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Fuirosos stream (NE Iberian Peninsula): for how much longer?

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ABSTRACT

Fuirosos stream (NE Iberian Peninsula): for how much longer?

This paper describes the hydrology of Fuirosos a small intermittent stream draining a forested catchment located close to Barcelona (NE Iberian Peninsula) that has been intensively studied over the last 20 years. Discharge regime at Fuirosos is strongly related to the precipitation regime and showed, during the entire study period, a significant decrease, at a rate of -0.4 L/s/y which represents 1.3 % of the estimated average discharge. Further, drought duration is lengthening at a rate of 1.9 d/y, mainly as a consequence of delay of the rewetting phase. Overall, if these trends continue at their current rates, Fuirosos will be converted into an ephemeral stream during the second half of this century. Fuirosos is at the center of an intense research activity focused on the ecology of this aquatic ecosystem. Research topics range from measuring microbial processes in sand sediments to analyzing solute responses under extreme flow conditions (flood and droughts), including metabolism measurements, nutrient retention balances, macro-benthos diversity and leaf inputs in stream reaches or water/solute exchange at the stream-hyporheic interface. Most of these studies revealed that its ecology is related unequivocally to the hydrological regime. Accordingly, the second part of the present work summarizes and reviews these ecological and biogeochemical studies.

Key words: stream hydrology, intermittency, droughts, high flows, temporal series

RESUMEN

El arroyo de Fuirosos (NE de la Península ibérica): ¿Por cuánto tiempo?

Este artículo describe la hidrología de Fuirosos, un pequeño río intermitente que drena una cuenca forestada cerca de Barcelona (NE de la Peninsula Iberica) intensamente estudiado durante los últimos 20 años. El caudal de Fuirosos está estrechamente vinculado a las precipitaciones y muestra un decremento significativo a una tasa anual de -0.4 L/s que representa un 1.3 % del caudal promedio. Además, la duración de los periodos secos, sin escorrentía superficial, se están extendiendo a una tasa anual de 1.9 días principalmente a causa de un retardo del retorno de la escorrentía superficial. Si estas tasas siguen al ritmo actual, Fuirosos se convertirá en un río efímero en la segunda mitad de este siglo. Fuirosos está en el centro de una intensa actividad de investigación en ecología de los ecosistemas acuáticos. La investigación cubre numerosos temas que oscilan entre estimas de procesos microbianos en sedimentos hasta el análisis de las respuestas de solutos durante eventos hidrológicos extremos (crecidas y sequías), pasando por medidas metabólicas, balances de nutrientes, diversidad de macrobentos, estimación de inputs de hojarasca, intercambio de nutrientes entre el río y los sedimentos hiporeicos. Estos estudios inciden en la importancia de la hidrología en el funcionamiento de este ecosistema. La segunda parte de este trabajo hará una revisión del conjunto de todas estas investigaciones.

Palabras clave: *hidrología fluvial, intermitencia, sequía, crecidas, series temporales*

INTRODUCTION

This paper focuses on Fuirosos: a small intermittent stream in the Mediterranean region which has been the subject of intense ecological and biogeochemical research since 1998. I will first describe its hydrology and I'll summarize and review these studies and its relevance to fluvial ecology, especially that focused on intermittent and ephemeral lotic systems (hereinafter IRES).

IRES are an expanding research topic in fluvial ecology/biogeochemistry. This interest is undoubtedly motivated by the countless threats facing all lotic systems: climate change, water withdrawal, land use changes, contamination and biodiversity alteration (IPPC, 2013). These threats are amplified in water-limited systems, such as those located in densely populated Mediterranean basins, providing a sound argument for their study. However, IRES per se present attractive research potential. The simple fact that discharge follows acute wet-dry cycles and that it can increase by several orders of magnitude (i.e., from less than 1 L/s to > 1000 L/s) in a few hours, offers the opportunity to test an array of fundamental themes related to the hydrological, biogeochemical and ecological functioning of lotic ecosystems. These include, resilience-resistance of ecosystems (Hershkovitz & Gasith, 2013), fluvial network longitudinal connectivity (Wohl *et al.*, 2018), interactions with terrestrial systems (D'Odorico *et al.*, 2010), ecotone boundaries (Decamps *et al.*, 1990) and the passive-reactive dualism of riverine “pipes” (Cole *et al.*, 2007).

Fluvial ecology and biogeochemistry research have been undertaken at Fuirosos over the last 20 years, and in the expanding field of IRES research, it is considered a reference site for scientists. For instance, a photo of its dry stream bed is frequently used in publications that highlight the need to study, protect or manage IRES across the world (Acuña *et al.*, 2014; Steward *et al.*, 2013; Merçé *et al.*, 2018). It is, however, important to note that eco-biogeochemical research spread over almost two decades is not synonymous with long term-monitoring. Studies performed at Fuirosos have covered a broad spectrum of ecological and biogeochemical topics. Most of these studies were short-term researches that lasted from a few weeks to a few months and those that integrated observations over 1 to 4 years have been much less frequent.

In short, I consider Fuirosos a research area that undoubtedly catalyzed extended and important eco-biogeochemical research, but it cannot be categorized as a long-term monitoring study area because long-term sampling (larger than the decadal scale) is unfortunately limited to just a few variables (i.e., hydrology, dissolved organic carbon, nitrate, chloride and sulfate). These add up to only a small portion of the numerous key environmental and biogeochemical descriptors that an exhaustive long-term monitoring plan for a catchment area should include.

