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Developing a novel approach to analyse the regimes of temporary streams and their controls on aquatic biota

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Abstract

Temporary streams are those water courses that undergo the recurrent cessation of flow or the complete drying of their channel. The biological communities in temporary stream reaches are strongly dependent on the temporal changes of the aquatic habitats determined by the hydrological conditions. The use of the aquatic fauna structural and functional characteristics to assess the ecological quality of a temporary stream reach can not therefore be made without taking into account the controls imposed by the hydrological regime. This paper develops some methods for analysing temporary streams' aquatic regimes, based on the definition of six *aquatic states* that summarize the sets of mesohabitats occurring on a given reach at a particular moment, depending on the hydrological conditions: *flood, riffles, connected, pools, dry* and *arid*. We used the water discharge records from gauging stations or simulations using rainfall-runoff models to infer the temporal patterns of occurrence of these states using the developed *aquatic states frequency graph*. The visual analysis of this graph is complemented by the development of two metrics based on the permanence of flow and the seasonal predictability of zero flow periods. Finally, a classification of the aquatic regimes of temporary streams in terms of their influence over the development of aquatic life is put forward, defining *Permanent, Temporary-pools, Temporary-dry* and *Episodic* regime types. All these methods were tested with data from eight temporary streams around the Mediterranean from MIRAGE project and its application was a precondition to assess the ecological quality of these streams using the current methods prescribed in the European Water Framework Directive for macroinvertebrate communities.

1 Introduction

Temporary streams are water courses that undergo the recurrent cessation of flow or the complete drying of their channel. This type of water course is not only widespread in dry climate areas (e.g. Rossouw et al., 2005; Levick et al., 2008), but constitutes also the first-order stream network in most drainage basins in wetter climates (Fritz et al., 2006). The prevalence of these streams is expected to increase in the near future because of both climate warming and rising water consumption due to human activities (Tooth, 2000; Larned et al., 2010). The interruption of the aquatic conditions in temporary streams plays a determinant role in their ecological communities (Boulton, 1989; Arscott et al., 2010), so much so that temporary streams should be considered a distinct class of ecosystems instead of simply hydrologically challenged permanent streams (Larned et al., 2010). Indeed, though there are still severe gaps in our knowledge of these streams that affect their sound management, the traditional perception among managers that a "healthy" stream must flow all the year round can no longer be sustained (Boulton et al., 2000).

Many studies have been devoted to the hydrological characterization of temporary streams using diverse metrics. The frequency of the zero-flow periods (or its complementary, flow permanence) is the first criterion for all of them (e.g. Hedman and Osterkamp, 1982; Poff, 1996), whereas the seasonality of these periods is also used in some classifications (Uys and O'Keeffe, 1997; Rossouw et al., 2005; Kennard et al., 2010). A few authors also take into account the occurrence of isolated pools during periods without flow (Uys and O'Keeffe, 1997; Boulton et al., 2000). In fact, in ecological terms, the more relevant features of the water regime in temporary streams are the temporal and spatial patterns of occurrence or disappearance of the features of the aquatic habitats that depend on the presence and flow of water (hereafter called mesohabitats), such as riffles and pools, as well as the connectivity of water flow between them (e.g. Lake, 2007; Bonada et al., 2007; Chaves et al., 2008). Nevertheless, the information recorded at network gauging stations consists of water discharges, but the occurrence of the diverse habitats and particularly of pools during periods of zero discharge is not recorded despite their prominent ecological role (e.g. Uys and O'Keeffe, 1997; Bond and Cottingham, 2008).

If predictability hypotheses concerning the hydrological controls on aquatic life may be launched for temporary streams, the methods for measuring the ecological status of

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these streams and rivers, mainly based on the biological conditions (primary producers, macro-invertebrates and fish) may be established. The ecological status is the key condition of European streams to be evaluated, according to the current regulations for the management of waters, the so called Water Framework Directive (WFD; European Communities, 2000). When the ecological status of a stream is less than good, the water authorities should set up measures to recover this status within a River Basin Management Plan. But biological sampling to determine the ecological status of temporary streams cannot be the same if different mesohabitats are present or not as the sampling designed for permanent ones (plenty of riffles); is inadequate if water is not present on the sampling date or the aquatic life is reduced to those animals found in isolated pools. In this latter case the biological communities found (even if they are pristine) may be significantly poorer in taxa or lower in diversity than the reference ones living in permanent streams. The importance of pools for establishing the ecological status in Mediterranean streams was highlighted by Buffagni et al. (2009) and suggested that pool mesohabitat may give a better indication of biological quality than riffles during the riffle or connected pool phase when sampled separately. How biological metrics defining the ecological status using macroinvertebrates may change from wet to dry periods was investigated recently by Munné and Prat (2011). In another study, the comparison of spring samples when riffles are present gave similar values between years (Rose et al., 2008) despite the hydrological conditions of the year (dry or wet). Several authors have shown that only when the hydrological controls on aquatic life are completely understood, can the impact of human changes on the duration and predictability of dry conditions in biota and ecological status be assessed (Benejam et al., 2010; Dewson et al., 2007). So, for temporary rivers it appears necessary that before the evaluation of biological condition of the streams for calculating the ecological status, the hydrological conditions (e.g. the mesohabitat phase) should be studied.

Within this context, the present study proposes the analysis of the hydrological regime of temporary streams on the basis of the temporal patterns of the aquatic mesohabitats occurrence relevant to the development of aquatic life at the reach scale.

