is expected to be present at each river site analysed.

On the other hand, river regime classification with information on permanence of flow (*Mf*), pools (*Mp*) and dry channel (*Md*), together with seasonal predictability (Sd_6), may help managers to decide whether ecological status can be assessed by means of standard biomonitoring methods, mainly developed for perennial rivers, and thus partially avoid the exclusion of many temporary rivers from biomonitoring programs. For example, in a river with a flow permanence of 60–70% (SF or AF regime, see Table 2) showing high seasonal predictability, current methods could be used if the sampling calendar is adapted to the period with the greatest probability of finding lotic conditions (Prat et al., 2014). This is the case of many Mediterranean-climate rivers, in which the dry season is highly predictable (Bonada and Resh, 2013; Tonkin et al., 2017) and biotic indices based on macroinvertebrates have proved successful (Mazor et al., 2014; Munné and Prat, 2011; Cid et al., 2016).

However, even this adaptive approach could be limited in these types of rivers, depending on the level of aquatic habitat fragmentation (e.g. spatial isolation) during the dry season, which could lower organisms' recolonization potential (Datry et al., 2014b). In contrast, for a river with a flow permanence (*Mf*) and pool permanence (*Mp*) of <0.4, and with low seasonal predictability (e.g. Oc or Ep regimes, Table 2), current methods for the assessment of the ecological status are usually non-applicable. Even in reference sites, aquatic communities subjected to these regimes are usually poor in species and those that persist are tolerant to disturbances and human impacts; this will result in the underestimation of the ecological status and thus constrain the applicability of commonly used methods (Bonada et al., 2007; Buffagni et al., 2009; Cid et al., 2017; Munné and Prat, 2011). In these cases, characterized by the fact that most of the time rivers are dry and water flows sporadically in episodes of storms, its status should be evaluated preferably according to a hydromorphological assessment. Besides, the development of novel methods based on terrestrial communities can be a good solution (Sánchez-Montoya et al., 2016; Corti and Datry, 2015). Similarly, in those systems where pool habitats predominate throughout the year, specific methods could also be adapted and/or developed.

Further development of the TRESH software will include the methods to provide a complete evaluation for the ecological status of temporary streams.

7. Discussion and perspectives

7.1. Design changes during the development and interim application of TREHS

TREHS was developed under the LIFE + TRivers project and devised as a tool for applying the methods formulated during the MIRAGE project to the implementation of the WFD in temporary rivers. During its development and interim application, however, the original idea changed significantly, mainly due to the incorporation of information alternative to water discharge records, as well as the development of the FPD plot and regime classification with the advent of information on the occurrence of stagnant pools. The development of the FPD plot and the associated classification of regimes needed several months of discussion, but was established as a useful framework for deliberation, comparisons and communication.

TREHS was applied to 119 stations from the Catalan river basin district (ACA), the Júcar river basin district (CHJ) and the Ebro river basin district (CHE). The stations investigated were selected from stations in the first two districts where temporariness made the implementation of the WFD difficult, and from stations with zero-flow records in the third district. Alongside other methods, river regimes were assessed with the help of observations in 73 of these stations, as shown in Fig. 2. The most striking result is that these regimes cover most of the FPD plot, with at least two stations in every one of the regime classes. Two examples of TREHS application to real rivers are shown in Appendices B and C.

The hydrological part of TREHS has proved an advantageous tool for gathering, managing and analysing hydrological data from temporary rivers, particularly when there are no available flow records. Furthermore, it liberates researchers and managers from their traditional dependence on flow records or tentative model simulations, which may become disproportionate in these environments, while it offers new possibilities for a range of alternative observations, such as citizen science. At present, a smartphone application (Riu.neT) is being developed for making it easier and more functional to gather information on temporary river regimes and assess their ecological quality when possible.

In addition, the assessment of the regime of the temporary rivers investigated, as well as the 'aquatic states' background, became an essential framework for sound sampling and evaluation of the biological communities, as well as for comparing biological determinations between diverse investigated rivers.

7.2. Weaknesses of TREHS

Nevertheless, there are several weak points in TREHS that will need (if feasible) further development:

– The hydrological part of TREHS manages somewhat fuzzy information, mainly at the single station scale. This uncertainty is partly due to the intrinsic variability of the regime of temporary rivers in both time and space, and partly due to the constraints caused by limited sampling in the case of observations and by interviewee subjectivity in the case of interviews. Nevertheless, this information is much better than the frequent lack of flow records; and the user is advised on the levels of uncertainty and robustness associated with the data. He/she can, therefore, look for more information at the same station or at a nearby one, if necessary, in order to obtain the data necessary for an adequate hydrological assessment and diagnosis.

– In its present form, TREHS is not able to handle hydrological events occurring at shorter time scales than the month, whereas it is well known that runoff events triggered by storms are usually flashy and may occur in days or hours. As already stated in Section 4.1, there are difficulties when daily flows are aggregated to the monthly scale. In fact, it is possible to store in situ or photographic observations of aquatic states at a time scale down to daily step in TREHS, but the analysis or display of this information is being made at the seasonal scale, looking for long-term patterns instead for a given time period. Shorter time steps may be used for analysing the recent history of aquatic states before and during biological sampling using the same principles (qualitative states instead of flow measurements, see an example in Gallart et al., 2012), but this cannot be made within TREHS.

– The metrics frontier values used to separate the regime classes in the FPD plot in Fig. 2 were tentatively defined in order to provide users with a clear terminology for cataloguing, comparing and exchanging the information gathered with interviews and observations. It may nevertheless happen that, when more data are available, the classes defined turn out to be excessively provisional and insufficient for assessing the hydrological controls on aquatic life. Further developments should aim at improving the classification, if sufficient biological data become available. Actually, TREHS uses the differences between the reference and actual regime metrics for determining the hydrological status, but not the respective regime classes defined in the FPD plot.

– As the TREHS classification of the regime of temporary rivers does not take into account the representation of the temporal structure of the aquatic phases, it may be expected that the biological significance of the classes designed will have different biological implications in diverging climate settings. This is not, however, an impediment to its use, because, if necessary, other climate categories can be added to the simpler flow-pools-dry classification (see an example in Uys and O'Keeffe, 1997).