Executing long-term monitoring, on a decadal scale, in a small intermittent headwater stream characterized by abrupt, short and erratic high flows and large droughts of unpredictable duration, is not an easy task. For instance, whatever the duration, a long–term sampling based on monthly sampling frequency is inadequate to capture and describe the hydrological flashiness of small streams (Butturini, 2005) or to relate it to a biogeochemical descriptor (Kirchner *et al.*, 2004). At Fuirosos, the biogeochemical sampling intervals have ranged from hourly to weekly, starting in late 1998 (with a break from 2003 to 2005). Since 2016, the biogeochemical sampling has been restricted to dissolved organic carbon (DOC) and nitrate and takes place at weekly intervals. Although the chemical sampling frequency is not strictly “high” (Kirchner *et al.*, 2004), the long-term monitoring has included biogeochemical variables collected at high-moderate sampling frequency for almost 20 years. To the best of my knowledge, there have been only two hydro-biogeochemical temporal study series of comparable length in the Iberian Peninsula: la Castanya stream, at Montseny mountain (focused mainly on geochemistry and nitrate, Avila & Rodà, 2012), and Vallcebre Research Catchments (focused mainly on hydrology and sediment transport, Llorens *et al.*, 2018).

This text has two parts. The first, part describes in some detail its hydrology; unavoidably, the most relevant driver for almost all ecological-biogeochemical parameters studied at Fuirosos. More specifically, I will describe the changes in discharge from 1998 to 2017. I anticipate that discharge is decreasing, which is nothing new. This trend has already been recognized in dozens of rivers in the Iberian Peninsula (see below for references). Thus, the question that arises is: is the discharge decrease rate similar to that reported in the literature? There is no easy answer. The decrease of discharge in Iberian rivers has been quantified by analyzing the discharge regimes of large lotic systems affected by climatic and anthropogenic multiple stressors (damming, water abstraction/derivation). It follows that the discharge decreases in streams almost free from local human impacts is expected to be smaller. On the other hand, the Fuirosos catchment area is far smaller than that of large rivers. Therefore, it should be much more sensitive to climatic alterations than large rivers (Sponseller *et al.*, 2013). Either way, decreasing discharge at Fuirosos invites the attempt to predict when it will be converted into a "ghost stream". Thus, the title of this work: Fuirosos as a lotic system. For how long?

In the second part of this work I aim to provide a global view of the research activity at Fuirosos and its impact on research in IRES. Further, I will assess whether Fuirosos still represents an attractive study area for environmental scientists. In short: research at Fuirosos; past, present and for how much longer?

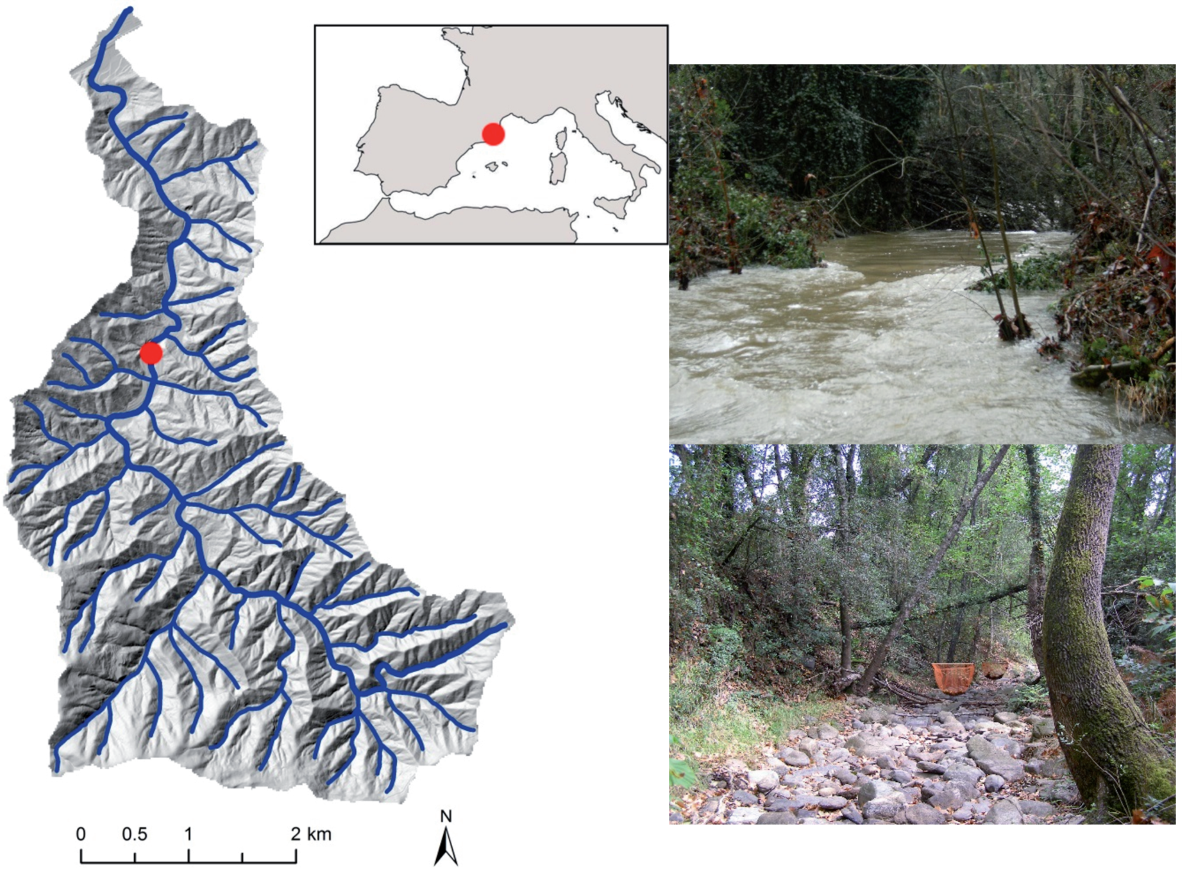

Figure 1. On the left: The Fuirosos catchment and its drainage network (blue lines). The red dot shows the location of the long-term sampling site. On the right: two photos of Fuirosos during high flow and drought (note the orange baskets for collecting the organic matter inputs from riparian vegetation). *A la izquierda: La cuenca de Fuirosos con su red de drenaje (líneas azules). El punto rojo indica la posición del punto de muestreo a largo plazo. A la derecha: dos fotografías del arroyo durante una crecida y el periodo seco (las cestas de color naranja sirven para recolectar la hojarasca de la vegetación de ribera que cae en el lecho fluvial).*