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First, the concept of Aquatic State, which summarizes the set of aquatic mesohabitats occurring on a given reach at a particular moment depending on the hydrological conditions is introduced. Six states are defined: flood, riffles, connected pools, disconnected pools, dry and arid (definitions provided below). The set of aquatic mesohabitats occurring on a temporary stream reach is known to be crucial for the presence and abundance of aquatic fauna when sampled. Thus, pools act as refuges for fish, providing places of survival during the absence of flow (Magoulik and Kobza, 2003) or influencing their fitness (Spranza and Stanley, 2000). The effect of the aquatic state on the community of macroinvertebrates has been studied in some detail (Feminella, 1996; Bonada et al., 2006; Acuña et al., 2005), as well as the interaction between different trophic levels (Ludlam and Magoulick, 2009). The comparison of communities following multiyear droughts (Magalhäes et al., 2007) or the comparison between communities in temporary and permanent streams (Mas-Martí et al., 2010) emphasized the importance of knowing the actual aquatic state and its evolution over time. It is known that fauna in temporary streams are more complex and taxa richness may be even higher than in permanent ones, because the replacement of different aquatic states through the year gives opportunities to a succession of species, making the final richness higher than in permanent streams (e.g. Bonada et al., 2006; García-Roger et al., 2011). The index EPT (Number of taxa of Ephemeroptera, Plecoptera and Trichoptera) and EPT versus OCH (Taxa of Odonata, Coleoptera and Heteroptera) has proved to be a good indicator of the change of aquatic state (Bonada et al., 2006).The six aquatic states defined below somewhat embrace the five “hydrologic conditions” defined by Fritz et al. (2006), from “no surface water” (0) to “surface flow continuous” (4), but here we put more emphasis on the relevance of the states for biological communities than in the hydrological conditions “per se”.

However, there are nearly no data on the presence, duration and inter-annual variability of different aquatic states in temporary streams, and we can not expect that this kind of data will be operationally recorded in the near future. Therefore, it is necessary to anticipate the temporal patterns of occurrence of these states from the available

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flow records or simulations, which is the second step proposed below. If the water discharge thresholds that separate the aquatic states are defined, the available flow statistics may be transformed into aquatic states statistics. A similar procedure is in common use to assess the chronicle of mesohabitats for fishes from water discharge data, in permanent streams (e.g. Capra et al., 1995). Boulton (2003) outlined the existence of "critical stages" in macroinvertebrate aquatic systems, defined by critical thresholds of discharge or water level at which mesohabitats become isolated or dry during a drought; the approach in the present study is consistent with that scheme, although more attention is paid here to the states between the thresholds and to the linkages with hydrologic data for making possible the operational application to stream regimes analysis. Moreover the analysis of the complex temporal patterns of occurrence of aquatic states is then made more apparent through the development of the Aquatic States Frequency Graph (ASFG), which shows the monthly frequency of occurrence of the diverse aquatic states throughout the year.

This graphic method allows a quick visualisation of the aquatic regime of a temporary stream, but its efficient characterisation needs the use of some metrics to rank and compare regimes, as well as to analyse relationships with biological indices or metrics. This is undertaken furthermore, through the development and testing of some metrics based on the statistics of the more ecologically relevant feature of water discharge records: the periods with zero flows. This is also one of the novelties of our approach compared with previous works.

Finally, a classification of the aquatic regimes of temporary streams is introduced. This is a conceptual classification based on the controls imposed by the temporal patterns of occurrence of aquatic mesohabitats on biological communities and their relevance for monitoring purposes. This is an important step to be used in the future for managers, specially when the WFD rationale is applied to determine the Ecological Status of these streams. Nevertheless, to be operational, this classification should be able for application to stream reaches using recorded or modelled hydrological data. Using this approach we emphasize the fact that prior to any biological sampling; the

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application of the metrics proposed has to be calculated and the actual mesohabitat condition known for judging if the current methodologies available for the measure of Ecological Status may be applied.

In summary, this analysis is intended to be useful for three main purposes: improvement in the investigation of the hydrological constraints on the development of aquatic life, the characterisation and classification of aquatic stream regimes (mesohabitat conditions), and the design of the biological sampling calendars (i.e. scheduling biota sampling at the more ecologically significant moments: see Bond and Cottingham, 2008). The ultimate goal is the development of tools for characterising the hydrological constraints on the development of aquatic life in stream reaches for both research and management applications. This method is being developed within the European MIRAGE project, which addresses the improvement of the Water Framework Directive by including temporary streams properly.

2 Methodological approach

The approach developed consists of four steps, as introduced above. In the first step, the mesohabitat conditions (here called aquatic states) relevant to the growth of aquatic life in temporary streams are clearly defined. The second step investigates the temporal patterns of occurrence of the aquatic states at the reach scale, inferred from gauging stations data and shown in a graph. As the periods with zero flow are the key identifiable hydrological driver of biological communities, investigating the metrics that best characterize the frequency and predictability of these periods is the objective of our third step. Finally, classification of the aquatic regimes of the temporary streams is attempted in the fourth step. The first and second steps follow a logical sequence, but the third and four steps are rather independent although they remain consistent with the first two.

The data used for implementing the methods come from the records from gauging stations at several sites around the European Mediterranean (Fig. 1). Table 1 shows the location and main hydrological characteristics of these sites. These gauging stations are located in streams with discharges that are not influenced by human activities, or only slightly, except for the Vène S station where summer flows are sustained by effluents from urban sewage systems (David et al., 2011). The Vallcebre and Vène streams are research areas where flow data were directly recorded by the teams involved in the MIRAGE project (Latron and Gallart, 2008; Perrin and Tournoud, 2009), whereas the flow data from the other stations were obtained from the respective basin authorities.

The time scale used here is the month, because it is easier to manage and to obtain from records or models and it is presumed sufficient for most ecological applications; data from 10 yr were used, whenever available The spatial scale is the stream reach (50–100 m long), which is the scale of gauging station measurements and usual field observations. The analysis of spatial patterns along stream courses or networks would need the use of distributed field observations or the simulations made with a model designed for this purpose (e.g. Arscott et al., 2010).

2.1 First step: defining the ecologically relevant aquatic states

The aquatic states summarize the set of aquatic mesohabitats occurring on a given reach at a particular moment, depending on the hydrological conditions. From a review of the literature (Hawkins et al., 1993; Gasith and Resh, 1999; Boulton, 2003; Fritz et al., 2006; Lake, 2007) and the expertise of some of the authors (e.g. Rieradevall et al., 1999; Bonada et al., 2006, 2007), the following aquatic states may be defined as relevant in the ecology of temporary stream reaches, in a sequence from the wetter to the drier.