– Flow discharge records, whether measured or simulated, were confirmed as an inadequate source of data for assessing the regime of temporary rivers. Not only is the measurement of water flow inadequate for correctly determining the occurrence of stagnant pools, but the design and inadequate maintenance of the gauging sections mean that there may be significant errors in the detection of low and zero flows. These limitations are particularly relevant when flows simulated with the help of a rainfall-runoff model are used to reproduce the natural flow regime, because they add the limitations associated with any hydrological modelling. Nevertheless, TREHS is not the cause of these limitations, but, on the contrary, is a useful tool for comparing diverse modelling approaches, not in terms of the simulated hydrographs, but in terms of the frequency and timing of zero-flow periods.

– TREHS is designed to be used at the station (reach) scale, while temporariness is also a spatial issue because diverse regimes may coexist at the same time along a sufficiently long river section. Given its current design, the analysis of spatial patterns of temporariness must be handled point by point, and any management with a GIS must use the TREHS results off-line.

TREHS does not afford any useful approach for the quality assessment of rivers with Occasional or Episodic regimes. It only helps to define them in this class. Ongoing methods based on terrestrial organisms may be a valuable approach for improving these regimes' ecological assessment and management in the absence of sufficient aquatic characterization (Sánchez-Montoya et al., 2016; Corti and Datry, 2015, Stubbington et al., 2017a).

7.3. Perspectives

The authors frankly expect that the developments gathered in TREHS will be a useful aid in the investigation and management of temporary rivers. In particular, the systematization of the collection and interpretation of data alternative to flow records, along with the development of the TREHS aquatic phases regime classification, may help to break through the confines imposed by the outdated approach of thinking of temporary rivers as simply hydrologically challenged perennial rivers instead of as a distinct class of ecosystems (Larned et al., 2010). Note that perennial rivers occupy just one point in the wide diversity of the FPD (Fig. 2) plot!

Indeed, these systematisations may provide the kernel of a useful conceptual and operational framework for spreading the study and monitoring of temporary rivers wherever they occur, such as the efforts being made in the SMIRES COST Action CA15113 (http://www.smires.eu/).

New data collecting methods, conceptual frameworks, metrics, terminology and classification are needed for this purpose. They should be discussed in collaborative international arenas such as the abovementioned COST Action.

Meanwhile, we indeed recommend noting down the concurrent aquatic state of the temporary river reach when biological samples are taken.

Acknowledgements

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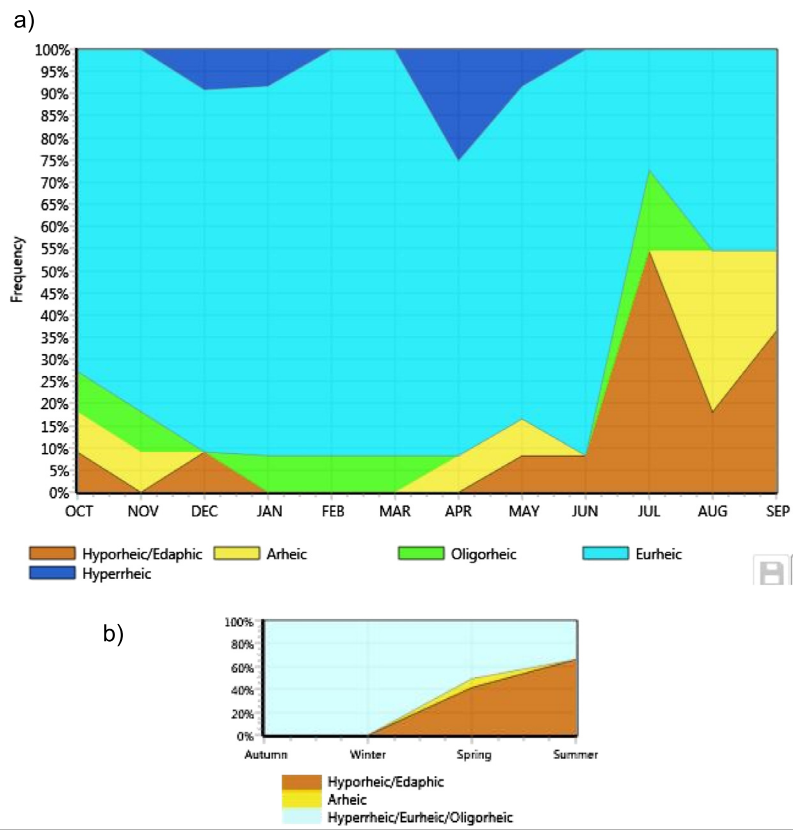
Appendix A. Graphs used in TREHS



Information provided (output)

- Relative frequency (%) of the aquatic states[1] throughout the year[2].

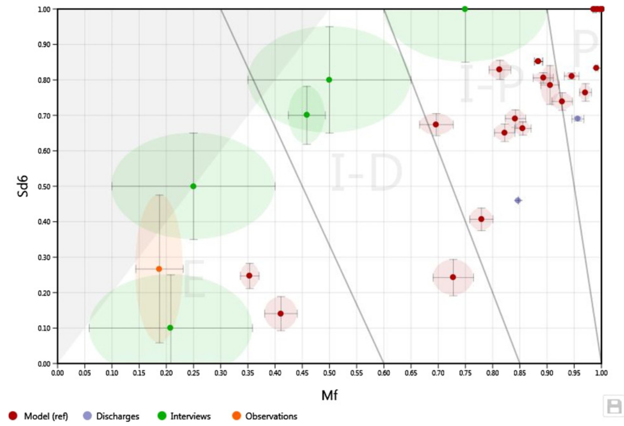
Application

- Visual assessment of temporal variability and seasonal predictability for the selection of the most appropriate sampling methods (e.g. if the degree of seasonality is high, traditional flow-phase biomonitoring methods can be used by adapting the sampling calendar to the period with the highest probability of finding lotic conditions).