MATERIALS AND METHODS

Study area

Fuirosos drains a granitic catchment of 17 km^2 located in the northeast of the Iberian Peninsula (41º 42' N; 2º 34' E). The catchment is not a remote site and its peculiarity rests on its geographical context, because it is a small almost undisturbed catchment inside a large and highly densely populated area (Barcelona metropolitan area is less than 30 km away) (Fig. 1).

Fuirosos is a small tributary of la Tordera, a river that drains directly into the Mediterranean Sea. The catchment has an elevation of 50 m to 700 m a.s.l. The main stem is 10 km long. The drainage density of the active channel is approximately 0.6 km^{-1}. The catchment is heavily incised, with river network incision density approaching 25 km^{-1} (Sala, 1982). The stream is not totally free of retention structures: there is a reservoir (nominal capacity: 45 10^3 m^3, however, about the 50 % is filled with sand sediments) located 6 km from the river mouth. This reservoir was built in the 1950s for irrigation. At present, it is unmanaged and is maintained for fire prevention activities.

The climate is typically Mediterranean, with winter and summer temperatures averaging 7 ºC and 22 ºC, respectively. Annual precipitation shows marked interannual oscillations and ranges between 400 mm and 1000 mm. Rainy periods are typically in fall and spring. In summer, high temperatures and low precipitation determine acute dry periods. In essence, Fuirosos is a typical intermittent stream with a wet period with running waters from October/November to June/-July and a no flow phase from July to September (more details appear in the sections following).

The catchment is densely forested (90 %) with the presence of some agricultural fields along the stream edges. Most of these are uncultivated, however, they are plowed periodically for fire prevention. Cork oak (*Quercus suber*) and pine tree (*Pinus halepensis*) are the main forest trees. Chestnut (*Castanea sativa*), hazel (*Corylus avellana*) and oak (*Quercus pubescens*) are located at the highest elevations. Alder (*Alnus glutinosa*) and plantations of plane tree (*Platanus hispanica*) are the main riparian trees. However, *Robinia pseudoacacia* is expanding, especially along the riparian strip and agricultural field boundaries.

Details about its biogeochemistry follow in the next section. Table 1 gives an overview of the range of variation of the most studied biogeochemical variables.

Statistical analysis

This work describes the hydrological regime at Fuirosos from fall 1998 to summer 2017, with

Table 1. Range of variation of several physical, ecological and biogeochemical parameters measured in stream water in different studies. Reported values are from the literature cited in the text. SUVA$_{254}$, E2:E3, HIX, BIX and FI are dissolved organic matter optical parameters (there are no dimensional parameters, except SUVA$_{254}$). These parameters provide qualitative information about origin (FI), aromaticity (SUVA$_{254}$), humification degree (HIX), freshness (BIX) and relative molecular size (E2:E3) of dissolved organic matter. *Rangos de variación de diferentes parámetros físicos, ecológicos y biogeoquímicos medidos en Fuirosos. Los rangos se han obtenido de la literatura citada en el texto. SUVA$_{254}$, E2:E3, HIX, BIX y FI son parámetros que describen características ópticas de la materia orgánica disuelta. Estos parámetros ópticos (son adimensionales, con la excepción del SUVA$_{254}$) aportan información relativa al origen (FI), aromaticidad (SUVA$_{254}$), nivel de humificación (HIX), nivel de degradación (BIX) y tamaño relativo (E2:E3) de la materia orgánica disuelta.*

Variable	Range
photosynthetically active radiation (PAR)	10-60 mE m/s
Benthic organic matter	5-410 gC/m^2
Benthic Chlorophyll	3-15 mgChl-a/m^2
Gross primary production	0.1-1.9 gO_2 m^{-2}d^{-1}
Ecosystem respiration	0.4-32 gO_2 m^{-2}d^{-1}
Benthic invertebrate biomass	0.2-2.5 gAFDM/m^2
Electrical conductivity	200-450 µS/cm
pH	6-7.5
O_2	10-100% sat
Cl^-	15-40 ppm
SO_4^{2-}	4-25 ppm
$N\text{-}NO_3^-$	<2.5 ppm
$N\text{-}NH_4^+$	0.02-0.3 ppm
Total dissolved P	<0.04 ppm
DOC	2-25 ppm
DON	0.2-3 ppm
DOM optical properties	
SUVA$_{254}$	4-11 L mgC L/m
E2:E3	4-7
HIX	0.85-0.95
BIX	0.64-0.45
FI	1.4-2

a hiatus in the series from November 2003 to July 2005.

The hydrological data set is generated by the author. Methodological details of the hydrological monitoring can be found in Butturini *et al.* (2008) and Guarch-Ribot (2017). A water pressure sensor transducer (Druck PDCR 1830) was installed in the stream channel and connected to a data logger (CR10x Campbell Inc.) that recorded data every 30 min. Discharge was measured periodically by slug salt additions. The relationship, water levels vs. measured discharges, was used to convert the entire water levels data set into discharges. In this work are analyzed mean daily discharge values.