– *Flood*: high-water state occurs when stream water velocity and discharge cause major movement of stream bed alluvium and the drift of most of the aquatic fauna in the reach. In permanent streams, this state would correspond to flow above bankfull discharge, but temporary streams may not show distinct channel banks. Observations of temporary streams suggest that floods cause a strong but short-lived disturbance in aquatic communities (Boulton and Lake, 1992; Lake, 2000; Arscott et al., 2010),

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whereas their occurrence is considered highly relevant to the health of river systems (Junk et al., 1989). This state is not differentiated from the following one neither in the Fritz et al's. (2006) nor in the Boulton's (2003) arrangements.

– *Riffles*: water discharge is high enough to allow the occurrence of all the available aquatic habitats in the reach, including the abundant presence of riffles, allowing optimum hydraulic connectivity between the diverse habitats. This is the habitual state in permanent streams and the one with the wider range of discharges in temporary streams. This state corresponds to the "surface flow continuous (4)" condition defined by Fritz et al. (2006), whereas Boulton (2003) differentiated two intermediate states above or below the critical step of water body "isolation from the littoral vegetation".

– *Connected pools*: water discharge is low but sufficient to connect most pools in the reach through water rivulets. Riffles are absent or limited to scarce rapid flow areas between main pools (Bonada et al., 2006). This state corresponds to the "flow only interstiticial (3)" condition by Fritz et al. (2006), and below the "loss of riffle" Boulton's (2003) critical step.

– *Pools*: surface discharge is close to zero, but a number of water pools remain in the stream bed. If this is alluvial, some sub-surface connectivity of water may occur that allows the preservation of the physico-chemical quality of the water in the pools. If the stream bed is impervious, the pool waters may suffer quality deterioration trends or cycles. The ecological importance of pools remaining after the cessation of flow has been highlighted in many papers (e.g. Boulton, 1989; Buffagni, et al., 2009). This state corresponds to both "surface water present but no visible flow (2)" and 'surface water in pools only (1) conditions defined by Fritz et al. (2006), whereas it is just mentioned but not differentiated from the former one by a critical step in Boulton (2003).

– *Dry*: most of the stream bed is devoid of surface water in the reach, although alluvium may remain wet enough to allow hyporheic life (alluvium water content is higher than the field capacity point). The hyporheic zone may be a refuge for many animals when surface water is absent (Boulton, 1989; Boulton et al., 1998), so it should be considered also as an aquatic mesohabitat. This state is included within the "no surface water (0)" condition defined by Fritz et al. (2006), and below the "loss of surface water" critical step defined by Boulton (2003).

– *Arid*: the entire stream bed is devoid of surface water in the reach and alluvium is dry, impeding active hyporheic life (alluvium water content is lower than field capacity and similar to the surrounding soils in terrestrial locations). Some invertebrates may survive as desiccation-resistant stages in dry substrata for some time (Boulton, 1989). This state is also included within the "no surface water (0)" condition of Fritz et al. (2006), and below the "drying hyporheic zone" critical step of Boulton (2003).

2.2 Second step. Time patterns of occurrence of aquatic states

Although temperature and electrical conductivity of either water or bed sediments may be used for recording the timing of hydrological conditions in the absence of flow (Constantz et al., 2001; Blasch et al., 2003; Fritz et al., 2006), the only information currently available on stream water regimes is from flow discharge records, from either measurements at gauging stations or simulations using rainfall-runoff models. Although in many cases daily flows are available, a monthly time scale (as mentioned above) is proposed for the analysis of the regimes, since it is more easily available from the records and models.

Flow data from a gauging station may be used to obtain the statistics of the occurrence of the wetter aquatic states (flood, riffles, connected, pools), following the procedure shown in Fig. 2 that is made easy to the reader through the use of the ASFG.xls spreadsheet available as Electronic Supplementary Material to this paper. Flow simulations obtained with a rainfall-runoff model may be alternatively used, but as most models will not be able to simulate zero water discharges, the identification of a discharge threshold equivalent to zero will be necessary.

The most critical step of the procedure is the selection of the threshold flow values that separate the occurrence of the diverse aquatic states. This that can be done with the help of the shape of the flow duration curve (distribution function of flow discharges, Fig. 3). To identify these thresholds correctly, field observations on the aquatic states

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synchronous with discharge measurements are needed. However, in the absence of these observations, thresholds can be provisionally estimated by taking into account the width and regularity of the stream bed reach near the gauging station.

The aquatic state corresponding to minimum recorded discharge values (close to zero) depends on the design of the gauging station and the characteristics of the reach. For reaches over alluvial sediments with gauging stations designed to impede sub-surface flow below them, very low flow may be expected to correspond approximately to the threshold between *dry* and *pool* aquatic states. In contrast, for stream reaches over impervious bedrock or alluvial ones with gauging stations allowing the bypass of sub-surface flow, minimum recorded flow may be expected to represent the threshold between *pool* and *connected* states. Consequently, discharge data cannot be used to derive information on the occurrence of the *arid* aquatic state in the first case and of the *dry* and *arid* aquatic states in the second case. Once the discharge thresholds between aquatic states are defined, they are used to convert the table of monthly discharges into the tables of occurrence of these aquatic states.

Then, the long-term monthly frequencies obtained for the diverse aquatic states are obtained and plotted on an Aquatic States Frequency Graph (ASFG), with the frequencies accumulating from drier to wetter states for every month. In this study, data from 10 yr of daily flows were used, whenever available. Figure 4 shows the examples of ASFGs obtained for the various study sites. The discharge threshold values between aquatic states were estimated without field observations, using the expertise of the authors, and minimum measured flows were taken as the threshold between *dry* and *pool* states in the interim.

2.3 Third step: metrics for characterizing the aquatic regime in temporary rivers

The ASFG method given above allows appraisal of the aquatic regime of the reach, as it describes the mean annual prevalence and timing of aquatic states for a stream reach by month. Nevertheless, the displayed information is too complex to be synthesized in a few metrics, and it depends on the selection of flow thresholds.