[1]Defined in Gallart et al. (2012) as transient sets of aquatic mesohabitats occurring in a stream reach at a particular moment depending on the hydrological conditions. These are: flood conditions (Hyperrheic), flow with all mesohabitats connected (*Eurheic*), sequence of pools connected by flowing water threads (*Oligorheic*), isolated pools (*Arheic*), absence of surface water with the wet alluvium (*Hyporheic*) and completely dry river bed and alluvium (*Edaphic*).

[2]When input data are from flow records or simulations, the temporal scale is represented on a monthly basis (a), and when they correspond to interviews, *in situ* or photographic observations, the temporal scale is represented on a seasonal basis (b).

Fig. A.1. Aquatic State Frequency Graph (ASFG), defined in Gallart et al. (2012).



Information provided (output)

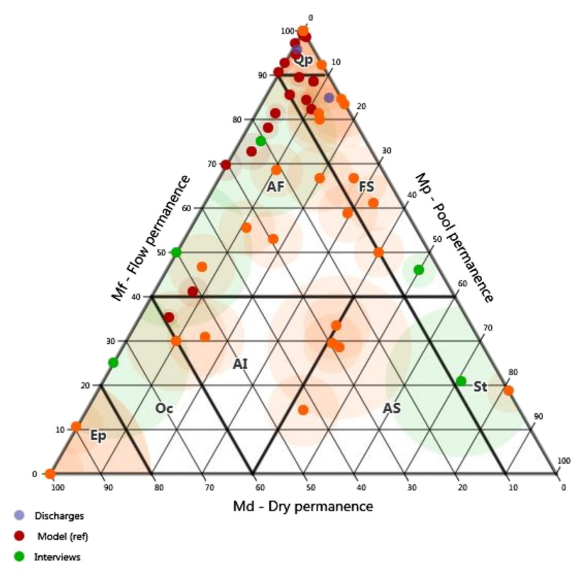
- Flow permanence (Mf) and its variability.
- Seasonal predictability (Sd6) and its variability.
- MIRAGE flow regime classification[3].

Application

- Quantitative assessment of the flow regime.
- Comparison of several sites and/or different sources of input data (e.g. flow records, flow simulations, interviews, observations).
- Visual estimation of flow regime alteration (i.e. hydrological status).

[3]The flow regime types defined by Gallart et al. (2012) –i.e. Perennial (P), Intermittent-pools (I-P), Intermittent-dry (I-P) and Ephemeral (E)- are shown in this plot for overall comparison. A more detailed classification is conducted in the Flow-Pool-Dry plot (FPD).

Fig. A.2. Temporary Regime Plot (TRP), defined in Gallart et al. (2012).



Information provided (output)

- Flow permanence (Mf) and its uncertainty (resolution).
- Pool permanence (Mp) and its uncertainty (resolution).
- Dry channel permanence (Md) and its uncertainty (resolution).
- TREHS temporary regime classification[4].

Application

- Information on the presence of surface water when flow ceases (i.e. isolated pools).
- Comparison of several sites and/or different sources of input data (e.g. flow records, flow simulations, interviews, observations).
- Visual estimate of flow regime alteration (i.e. hydrological status).

[4]The flow regime types defined in this paper are: Perennial (Pe), Quasi-perennial (Qp), Fluent-Stagnant (FS), Alternate-Fluent (AF), Stagnant (St), Alternate-Stagnant (AS), Alternate (AI), Occasional (Oc), Episodic (Ep). See Table 1 and Figure 2 for more detailed information.

Fig. A.3. Flow-Pools-Dry (FPD) plot, defined in this paper.

Appendix B. Example of TREHS application to the water body 01.04 corresponding to the Sénia River between La Sénia village and the Foies irrigation channel

The studied water body is placed in the Júcar River Basin District, between the Castelló and Tarragona provinces. In the studied segment, the river Sénia is characterized by a temporary hydrological regime, not being possible its ecological status assessment according to the biological, physico-chemical and chemical parameters required by the Water Framework Directive (WFD). Furthermore, this water body is subjected to a high water abstraction pressure mainly for irrigation waters; the hydrological regime is therefore a priori suspect of alteration.

Given that this is a temporary river, there are no recent flow gauging records that would allow to characterize the current hydrological regime. Furthermore, water quality data are not available because during sampling campaigns planned by the competent Authority the river is usually dry.

Application of TREHS to the study water body, on the one hand allows us to improve characterization of the current hydrological regime by using quantitative data from gauging records (if any), together with the use of qualitative data from interviews and in situ or photographic observations. On the other hand, the characterization of the current hydrological regime allows the design of an optimal sampling schedule for conducting ecological status assessments adapted to the seasons of the year in which there is a high probability that the river conveys water. Finally, if data or simulations describing the natural river regime are available, it allows analysing the degree of current hydrologic alteration by comparison of the metrics representing the natural regime with those representing the current regime.

To this end, the Sénia river water body 01.04 was subjected to a compilation of all existing hydrologic data, complemented with interviews and observations through orthophotographs.

The input data for this water body were the following:

a) Flow simulation records obtained with the PATRICAL hydrological model (Pérez, M.A., 2005; Pérez-Martín et al., 2013) as for a natural regime (Figs. B1 and B2).

It is worth to note that the PATRICAL model operates at monthly temporal scale and therefore it does not allow a sufficiently adequate interpretation of the hydrological regime in many temporary rivers. In this case the simulations resulted in a fully permanent regime (Fig. B1). As this was not consistent with the traditional perception of the regime, it was decided not to use these simulations in the further analysis in TREHS.

b) Historical Flow gauging records. These data are available for this water body (series corresponding to the period 1912–1930). Given that irrigation pressures in the area were produced in later periods, it can be assumed that this series adequately represents the natural regime of the river in the studied reaches (water body 01.04).