The data set includes daily air temperature and daily precipitation. This data set is the average of daily values from five meteorological stations managed by the "Diputación de Barcelona" and located in the proximity of the Fuirosos catchment (Pla de la Tanyada, Collsacreu, Hortsavinya, Dosrius, Malgrat). The nearest and farthest meteorological stations are located at 3.5 km and 18 km from Fuirosos, respectively.

Monotonic trend significance in the time series air temperature, precipitation and discharge pattern has been assessed with the Mann–Kendall test (Kendall, 1975). This is a rank-based test suitable for non-normally distributed data and is widely used in hydro-climatic studies. The magnitude of the trends is tested using Sen's slope (Sen, 1968).

Shape of smoothed probability distribution (SPD) of daily discharge helps to separate discharges into five categories (drought, pre-drought discharges, low discharges, basal discharges and high discharges; see results section). The smoothing kernel is Gaussian. Bandwidth of the SPD was selected automatically according to the Sain & Scoot (1996) criteria. Drought category is that with Q = 0 L/s. The other four discharge categories emerged from the location of the inflexion points of the SPD. An inflexion point is defined when the second derivative of the SPD has a minimum.

Simple linear regression models are used to test the temporal trends of annual contribution (in terms of frequency of occurrence) of each selected discharge category (see results section). Significance threshold of regression is fixed at $p < 0.05$. In this study, a year means a hydrological year from September/October to August.

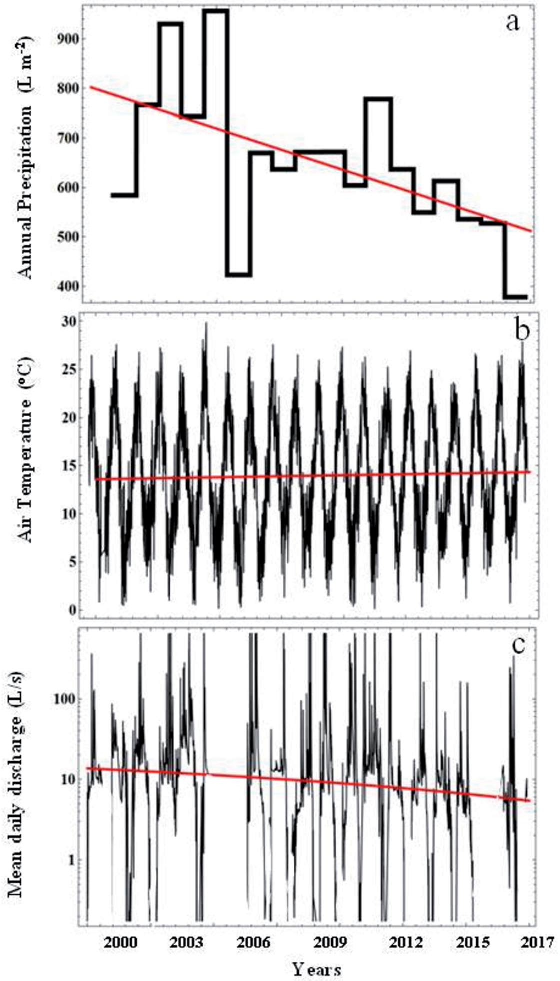

Figure 2. Temporal dynamic of total annual precipitation (panel a), daily mean air temperature (b) and daily mean discharge (c) at Fuirosos during the entire monitoring period. Red lines show the temporal trends (all significant, Mann-Kendall test, $p < 0.01$). *Dinámica temporal de la precipitación total anual de lluvia (panel a), la temperatura media del aire diaria (b) y el caudal diario medio (c) en Fuirosos durante el periodo de estudio. Las líneas rojas indican las tendencias temporales (todos significativos, Mann-Kendall test,* $p < 0.01$*).*

RESULTS AND DISCUSSION

Hydrology at Fuirosos: past, present and future

During the entire study period, total annual precipitation (Fig. 2a) varied greatly; between

380 L/m^2 and 912 mm. At a decadal scale, a significant decrease, at a rate of 15 mm/y, was detected (Mann–-Kendall $\tau = 0.031$, p-value < 0.01). Distribution of precipitations during the year also showed a tendency to change (data not shown). For instance, before 2008, the months of August and September typically accumulated more than 100 mm of precipitation. Since 2009, this threshold has only been crossed in two years (2014 and 2015).

Air temperature showed the typical seasonal pattern (Fig. 2b) with a summer maximum (21.5 °C in July and August) and a winter minimum (6.7 °C in January and February). At the decadal temporal scale, air temperature increased at a rate of 0.04 °C/y (Mann–Kendall $\tau = 0.02$, p-value < 0.01). The detected temperature increase is attributable mainly to an increase in the lowest average daily winter temperature values. In contrast, in summer, temperatures did not show any significant change.

The mean and median daily discharges during the whole study period were 32 and 7.5 L/s, respectively.

Fuirosos is intermittent with a large dry period (no flow) in summer and permanent flow from fall to early summer (Fig. 2c). Its discharge regime is a clear example of a rain-based regime (Morán-Tejera *et al.*, 2011) with an annual runoff significantly related to annual precipitation ($r^2 = 0.48$, $p < 0.005$).

Stream annual runoff relative to precipitation ranged between 20 % (2011 and 2012) and < 4 % (2013 and 2015) but it did not show any temporal trend ($r^2 = 0.001$, $p > 0.05$), suggesting that annual evapotranspiration did not display a significant change over time.