To circumvent these limitations, from the original discharge information we selected the metrics that synthesize the two main parameters that are relevant to river ecology: the duration and predictability periods with flow. Many studies are devoted to characterizing the flow regime of streams for ecological or management purposes with diverse metrics, but most of these metrics are conceived for permanent flow. For example, the Richards-Baker flashiness index (Baker et al., 2004) assigns zero flashiness values during the periods without flow because there is no change in the discharge values within them; subsequently but inconsistently, the longer the annual period without flow in a stream, the less flashy its regime is. In the present study, only metrics focusing on the analysis of the statistics of the cessation of flow were considered, as this is the only flow discharge feature directly linked to some major change in the aquatic states available from flow records. It may be hypothesized that the cessation of flow is the key feature defining the aquatic regime in a temporary stream (Boulton, 1989), and therefore the statistics of its metrics will summarize the main characteristics of the regimes of its aquatic states, seen in its ASFG.

The relative time with or without water flow is usually the metrics used for identifying temporary streams (e.g. Hedman and Osterkamp, 1982; Hewlett, 1982). Among regional flow regime studies, Poff (1996), in a widely used approach, employed only the mean number of days with zero flow per year; and Kennard et al. (2010) used both the mean and the coefficient of variation of the number of days with zero flow per year, although there are no studies analysing the ecological significance of this latter metric. In an ecological study of a single stream in New Zealand, Arscott et al. (2010) characterised the aquatic regime at several points by using flow permanence (long-term annual average of the percentage of time a given site had flowing water), flow duration (days of flow at a site prior to each sample date) and drying frequency (average number of drying transitions per year). Arscott's results showed that flow permanence and duration correlated closely, with the former being a good predictor of ecological features (see also Larned et al., 2010).

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From these studies, it can be concluded that two metrics deserve to be retained for further investigation here: a measurement of flow permanence (a concept less ambiguous than flow duration), as the long-term mean annual relative number of months with flow, Mf (taking values between 0 and 1), and the drying frequency Df, as in Arscott et al. (2010).

As well as these flow permanence and drying frequency metrics, several authors point to the relevant ecological role of the predictability of wetting or drying periods, because this predictability allows the development of taxa specialized in living in temporary conditions (e.g. Williams, 2006; Wissinger et al., 2008). As no specific suitable metrics were found in the literature, the predictability of the zero-flow periods was analysed using the P, C and M predictability metrics of Colwell (1974), and a new measurement, seasonality of drying (Sd_6), was developed.

Colwell (1974), on the basis of Shannon's entropy, defined three metrics adequate for analysing the periodicity of the qualitative states of a system. These metrics were first defined on the basis of monthly system states for analysing seasonal periodicity during the year, but other time scales may be used. Following this author, seasonal predictability (P) of the monthly states of a system may be attained by two separable additional components: constancy (C), a measurement of state permanence, and contingency (M), a measurement of the repeatability of the time pattern in successive years. Here, the two system states considered are zero and positive values of discharge in the records of the gauging stations.

In addition to these metrics, the six-month seasonal predictability of dry periods (Sd_6) defined in Eq. (1) is here proposed as a new metric for characterizing the seasonality of the dry (zero-discharge values) conditions on a stream reach:

$$\mathrm{Sd}_6 = 1 - \left(\sum_1^6 \mathrm{Fd}_i / \sum_1^6 \mathrm{Fd}_j \right) \tag{1}$$

where Fd_i represents the multi-annual frequencies of 0-flow months for the contiguous 6 wetter months of the year and Fd_j represents the multi-annual frequencies of 0-flow

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months for the remaining 6 drier months. Wet and dry 6-month periods mean here those with fewer and more zero-flow frequencies, respectively. The calculation of this metric is also made easy to the reader through the use of the ASFG.xls spreadsheet available as Supplement to this paper.

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. It is worth stating that Sd_6 is defined at the 6-month scale, whereas the Colwell (1974) metrics were applied at the monthly scale.

The redundancy between these six metrics (Mf, Sd_6, Df, P, C and M) was analysed by calculating the linear correlation coefficients when applied to the eight basins studied here (Table 2). All three of Colwell's (1974) predictability metrics (P, C and M) correlated significantly with flow permanence (Mf) and the first two correlated negatively with drying frequency (Df), whereas Sd_6 only correlated significantly with predictability (P). Indeed, a factor analysis (maximum likelihood factors method) built with this correlation matrix showed that two factors explained 89 % of variance, in which Mf, Df, P, C and M metrics had high absolute loads in the first factor, whereas only Sd_6 had a high load in the second factor (Table 3). The possible role of the time scale in the use of P, C and M metrics was analysed by calculating them on the same 6-month periods used for the Sd_6 metric; the resulting 6-month values had correlation coefficients higher than 0.98 with the monthly values, showing that negligible information was added with this change of scale.

As a result of these tests, only flow permanence (Mf) and the seasonal predictability of dry periods (Sd_6) were selected for the subsequent analyses. The former (or its conversion into the number of days with zero-flows) has been widely used and found to be significant for explaining the aquatic fauna, whereas the latter is the more orthogonal of the metrics tested and is easy to put in plain words in interviews when instrumental information is not available. This does not mean that the other metrics tested might not

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be useful for deeper analyses or for the investigation of aquatic regimes in other types of climate.

2.4 Fourth step: classifying temporary stream aquatic regimes

Although the ASFG and regime metrics shown in the preceding sections are deemed sufficient for analysing and comparing temporary stream regimes, a classification of temporary streams within the perspective of the present paper is necessary for operational purposes, as different stream regimes will need different sampling strategies and standards for defining the biological quality of stream waters (e.g. Bond and Cottingham, 2008), which is one of the most important objectives of the MIRAGE project. Although there is some agreement on the main terminology for classification of temporary stream regimes, the criteria used to establish the limits between the regime classes vary between different authors (Rossouw et al., 2005; Levick et al., 2008). On the basis of the above considerations and the classifications proposed by Uys and O'Keeffe (1997) and Boulton et al. (2000), four main conceptual types of streams were defined by the MIRAGE project in function of the controls imposed by the time patterns of occurrence of aquatic mesohabitats on biological communities and their relevance for monitoring purposes:

P (permanent or perennial): no relevant recurrent controls imposed on biological communities by lack of flow. Monitoring methods have already been defined (e.g. Hering et al., 2006).