After these historical flow gauging data, this river segment behaves as temporary (Fig. B3), being dry during mainly from July to January (Fig. B4).

c) Interviews. These were made with the staff of the river domain of the Confederación Hidrográfica del Júcar, who is the competent River Authority. This hydrologic information responds to the most recent hydrological regime. According to this data, the river became ephemeral during the last years and water flows only during rainy episodes. Flow permanence was estimated as $Mf = 0.011$ (four flowing days per year), without any clear seasonal pattern (Fig. B5).

d) In situ and photographic observations. A detailed analysis of the water body using available ortophotographs between 2004 and 2017 was made. This allowed the complementation of the hydrological information respect to the current situation.

Observations collected data since 2004, allowing representing the reality of this River segment during a broader time period than interviews.

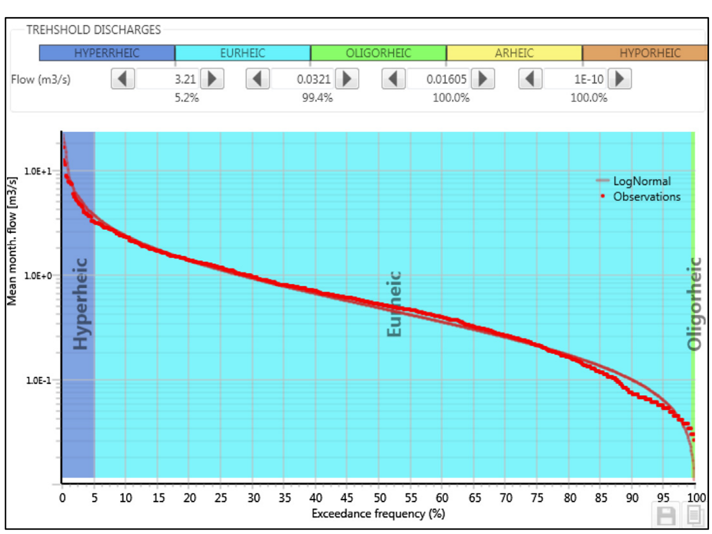


Fig. B1. Flow duration curve for the flow series simulated with the PATRICAL model.

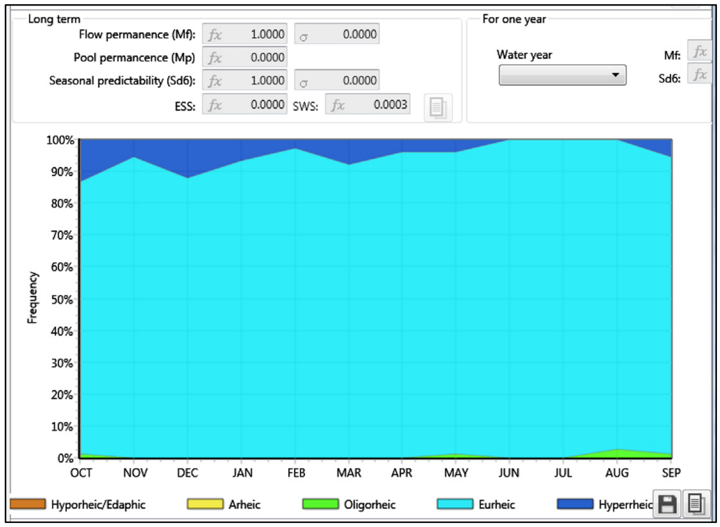


Fig. B2. TREHS metrics and Aquatic States Frequency Graph derived from flow simulations of Fig. B1.

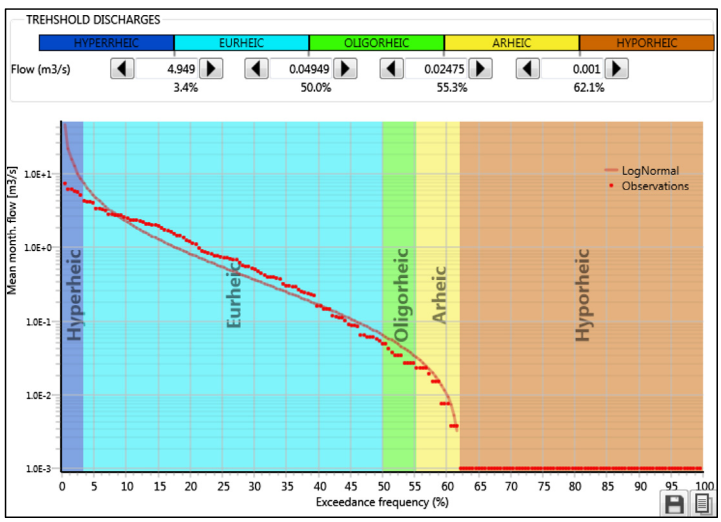


Fig. B3. Flow duration curve and interim thresholds between aquatic states for the historical flow series 1912–1930.

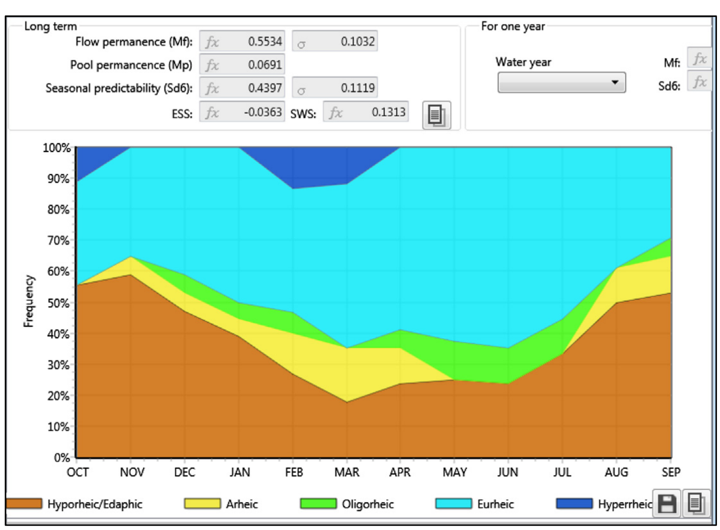


Fig. B4. TREHS metrics and Aquatic States Frequency Graph derived from flow records of Fig. B3.