Probability distribution of daily discharges showed a clear bimodal shape. The largest peak corresponded to drought (Q = 0 L/s, 19 % of observations). The second largest was at Q = 13.2 L/s (8 % of observations). In addition, the discharge distribution showed three inflection points at 2.25, 6.6 and 26.2 L/s, respectively. Accordingly, discharges can be split into five categories: drought (Q = 0 L/s); pre-drought ($0 < Q \leq 2.25$ L/s); low discharges ($2.25 < Q \leq 6.6$ L/s); basal discharges ($6.6 < Q \leq 26$ L/s) and high discharges ($Q > 26$ L/s) (Fig. 3). The temporal patterns of these discharge categories are separately described in the next paragraph.

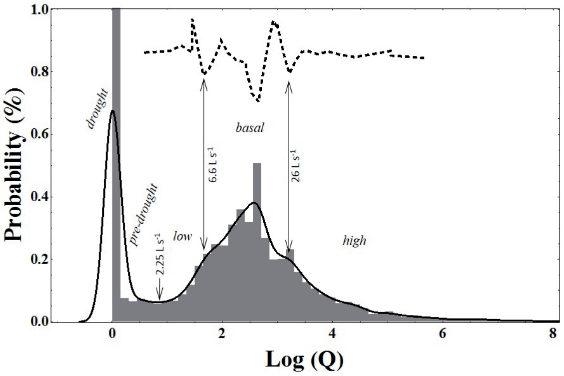

Figure 3. Probability distribution of mean daily discharges at Fuirosos. Solid black line shows the smoothed distribution obtained with the Gaussian kernel. Vertical arrows show the position of a local minimum and two inflection points in the smoothed distribution that allow for identification of the discharge categories (in italics). Positions of the two inflection points are determined by the second derivative of the smoothed distribution (dashed line, see materials and methods section for details). *Distribución de probabilidad del caudal medio diario en Fuirosos. La línea negra continua ilustra la distribución suavizada obtenida con el kernel Gaussiano. Las flechas verticales indican la posición de un mínimo local y de dos puntos de inflexión de la distribución suavizada que permiten identificar las categorías de caudales (en itálica). La posición de los puntos de inflexión se ha determinado mediante la derivada segunda de la distribución suavizada (línea discontinua. Ver la sección de materiales y métodos para los detalles).*

Drought typically lasted for between 45 and 121 days. Only in 2002 Fuirosos showed a permanent hydrological regime. The duration of droughts showed a weak but significant gradual increase over time ($r^2 = 0.205$, $p < 0.05$) at a rate of 1.9 d/y. The gradual dilation of droughts is a consequence of a significant delaying of the rewetting ($r^2 = 0.296$, $p < 0.05$), that shifted from mid-September to early October (Fig. 4) which, in turn, responded to a decrease of rains in August and September. If the duration of droughts continues to increase at the present rate, they will last for half the year by 2045. However, caution should be applied to this extrapolation because the data set is strongly biased by a very severe drought in 2017, at the end of the temporal series. Overall, without being conclusive, these data suggest a tendency of the duration of drought episodes to increase.

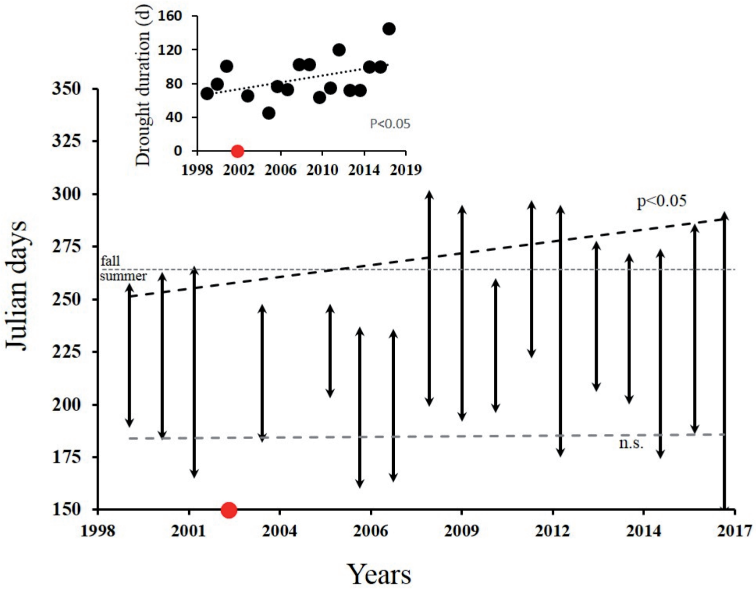

Figure 4. Temporal variability of length of each summer drought at Fuirosos during the study period. Arrows show start and end of each drought episode. Dashed lines are the linear interpolations of the temporal trend of the start (grey line, not significant) and end (black line, $p < 0.05$) of drought episodes. The inset shows the tendency of the absolute duration of summer droughts during the study period (dotted line is the linear interpolation, $p < 0.05$). Red dots represent the year without drought. This case was removed from the statistical analysis. *Variabilidad temporal de la duración de las sequías en Fuirosos durante el periodo de estudio. Las flechas indican el inicio y el final de cada episodio de sequía. Las líneas discontinuas describen la interpolación lineal de las tendencias temporales del inicio (línea gris, no significativa) y final (línea negra,* $p < 0.05$*) de las sequías. En el recuadro se ilustra la tendencia temporal de la duración de las sequías durante el periodo de estudio (línea de puntos,* $p < 0.05$*). El punto rojo indica el año sin sequía. Este caso se ha excluido del análisis estadístico.*

Temporal trends are clearest in the pre-drought and low discharges categories. In both cases, a significant increase over time was observed ($r^2 = 0.4$, $p > 0.05$ and $r^2 = 0.42$, $p > 0.01$, respectively). That increase is at the expense of basal discharges that significantly decreased ($r^2 = 0.27$, $p > 0.05$). On the contrary, neither the occurrence ($r^2 = 0.15$, $p > 0.05$) nor magnitude ($r^2 = 0.22$, $p > 0.05$) of high discharges showed any significant temporal trend (Fig. 5a-d).