IP (intermittent-pools): stream's aquatic regime allows every year the development of biological communities similar to those in permanent streams, but after the wet season flow is discontinued and only pools with impoverished communities remain. Ecological quality may be assessed as for permanent streams, though the biological sampling calendar may need adaptation to the hydrological regime. Sampling has to be done during the period with the more persistent flow.

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ID (intermittent-dry): streams usually cease to flow and dry out in summer, but in the wet season biological communities similar to those of permanent streams can be found, even if these may vary from year to year. Biological quality assessment needs to be measured with specific biological metrics somewhat different than those of permanent streams and (very important) a calendar adapted to the hydrological regime.

E (episodic-ephemeral): water flow and pools are short-lived and occasional. Therefore, most of the organisms found are opportunistic, adapted to a quick development of their biological cycle. Biological quality assessment needs other methods beyond the customary study of aquatic fauna (e.g. desiccation-resistant stages of aquatic fauna or terrestrial fauna).

As defined above, the classification of a stream reach in this scheme would need the analysis of its aquatic biology, in non-impacted water quality conditions, under diverse aquatic states and in comparison with other streams in the region (Reference approach, Bailey et al., 2004). Research is ongoing within the MIRAGE project to define the threshold values of the hydrological metrics defined in the former section for operationally classifying a stream reach on the basis of the statistics of zero-flow occurrence, and some interim trials were attempted in the Results section. The definition of these thresholds would allow the operational use of this classification for assisting the biological sampling strategy, as well as the interpretation of the biological communities found in terms of the ecological quality of the stream waters.

3 Results

Once the interim water discharge threshold values between the aquatic states were assessed, ASFGs for the eight gauging stations were obtained, as shown in Fig. 4. The relative importance of wet and dry states throughout the year and the degree of seasonality of the regime may be assessed at a glance from these graphs. These simple criteria were used to order the graphs in the figure, placing the wetter basins at the top and the more seasonal ones on the right-hand side.

The results obtained with the metrics of flow permanence, Mf, and seasonal predictability of dry periods, Sd_6, are shown in Fig. 5. Here, the stations with the highest flow permanence are located on the right and those with higher seasonal predictability at the top. The boundaries between the regime types are tentative, because more sites should be analyzed.

The wetter streams, Rambla Minateda and Vène at station S, are both at the outlets of karstic systems and have near-permanent regimes. Nevertheless, the Vène stream undergone occasional dry periods in some summers, whereas, in the Rambla de Minateda, dry periods were more scattered throughout the year. Therefore, the respective Sd_6 metrics had different values for these streams and are clearly separate in Figure 5. The aquatic communities found in these streams should be no different from those living in perennial streams in the region (*Permanent* type).

At Vallcebre, the regime followed the equinoctial regime of precipitation: flow is more frequent in spring, whereas floods occur mainly in autumn and droughts may be scattered over 9 months of the year. The Evrotas stream showed somewhat higher flow permanence and a more regular seasonal pattern, with a higher value in the Sd_6 metric in Fig. 5. It may be expected that the aquatic communities in both streams will be similar to those in perennial streams (*Permanent* type), whereas at Vallcebre the communities might be expected to be temporarily affected by the cessation of flow and eventually by the complete drying of the stream, but expected to be similar to those living in perennial streams if sampled sufficiently after the scarce dry periods (*Intermittent-pools* type).

Both the Manol and Celone streams had similar flow permanence, but the graph in Fig. 4 shows much greater regularity for the Celone stream, where continuous flow normally occurs from January to April. Indeed, the Celone stream had higher seasonality, as shown by the higher value of the Sd_6 metric in Fig. 5. It is worth noting that the features shown for the Manol stream in Fig. 4 and the low Sd_6 metric are linked to the occurrence of some sporadic periods of flow every year but with irregular seasonal organisation in diverse years (low predictability). This may also be seen by analysing the drying frequency Df metrics for these streams, which gives 1.17 annual drying sequences for the Manol, but only 0.92 for the Celone. The characteristics of the aquatic communities living in these stream reaches may be expected to differ in spite of the similar value of their flow permanence. Indeed, as habitat conditions are very predictable in the Celone stream, during the wet season (from December to May) aquatic fauna are likely to be similar in richness and variety to those in perennial streams (*Intermittent-pools* type). On the contrary, as aquatic habitats are much less predictable in the Manol stream, aquatic fauna living in this stream are likely to be always less abundant and diverse, yielding low values of the biological metrics due to the hydrological constraints (*Intermittent-dry* type).

Finally, both the Vène stream at station K and the Cobres stream show the lowest frequency of flow occurrence, although the Cobres stream had higher predictability of flow (during winter), as shown in Fig. 4, and a much higher value of the Sd_6 metric, as shown in Fig. 5. This difference is also shown here by the drying frequency Df metrics, which is as high as 1.63 for Vène at station K, but only 0.95 for the Cobres. As in the former example, the characteristics of the aquatic fauna living in these streams are likely to differ because of the large difference in habitat predictability: the aquatic communities living in the Cobres stream may be well adapted to a dry but predictable regime (*Intermittent-dry* type), whereas those living in the Vène K are expected to be rather opportunistic (*Ephemeral* type).

4 Discussion

4.1 Stream regime analysis

In spite of the difficulties in working out the limits between the aquatic states defined above, the interim assessment of the flow thresholds used for the ASFGs and the use of the flow permanence Mf and seasonal predictability of dry periods Sd_6 metrics

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provided a clear and nuanced analysis of the establishment of aquatic regimes that were relevant for ecological and management purposes on the gauged reaches. When more field information is available on the threshold discharges that define the aquatic states on these reaches, the boundaries between states may be refined in the ASFGs, but their general shape will not change much because they are driven by the statistics of the objective zero flow values.

The analysis of the ASFG suggests that the duration of the states might be calculated for every month. However, as this graph is a long-term probability analysis, the actual duration (in a given year) must be analysed directly from the data series using other metrics. Here, although only the mean annual frequency of drying transitions Df has been tested, other annual or monthly metrics might be useful to characterize the statistics of periods with or without flow. Indeed, at the test gauging stations the two metrics on flow permanence and predictability were sufficient to characterise and compare the aquatic regimes. However, if this kind of analysis is to be applied to temporary streams in other climates, some other metrics may be needed such as the timing of the drying period if its predictability is high.