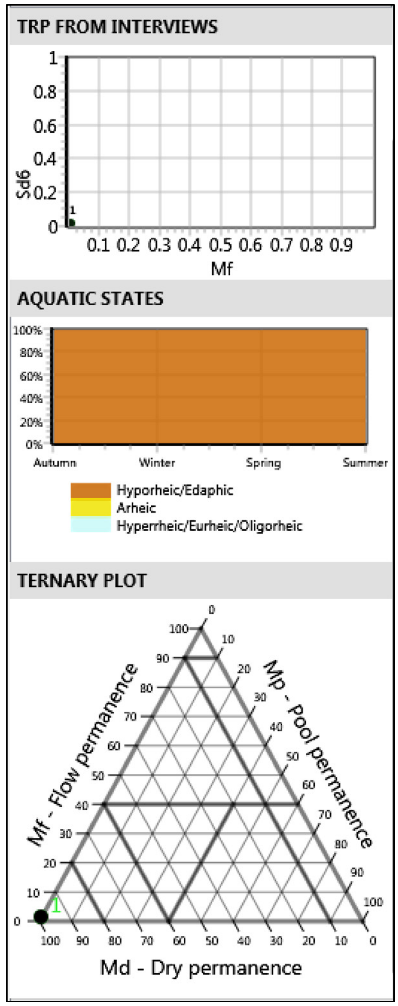


Fig. B5. TREHS results obtained with the information from interviews. Top: Temporary Regime Plot, showing both *Mf* and Sd_6 metrics close to 0. Middle: simplified Aquatic States Frequency Graph showing that only Hyporheic/Edaphic states could be estimated. Bottom: Flow-Pool-Dry plot where the river reach appears as Episodic (Ep), close to the permanently dry situation.

According to the observations analysed, the river is dry for long periods of time, and may even remain dry during several consecutive years. However it is not as harsh as shown in the interviews since there are years in which the river carries water in certain seasons. In this case, there are sufficient observations not only to allow the calculation of permanence metrics, but also to obtain those describing the temporal patterns of aquatic phases.

Flow duration was estimated as $Mf = 0.32$, with a clear seasonal pattern (Fig. B6).

Based in the data inputs provided, TREHS showed the following results:

1) Optimal sampling period. For this River section, from the hydrological point of view, the more recommendable sampling period is spring, because this is the season with the highest probability to find flowing water (33% in Eurheic/Oligorheic aquatic states). Furthermore, this season is the optimal season to perform standard sampling after the WFD. Nevertheless, the Competent Authority can adapt the sampling campaign in this River segment during a period that ensures the presence of flowing water. This recommendation is made after the current river regime, whereas the degree of alteration of the natural regime is analysed below in subsection 3.
2) River regime. The natural river regime may be characterized as *intermitente* following the Spanish regulations (WFD transposition) and Alternate-Fluent after the TREHS classification. The actual regime is characterized as Occasional (Oc) from observations and Episodic (Ep) from interviews, both following the TREHS classification (Figs. B7 and B9)
3) Hydrologic status. As can be deduced from the preceding paragraph, it can be considered that the hydrological state is highly altered, due to a severe decrease of the permanence of flow and surface water (Figs. B7, B8 and B9).

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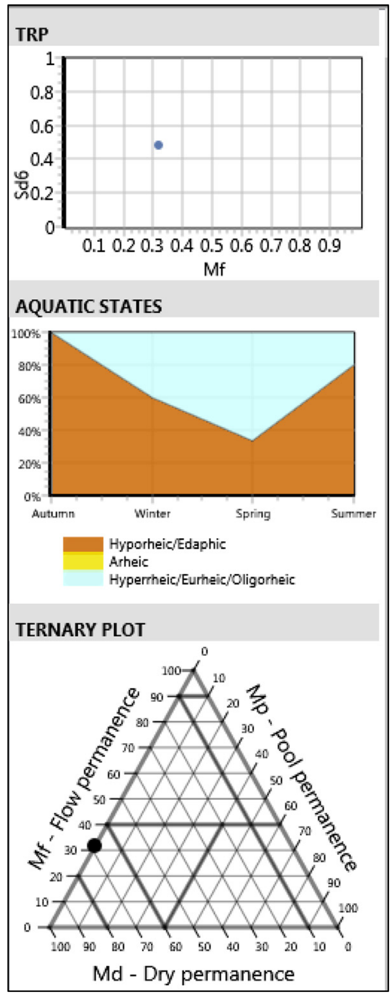

Fig. B6. TREHS results obtained with the information from observations (ortophotographs). Top: Temporary Regime Plot, showing both *Mf* and Sd_6 metrics in the area of predictable ephemeral rivers. Middle: simplified Aquatic States Frequency Graph showing an annual pattern similar to the one obtained with historical flows but significantly drier. Bottom: Flow-Pool-Dry plot where the river reach appears in the Occasional (Oc) regime without pool phases.

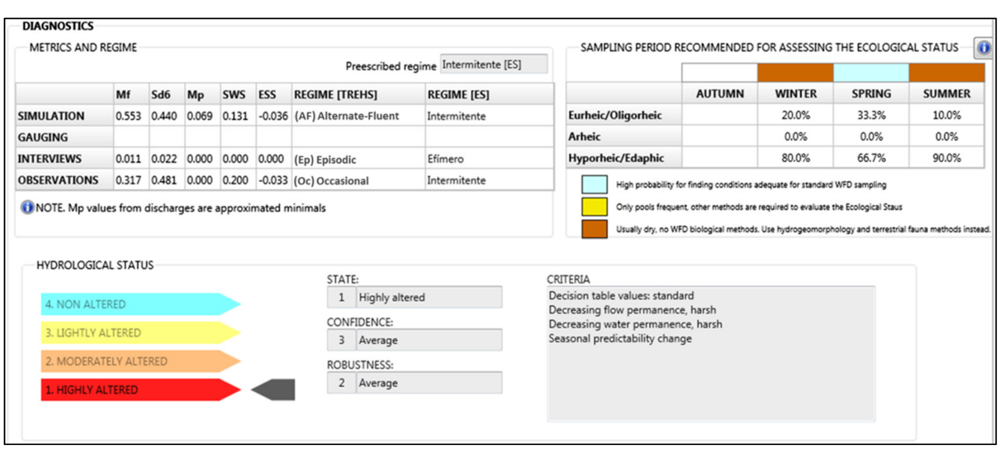

Fig. B7. TREHS diagnostics block. It shows: metrics obtained from the diverse sources of information; corresponding regimes using the TREHS classification as well as the Spanish regulations [ES]; recommended sampling period; hydrologic alteration along with the criteria used and the valuation of the confidence and robustness of the assessment. Note that in this case 'Simulation' refers to historical flow gauging.