The observed decadal changes in drought, pre-drought and low discharges categories are in line with those reported in altered and near-natural catchments in the south of Europe, (López-Moreno *et al.*, 2006; Mediero *et al.*, 2014; Stahl *et al.*, 2010; Coch & Mediero, 2016). These studies emphasize the increasing frequency of droughts and low flow conditions.

To conclude, I return to the entire hydrological data set (Fig. 2c). A rapid visual examination of this plot suggests an overall decrease of the discharge, especially since 2009. This view is corroborated by the statistics (Mann–Kendall test, $\tau = -0.15$, $p < 0.001$). The annual discharge decrease rate (ADDr) of the whole period, estimated using Sen's slope, is -0.4 L/s/y. ADDr represents 1.3 % and 5.5 % of the average and median discharge of the entire study period, respectively.

Extrapolating linearly from the ADDr, the annual mean and median discharge should reach 50 % in 2060 and 2035, respectively. Again, as stated before, caution is fundamental because this extrapolation does not take into account the large inter-annual climatic variability that exists in the Mediterranean region and it assumes that relative contributions of runoff components (hillslope runoff, groundwater recharge and forest evapotranspiration) will not change significantly. We know little about how these mechanisms react to drying or how they interact (Andrés-Domenech *et* *al.*, 2015). Notwithstanding, it is certain that, if ADDr continues at the present rate, Fuirosos will turn into an ephemeral stream in a very short time. Clearly, at Fuirosos, climate change is a very urgent stressor.

The ADDr value of 1.3 % (i.e., for mean discharge) is similar to that reported in other south-eastern European rivers (Stahl *et al.*, 2010). In more detail, in the Iberian Peninsula, the ADDr ranged from 0.25 % to more than 3 % and was greater than 1 % in most cases (Gallart *et al.*, 2011; Lorenzo-Lacruz *et al.*, 2012; Martínez-Fernández *et al.*, 2013; Buendia *et al.*, 2016, Table 2). However, the value of 5.5 % (i.e., the ADDr value when weighted against the median discharge) is particularly worrying. Here, it is important to note that ADDr values from the Iberian Peninsula come from data sets generated by monitoring stations managed by water agencies and located in large regulated rivers altered by climate change, damming structures and water abstraction/derivation. In these systems is difficult to distinguish the climate footprint from local anthropogenic stressors. Fuirosos, in contrast to larger rivers, is not affected by water abstraction, human settings are scarce and land use has not changed significantly over the entire study period. Thus, an ADDr value of 5.5 % suggests that semi-pristine headwater streams might be extremely sensitive to climatic anomalies. In consequence, in the context of implementing strategies in water resource management to buffer the effect of global climate change, headwaters might actuate as sentinels to alarm, in real-time, for upcoming water stress in larger regulated rivers.

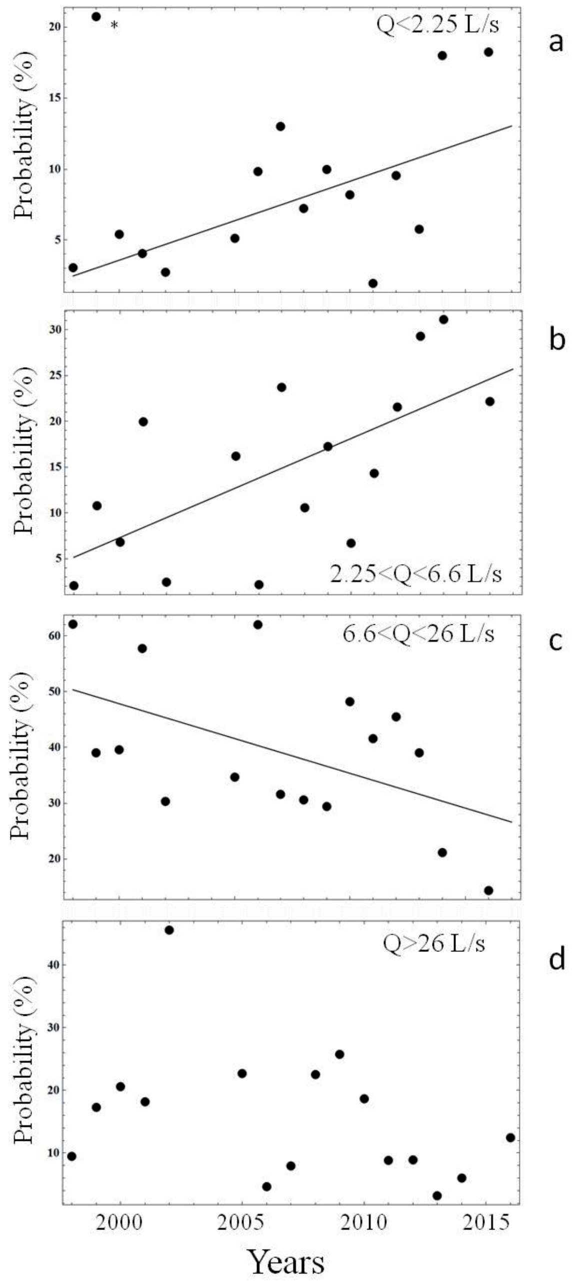

Figure 5. Temporal trends of the occurrence of four discharge categories identified at Fuirosos according to the probability distribution of mean daily discharges (see Figure 2). Solid lines show significant linear trends ($p < 0.05$). Panel a: the value with an asterisk was removed from the regression model. *Tendencia temporal de la frecuencia de ocurrencia de las cuatro categorías de caudales identificadas en Fuirosos, de acuerdo con la distribución de probabilidad de los caudales medio diarios (ver figura 2). Las líneas continuas ilustran las tendencias lineales significativas (*p *< 0.05). Panel a: el valor con un asterisco se ha eliminado del modelo de regresión.*

Research at Fuirosos: past, present and future

To the best of my knowledge, the Fuirosos stream attracted scientists in the 1970s and 1980s whose research focused mainly on sediment transport, erosion rates and morphological changes. These studies quantified changes in fluvial channel profiles (at an annual scale), highlighting their importance in shaping the fluvial network. However, hydrology was not monitored: the authors simply reported that surface runoff could disappear in drought years, such as 1981 (for more details see Sala, 1978, 1982). Unfortunately, these geomorphologic studies lack continuity.