Nevertheless, since most temporary streams are ungauged or poorly gauged, the methodology described above will be applicable to the relatively rare existing records from gauging stations. Rainfall-runoff models may be used to obtain simulated flow series for many sites at the monthly scale used, but there are two main difficulties: first, most models will not be able to simulate zero water discharges, so the identification of a discharge threshold equivalent to zero will be necessary to use the above-defined metrics (see also Kirkby et al., 2011); and second, simulated values will be natural ones not actual ones if these are affected by human activities.

Beyond the use of flow data and models, the permanence of flowing water in headwater streams has been operationally estimated from field surveys or topographic map data (Svec et al., 2005; Fritz et al., 2008). The presence of water at the pool scale has also been monitored by using temperature or electrical conductivity observations (Constantz et al., 2001; Blasch et al., 2002; Fritz et al., 2006) or, at the basin scale, remote

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sensing (Marcus and Fonstad, 2008). The estimates of flow permanence obtained through some of these methods might be used to find the zero discharge threshold of a model. Furthermore, the relatively simple meaning of the Mf and Sd_6 metrics may also allow the operational classification of a stream's aquatic regime assessment from interviews with people living near the streams.

Unfortunately, the drier aquatic states, particularly the *arid* state, cannot be suitably analysed from flow discharge records or simulations. The statistics of these states need other types of data beyond the water discharges usually measured or modelled in scientific or operational hydrology. Nevertheless, the examination of the ASFG may provide some insight into the possibilities of occurrence of these states over the course of the year and, when seasonality is high, it shows when pool occurrence or alluvium moisture needs to be tested for their recognition.

4.2 Ecological implications

As the six aquatic states and the subsequent analyses developed above were designed on the basis of preceding ecological studies in temporary waters, they can be expected to be useful for analysing the controls of the aquatic regime in the aquatic biological communities.

The first results obtained in the European MIRAGE project do indeed suggest this. Table 4 gives data on biological community metrics obtained with the methods described in Garcia-Roger et al. (2011) which are similar to those used at pan-European scale (Buffagni et al., 2006). The resulting biological water quality metrics are provided for four streams currently investigated in the MIRAGE project. Three of them have high flow permanence Mf and seasonality Sd_6 values (Vallcebre, Vène S station and Evrotas). Compared with permanent streams in the same area, their biological community metrics do not deviate very much in the wet period (i.e. spring). On the contrary, the Vène K stream, which has much lower values in the two metrics (see Fig. 5), would be classified as of poor ecological quality using the biological standards developed for permanent streams, in spite of its near-pristine quality. The low ecological values observed at Vène S station in spite of its favourable regime are attributed to the fact that, as shown by chemical analyses, the water quality of this reach is highly disturbed because of the spill of effluents from urban waste water treatment plants (David et al., 2011).

These methods described above offer the possibility of extending the biological methods used in permanent streams to the range of temporary stream types if an adequate definition of the sampling period is made. The recovery of the community is highly dependent not only on the duration of the dry period, but also on the predictability of such a period over years. However, if flow is present in the wet period for several months (usually spring), riffles offer the opportunity to measure biological quality using macro-invertebrates (Rose et al., 2008). Nevertheless, the time of sampling must be determined by the hydrological conditions rather than the time of year because, as demonstrated by Munné and Prat (2011), wet summers and springs give higher values of metrics than dry springs do. Therefore, the moment when the sample is taken is crucial in establishing ecological status and should not be linked to a specific time of the year, but to a specific condition of the hydrograph. This was a key issue in the MIRAGE project and data in Table 4 were collected following this rule. From these data and the works of Rose et al. (2008) and Munné and Prat (2009), we can conclude that in temporary streams, if samples are taken at the appropriate stage of the hydrograph (after flow has resumed in the stream and been present in it for at least a month), ecological status may be measured by the same methods as in permanent streams if the values of the Mf and SD_6 metrics are rather high. Despite the fluctuations in community assemblages described in Feminella (1996), Bonada et al. (2006, 2007) and Bêche and Resh (2007) and despite the changes from riffle-dominant species (EPT) to pool-dominant species (OCH), consistency of ecological status may be measured in both riffle-dominant and connected-pool conditions (Bonada et al., 2007; Rose et al., 2008).

Nevertheless, in streams with low flow permanence Mf and/or low seasonal predictability Sd_6, such as the Vène at K station, the hydrological controls on biological communities are so high that the ecological quality must be measured using either

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standards particularly designed for them or other alternative methods (e.g. desiccation-resistant stages of aquatic fauna, terrestrial fauna, riparian environment...).

Researchers with data on biological water quality metrics in temporary streams are invited to test the methods described above, in order to investigate how temporary stream aquatic regimes control aquatic fauna. The preparation of the Aquatic States Frequency Graph and the calculation of the Mf and Sd_6 metrics from flow data may be made through the use of the ASFG.xls spreadsheet available as Electronic Supplementary Material to this paper.

Supplementary material related to this article is available online at: http://www.hydrol-earth-syst-sci-discuss.net/8/9637/2011/ hessd-8-9637-2011-supplement.zip.

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Table 1. Main characteristics of the studied basins. Catchment area in km^2; MAP= mean annual precipitation (mm); ETP= mean annual reference evapotranspiration (mm); MAR= mean annual runoff (mm).

Operational basin	Stream	station	Catchment area	MAP	ETP	MAR
Thau lagoon	Vène	Karst (K)	1.4*	668	1336	590*
Thau lagoon	Vène	Sanglier (S)	35	668	1336	332*
Candelaro	Celone	S. Vincenzo	85.8	723.6	1024	176
Guadiana	Cobres	Entradas	51	500	1080	116
Segura	Minateda	Minateda	1166*	316	770	9.6*
Llobregat	Vallcebre	Can Vila	0.56	823	862	260
Muga	Manol	Santa Llogaia	163	748	794	118
Evrotas	Evrotas	Vrontamas	2418*	802	980	47*

* Karstic areas with uncertain real groundwater recharge area.

Table 2. Linear correlation coefficients between the metrics tested to analyse the statistics of zero flow periods in the basins studied.