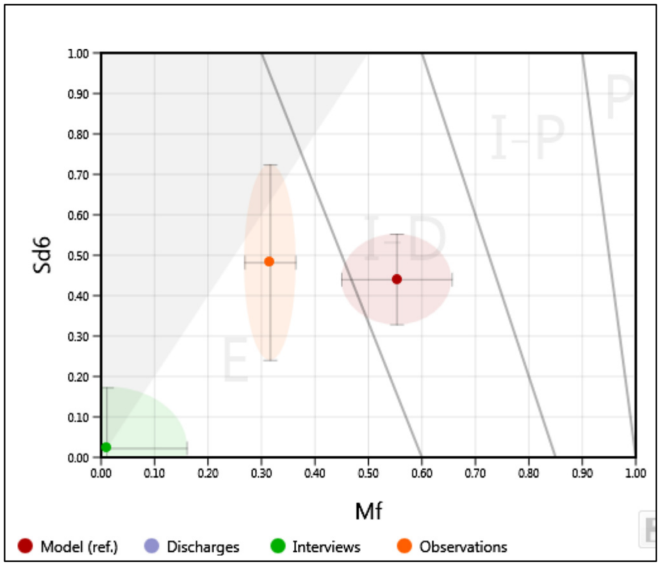

Fig. B8. Temporary regime plot for the diverse sources of data used. Ellipsoids show the uncertainty of the metrics. In this case Model (ref.) refers to the historical flow records.

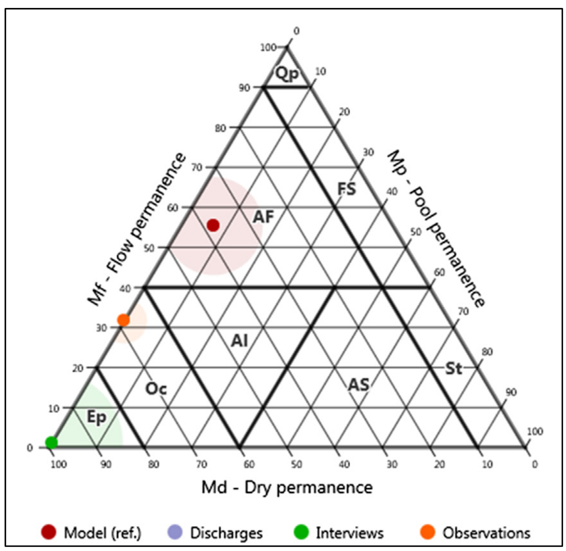

Fig. B9. Flow-Pools-Dry (FPD) plot for the diverse sources of data used. Circles show the uncertainty (resolution) of the metrics. In this case Model (ref.) refers to the historical flow records.

Appendix C. Example of TREHS application to the water body 1900010 corresponding to the Daró River from the headwaters to the confluence with the Marqueta stream (Catalan river basin district, Spain)

The studied water body is placed in the Catalan River Basin District, in the province of Girona. The Daró is a temporary river that has its source in the Gavarres massif, a densely forested semi-natural low mountain area, and flows into the Ter River. The studied river segment is a natural fluvial reserve that belongs to the network of reference sites in Catalonia. Among other aquatic species of interest, several populations of the three-spined stickleback (*Gasterosteus aculeatus*) are present.

There are no flow records adequate to characterize the current hydrological regime of this water body because the closest gauging station in the Daró River is at La Bisbal de l'Empordà, in the subsequent water body located several kilometres downstream, which is affected by several pressures on water resources for irrigation and urban consumption. The application of TREHS to the studied water body seeks to characterize the current hydrological regime mainly for conservation and management purposes within a land use and global change setting.

The input data for the Daró River water body 1,900,010 to TREHS were the following:

e) Flow simulation series obtained with the SACRAMENTO hydrological model (1940–2000) as for a natural regime, implemented through a regional calibration approach (ACA, 2004): Figs. C1 and C2.

f) Flow simulation series obtained with the Thornthwaite-Mather (TM) water balance model (Steenhuis & Van der Molen, 1986) for the same period, as for a natural regime under densely forested cover (Figs. C3 and C4). This simulation was attempted because it is well known that most

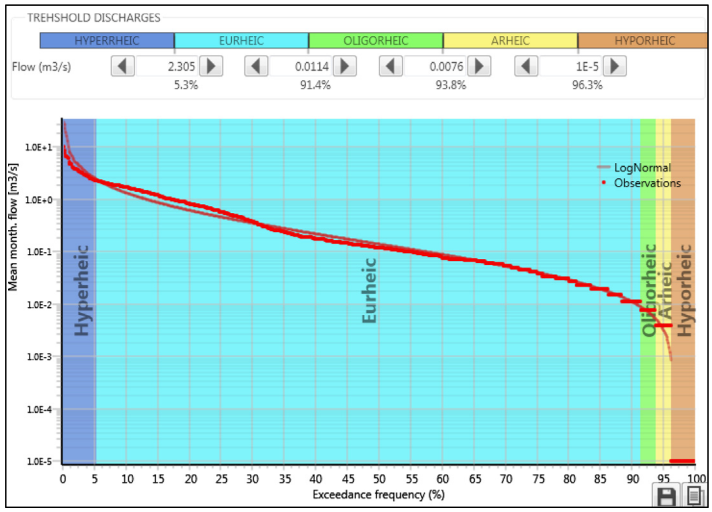

Fig. C1. Flow duration curve for the flow series simulated with the SACRAMENTO model.