Academic fluvial ecology studies recommenced in fall 1998. Since then, studies have been performed without interruption, mainly involving researches affiliated to the University of Barcelona, the University of Girona, CEAB-CSIC and ICRA (Girona).

Studies began with a European project named NICOLAS, focused on the impact of riparian zones on nitrate mitigation in groundwater-stream interface. Thus, at the beginning, focus was on riparian strip rather than the stream itself. However, this project afforded the opportunity to start the hydrological and biogeochemical monitoring of the stream.

This research evidenced how abrupt hydrological changes modulate: 1) the amount of water stored in the groundwater riparian zone and the hydraulic gradient in groundwater and, in consequence, water fluxes between that interface and the stream channel (Butturini *et al.*, 2002, 2003), and; 2) nitrate retention, leaching and denitrification in riparian soil and groundwater (Sabater *et al.*, 2003; Bernal *et al.*, 2007). Simultaneously, the carbon cycle in Fuirosos was attracting attention. Thus, input of organic matter (leaves and wood) from the riparian zone and the concentration of dissolved organic matter (in terms of carbon, DOC and nitrogen, DON) in the stream were monitored. The most important result obtained featured quantification of the volume of leaves that remained stored at the stream bed under summer no flow conditions (almost 0.4 kg/m^2 of dry mass), when the hydric stress triggered a summer leaf fall episode (Sabater *et al.*, 2001). This observation was quickly recognized as an important characteristic and stimulated study of the impact of drying-rewetting cycles on stream biogeochemistry, organic matter degradation and production/respiration balances.

I will now examine all these aspects in detail.

In a biogeochemical context, summer drought periods followed by post-drought flushing of

Table 2. List of rivers in the Iberian Peninsula that showed discharge decrease. *Lista de ríos de la península Ibérica que han sufrido una disminución del caudal.*

Study area	Monitoring period	Catchment area (km^2)	Discharge annual decrease (%)	Causes	Reference
Ter (Roda de Ter)	1950-1996	1386	0.25	Forest cover increase	Gallart *et al*. (2011)
Cardener (Olius)	1954-1996	256	0.82		
Llobregat (La Baells)	1976-1999	504	1.1		
187 large sub-basins	1945-2000	Large basins	>3% Segura; 1-3% Tajo, Gudalquivir, Guadiana, Jucar; <1% Cantabrian, Miño, Duero, Ebro	Water management strategies (dams)	Lorenzo-Lacruz *et al*. (2012)
Duero (56 gauging stations)	1961-2006	35–45	Not quantified	Decrease in winter precipitation and reduction of snowmelt	Morán-Tejeda *et al*. (2011)
287 rivers	1961-2009	Large basins	Not quantified	Higher evapotranspiration and decrease in precipitation	Vicente-Serrano *et al*. (2014)
Duero (17 sub-basins)	1966-2005	14–2384	1.11	Forest cover increase and higher temperature	Martínez-Fernández *et al*. (2013)
Tajo (4 sub-basins)			1.49		
Júcar (5 sub-basins)			1.68		
Ebro (35 sub-basins)			1.41		
Noguera Pallaresa (Ebro sub-basin)	1965-2009	2807	0.5–1.3	Higher temperature and potential evapotranspiration, and forest cover increase	Buendia *et al*. (2016)
Turia (Júcar sub-basin)	1973-2008	3936	Not quantified	Higher temperature (forest cover decrease)	Salmoral *et al*. (2015)

nitrate, especially DOC (Bernal *et al.*, 2002), revealed: a) the fast mobilization of solutes from near or in-stream compartments (riparian zone, hyporheic zone, stream bed) and; b) the relative irrelevance of groundwater flow paths. These solute-discharge responses were different to those reported in Mediterranean perennial streams (Andrea *et al.*, 2006) and were almost opposite to those described in temperate (and human impacted) lotic systems (Bowes *et al.*, 2015). Overall, these results evidenced the impact of the hydrological regime on stream-terrestrial environmental connectivity.

Several studies focused more specifically on the drying-rewetting cycle. As mentioned in the previous section, drying typically occurring from May to July, when discharge decreases progressively to cessation.

In terms of inorganic nitrogen and inorganic phosphorus availability, a decrease of nitrogen (N:P < 16) has been observed during drying, in contrast to the rewetting phase (N:P > 16). In consequence, while during most of the hydrological year, P is expected to the most limiting nutrient, the balance shifts toward N limitation during drying. This pattern has been attributed to increased in-stream processes during drying and to phosphorus mobilization under anoxic conditions in the hyporheic zone (Von Schiller *et al.*, 2011). However, nitrogen limitation might be also exacerbated by a reduction of N inputs from the catchment as a consequence of N uptake by terrestrial vegetation.