	Mf	Sd_6	Df	P	C	M
Mf	1	0.50	**−0.82**	**0.77**	**0.89**	**−0.74**
Sd_6	0.50	1	**−0.72**	**0.80**	0.58	0.11
Df	**−0.82**	**−0.72**	1	**−0.95**	**−0.92**	0.45
P	**0.77**	**0.80**	**−0.95**	1	**0.93**	−0.38
C	**0.89**	0.58	**−0.92**	**0.93**	1	−0.69
M	**−0.74**	0.11	0.45	−0.38	−0.69	1

Values in **bold** are significant at the $p < 0.05$ level.

Table 3. Maximum likelihood factor loadings of the metrics analysed in Table 2.

Metrics	Factor 1	Factor 2
Mf	**−0.8799**	0.1570
Sd_6	−0.3221	**0.8316**
Df	**0.7727**	−0.53456
P	**−0.7424**	0.6278
C	**−0.9200**	0.31658
M	**0.8765**	0.4599

Figures in **bold** show absolute loadings > 0.7.

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Table 4. Community and biological water quality metrics for macro-invertebrates at several sites studied in the MIRAGE project. S = number of taxa; EPTtax = number of families of Ephemeroptera, Plecoptera and Trichoptera; OCHtax = Number of families of Odonata, Coleoptera and Heteroptera; H' = Shannon-Wiener diversity Index. IBMWP, IASPT and IMMi-T indexes are biological quality indexes expressed in EQR. Data from García-Roger et al. (MIRAGE internal report).

Sites	S	EPTtax	OCH tax	H'	Evenness	IBMWP	IASPT	IMMi-T
Vallcebre	28	10	5	1.67	0.50	0.73	0.71	0.88
Vêne S	7	0	0	0.84	0.60	0.04	0.00	0.02
Vêne K	4	0	0	0.41	0.21	0.09	0.11	0.08
Evrotas	21	8	5	1.65	0.64	0.58	0.78	0.81

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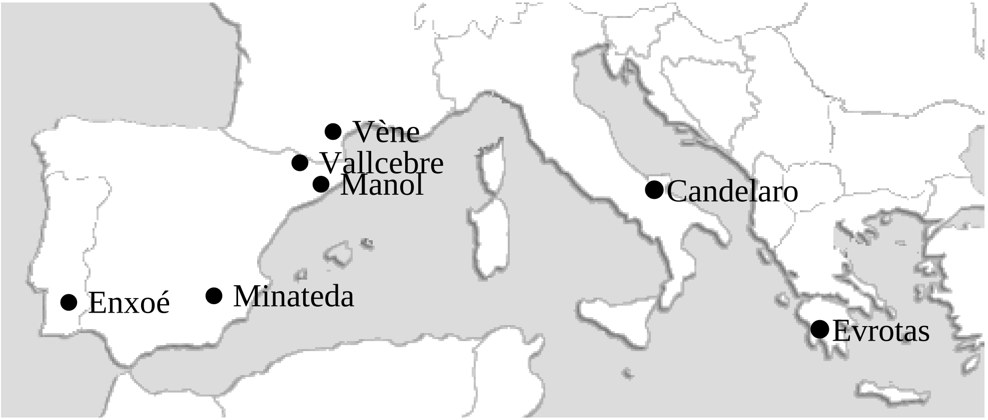

Fig. 1. Location of the streams studied.

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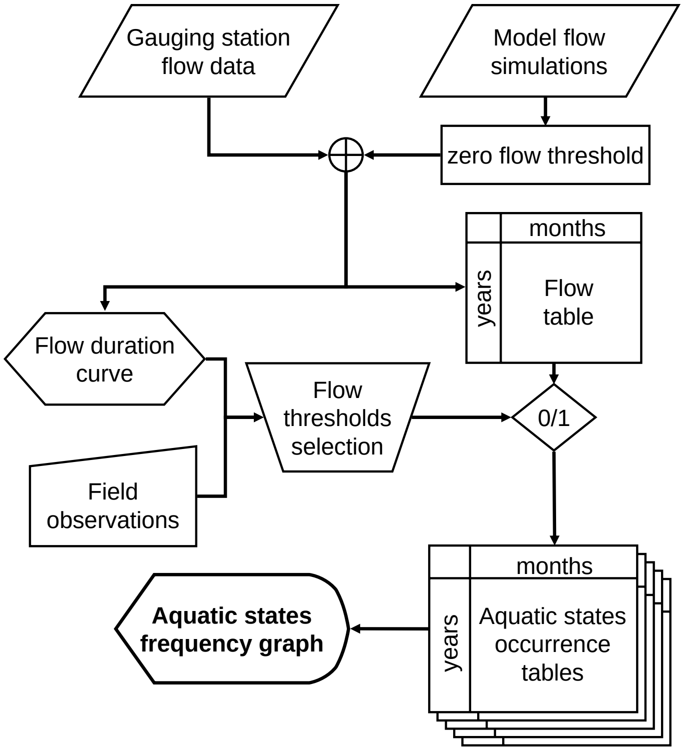

Fig. 2. Schematic flow chart for the procedure developed to estimate the temporal patterns of occurrence of the aquatic states from the available water flow data. The final products are the aquatic states frequency graphs (Fig. 4).