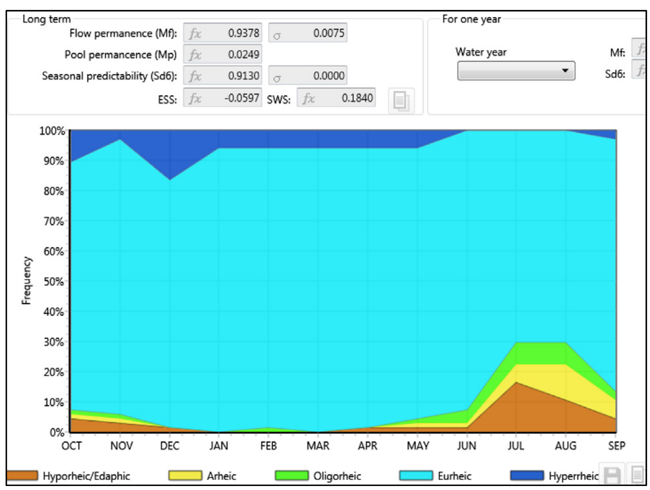

Fig. C2. TREHS metrics and Aquatic States Frequency Graph derived from flow simulations of Fig. C1.

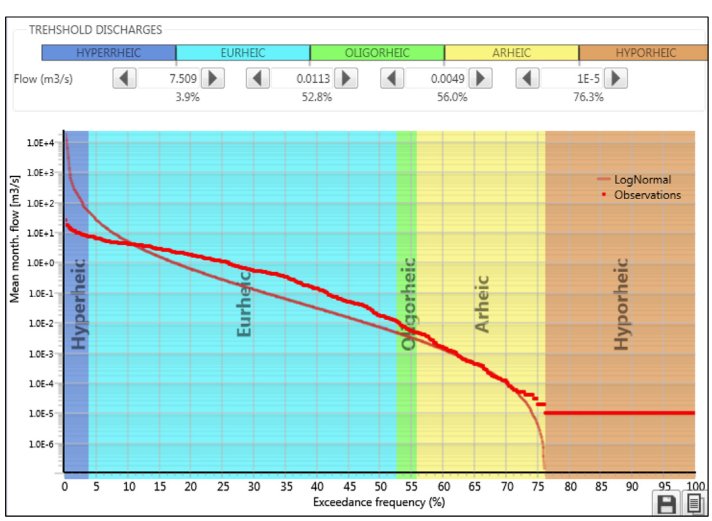

Fig. C3. Flow duration curve for the flow series simulated with the Thornthwaite-Mather model.

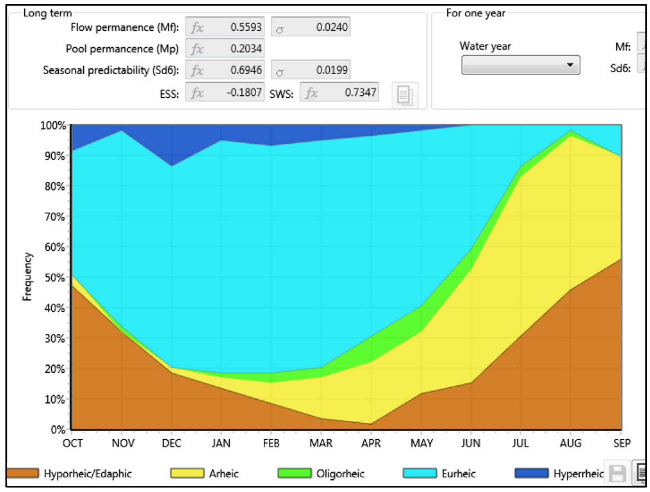

Fig. C4. TREHS metrics and Aquatic States Frequency Graph derived from flow records of Fig. C3.

headwater basins in the Catalan River Basin District suffered a significant decrease of flows during the last decades due to the encroachment of forest cover subsequent to land abandonment (e.g. Gallart et al., 2011). Note that the threshold between *Oligorheic* and *Arheic* states was fixed by 5 l s^{-1} (assuming that this flow was mainly through the alluvium) and between Arheic and Hyporheic by 0.01 l s^{-1}.

g) Interviews. Given the low density population in the area, only one interview was made with the Major of the village of Cruïlles, which is located in the lower part of the water body, where the Daró River leaves the Gavarres massif and flows into the Baix Empordà lowland (Fig. C5).

h) In situ and photographic observations. A river reach in this water body was repeatedly visited during 2015 in order to take biological samples and to record the concurrent aquatic states. Furthermore, several ortophotographs and ground-level Street View photographs were interpreted for determining the corresponding aquatic phases. Although a total of 20 observations were made, the temporal patterns of aquatic phases could not be determined because an insufficient number of observations was unambiguously obtained for autumn and winter (two observations in

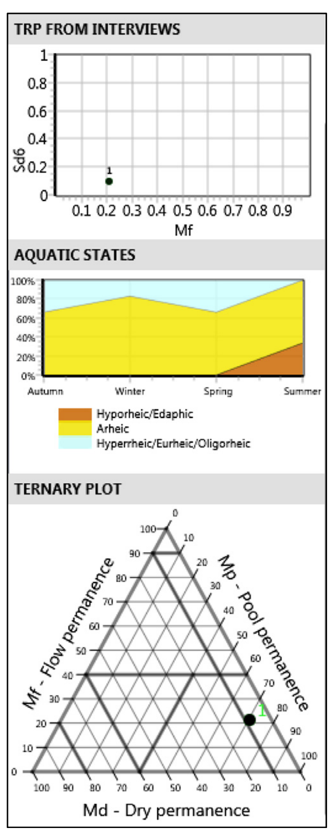

Fig. C5. TREHS results obtained with the information from interviews. Top: Temporary Regime Plot, showing both *Mf* and Sd_6 metrics corresponding to ephemeral rivers. Middle: simplified Aquatic States Frequency Graph showing the high frequency of the Arheic state (pools phase) throughout the year, whereas the stream is only dry during summer. Bottom: Flow-Pool-Dry plot where the river reach is located in the Stagnant (St) regime area.

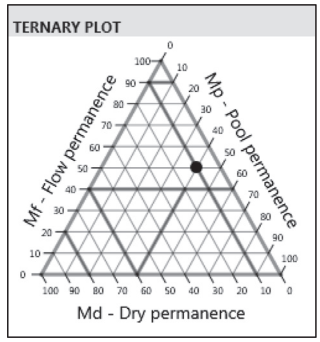

Fig. C6. TREHS results obtained with the information from direct and photographic observations. The river appears in the Alternate-Fluent (AF) regime in the Flow-Pool-Dry plot.

every one of these seasons). Consequently, only the metrics corresponding to the permanence of aquatic phases were obtained, showing an Alternate-Fluent (FS) river regime, with $Mf = 0.50$ and $Mp = 0.40$ (Fig. C6).

Once the data were introduced into TREHS, the following results were obtained:

4) Optimal sampling period. This water body presents surface water during most of the year, whereas flow phase seems more frequent in spring and probably in winter or autumn. If only the sampling visits are taken into account, from five visits, none was made during a dry phase, three in Arheic state (pools phase; two in summer and one in spring), one in Oligorheic state (flow phase, autumn) and another one in Eurheic state (flow phase, spring).
5) River regime. The natural river regime may be characterized as *temporal* following the Spanish regulations (WFD transpositions) and Quasi-perennial (Qp) following the TREHS classification, if the SACRAMENTO simulations are used. Nevertheless, under the TM model simulations, the river regimes turned into *intermitente* and Alternate-Fluent (AF) using the respective classifications. The actual regime is characterized as Alternate-Fluent (AF) from observations and Stagnant (St) from interviews, both following the TREHS classification (Fig. C9).

Fig. C7. TREHS diagnostics blocks when the SACRAMENTO (upper) and TM (lower) model flow simulations are used to infer the natural regime. It shows: metrics obtained from the diverse sources of information; corresponding regimes using the TREHS classification as well as the Spanish regulations [ES]; recommended sampling period; hydrologic alteration along with the criteria used and the valuation of the confidence and robustness of the assessment.

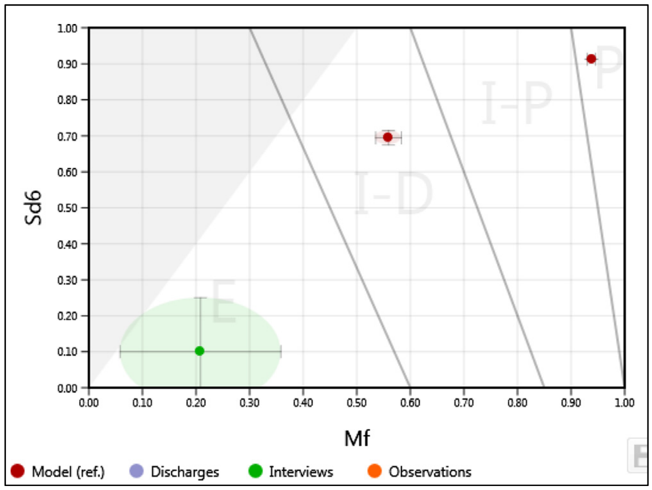

Fig. C8. Temporary regime plot for the diverse sources of data used. Ellipsoids show the uncertainty of the metrics. In this case two Model (ref.) are shown; the upper point refers to the SACRAMENTO simulations and the lower to the TM simulations for a densely forested land cover.

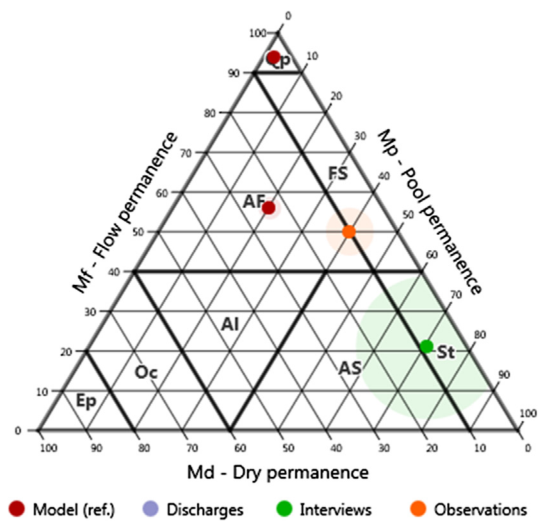

Fig. C9. Flow-Pools-Dry (FPD) plot for the diverse sources of data used. Circles show the uncertainty (resolution) of the metrics. In this case two Model (ref.) are shown; the upper point refers to the SACRAMENTO simulations and the lower to the TM simulations for a densely forested land cover.

6) Hydrologic status. Although there are no relevant known pressures on water resources in the studied water body, TREHS showed some hydrologic alteration that shifted from negligible to high depending on the flow simulations and the type of data used for assessing the current regime. Indeed, contrasting the SACRAMENTO simulations versus interviews yielded a high alteration, whereas contrasting the TM simulations versus observations yielded negligible alteration (Fig. C7 below). It is clear that both observations and interviews claim that the frequency of the dry river bed phase (*Md* metric) is low, but this is due to high permanence of either flow phase (*Mf* metric) or pools phase (*Mp* metric).

Given the current characteristics of the land cover in the headwaters, the flow simulations made with the TM model are deemed as more appropriate for depicting the present-day natural regime of the water body. On the other hand, the in situ and photographic observations may be assumed as more representative of the current regime of the water body than the interview, given both the lack of replication and the biased location of the interview.

For environmental protection purposes, the results obtained with TREHS show that this water body is characterized by a high permanence of surface water and a low permanence of the dry phase, whereas the permanence of the flow phase might have been subject to some decrease in the last decades due land abandonment in the Gavarres massif. It is recommended to protect the quantity and quality of the water during the pools phase, because this phase waters are very fragile to abstractions and pollution. On the other hand, land cover management strategies to restraint forest encroachment after land abandonment for preventing wildfires may be also useful to restore more frequent flow phases.

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Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2017.06.209.

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