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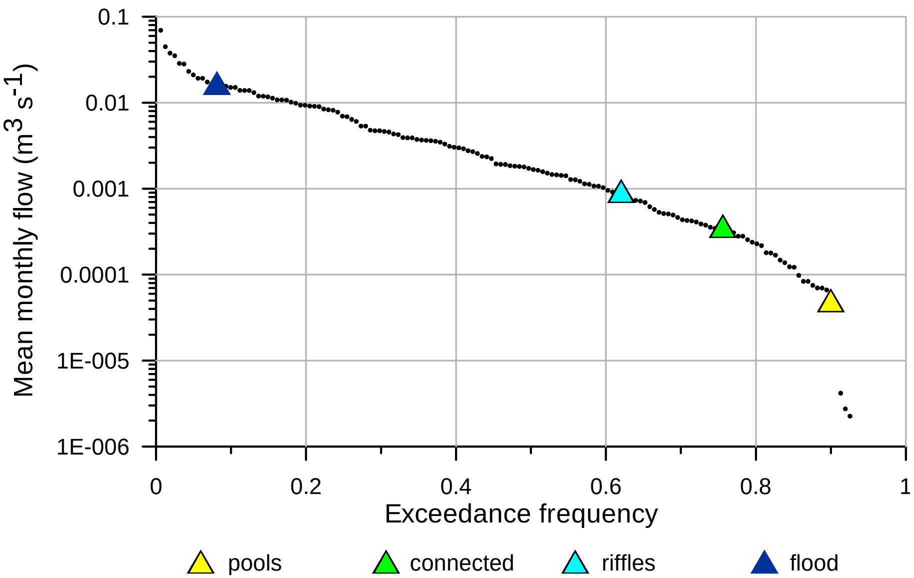

Fig. 3. Flow duration curve for the Can Vila station, with identification of the minimum discharge thresholds that separate the diverse aquatic states.

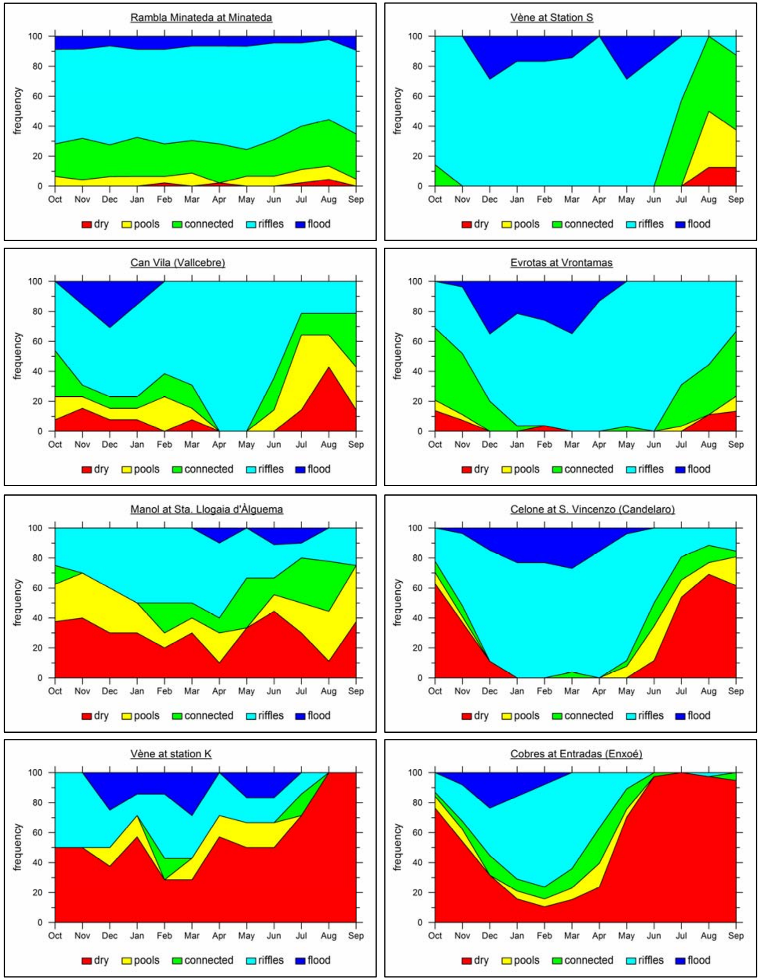

Fig. 4. Aquatic states frequency graphs for the eight stream gauging stations studied.

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The regimes of temporary streams and their controls on aquatic biota

F. Gallart et al.

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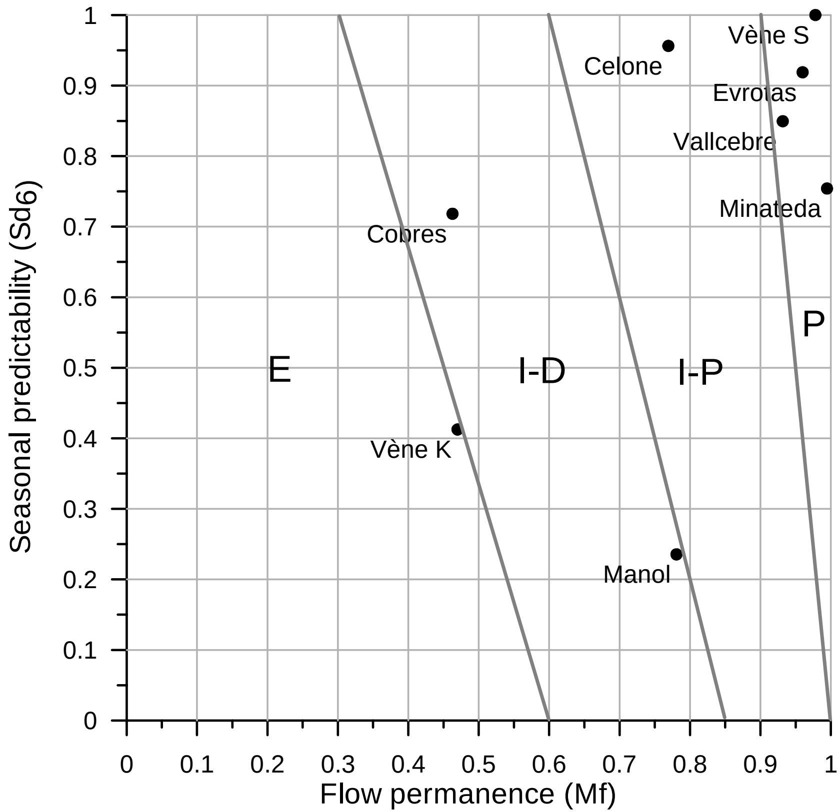

Fig. 5. Plot of the stations studied using the two metrics tested: Flow permanence (Mf) and seasonal predictability of the zero-flow months (Sd_6). The oblique grey lines show the approximate interim separation between the four regime types: *P* (*Permanent*), *I-P* (*Intermittent-pools*), *I-D* (*Intermittent-dry*), *E* (*Episodic-ephemeral*).

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