The quality of dissolved organic matter (DOM) has also become a key issue in aquatic science during the last 20 years and Fuirosos was the first stream in the Iberian Peninsula to undergo long-term DOM monitoring which included quantitative variables (dissolved organic carbon, DOC and nitrogen, DON) and qualitative descriptors. The first DOM qualitative parameters to be studied were the ratio DOC:DON, and the distribution of DOM molecular sizes, that provide insights into potential DOM bioavailability for microbiota. The DOC:DON ratio typically ranged between 40 and 10. The largest oscillations coincided with rewetting, with ration values of DOC:DON > 40 during baseflow and DOC:DON < 10 during high flows. High values might reflect the leaching of terrestrial N-poor organic matter, such as decayed leaves, stored in the streambed during drought. In contrast, a low DOC:DON ratio during high flow might reflect the input of N-rich organic matter from throughfall of shallow soils (Bernal *et al.*, 2005). Simultaneously, analysis of the distribution of DOM molecular sizes evidenced that the riparian compartment retained DOC fractions larger than 10 kDa, whereas the smallest fractions (< 1 kDa) were nearly unreactive (Vazquez *et al.*, 2007).

A step forward in the analysis of DOM quality occurred with the introduction of spectroscopic techniques (absorbance and fluorescence). Although spectroscopy provides an incomplete description of DOM molecular heterogeneity it is especially useful in water bodies where aromatic-unsaturated substances predominate over aliphatic-saturated, as is the case with Fuirosos. DOM, at Fuirosos, consists of prevailing humic-like substances of terrigenous/allochthonous origin. However, these studies also evidenced that under drying conditions the non-humic microbial derived fractions seem to be slightly more relevant, suggesting in-situ DOM production (Vazquez *et al.*, 2011; von Schiller *et al.*, 2015; Granados *et al.*, 2020). Thus, DOM quality is strongly coupled to drying. Moreover, these studies evidenced that humic substances are more reactive than previously thought (Harjung *et al.*, 2018) and the fragmentation of the river continuum into a set of ephemeral disconnected stagnant pools determined a mosaic of heterogeneous biogeochemical spots with markedly different signatures in DOM quantity and quality (Vazquez *et al.*, 2011).

All these studies focused mainly on drying. However, DOM qualitative changes were not constrained to this period. Thus, an intensive, 2.5-year long monitoring revealed that DOM molecules under high flows were essentially more degraded, aromatic, humified and larger in size than during baseflows, clearly evidencing the importance of DOM leaching from forest soil. Time series also revealed that beyond the magnitude of storm episodes, the magnitude of the previous storm and the time elapsed since the start of the rewetting period also influenced the DOM quality (Guarch-Ribot & Butturini, 2016). For instance, DOC flushing during a storm episode might be partially neutralized by the magnitude of the antecedent storm episode. However, spectroscopy fails to characterize the non-aromatic compounds (e.g., saturated aliphatic, polysaccharide, amino acids) and these "optically transparent" molecules probably increase their concentration during drying (Ylla *et al.*, 2010, 2011).

The biogeochemical studies summarized in the preceding paragraphs were grounded in field observation. Simultaneously, several field experiments were performed in Fuirosos. Most of these experiments were executed following the in-situ controlled nutrients enrichment additions approach that provides experimental evidence of the connection between biogeochemistry and aquatic biota (especially benthic biota) and highlights the fluvial ecosystem functioning at the reach scale. At Fuirosos, nutrient additions were performed over different time scales: short additions (typically less than 1 day), large additions (44 days long) and long-term additions (4 years long).

Large nutrient additions induced an increase in algal density, however, no changes in net primary production and community respiration were observed (Sabater *et al.*, 2005). On the other hand, the long-term moderate N and P enriched experiment induced a significant increase in epilithic algal biomass (Veraart *et al.*, 2008) and an increase of exoenzymatic bacterial activities (peptidase, β-glucosidase) that degrade algae derived substances. Yet, these changes in the benthic communities had little effect on higher trophic levels (Sabater *et al.*, 2011).

A set of short ammonium and phosphate additions performed over two hydrological years revealed that retention efficiency of these two nutrients was strongly affected by discharge and unaffected by seasonal patterns. Overall, nutrient retention variability was lower when compared to a permanent stream of comparable size, suggesting high resilience of biota responsible for nutrient uptake. Notably, ammonium retention efficiency at Fuirosos was lower than in the permanent stream (Von Shiller *et al.*, 2008), probably because for most of the time at Fuirosos nitrogen is not limited (Von Schiller *et al.*, 2011).

In parallel to these biogeochemical studies, several researches focused on the characterization and functioning of the biotic community. These studies included measurements of microbiota activities in sediments and particulate organic substrata, estimation of reach scale metabolism and quantification of leaf inputs, decay and colonization. All these studies share a focus on the carbon cycle.

Riparian strips delivered between 0.3 and 1.1 $gC/m^2/d$ of particulate organic matter (POM, a mix of detritus, leaves and branches) to the stream. In summer, under drought and no flow conditions, the stream bed retained up 400 gC/m^2 of benthic POM (Acuña *et al.*, 2005). This energetic carbon input strongly influenced stream metabolism. For instance, ecosystem respiration rates (ER) peaked at a value of about 30 $gO_2/m^2/d$ during the rewetting. This rate was among the highest value reported in the literature and reflected the importance of abundant benthic POM stored during the drought period (Acuña *et al.*, 2004). These studies prompted a 10-year monitoring of riparian POM inputs in one stream reach. This study, beyond remarking on the impact of drought duration on quantity and quality of POM, also suggested that the El Niño Southern Oscillation might partially explain the interannual variability of POM inputs, through changes in precipitation (Sanpera-Calbet *et al.*, 2016).

For observation at a smaller scale, the study of biota (prokaryotes, fungi, protozoa and macroinvertebrates) is a cornerstone of the research at Fuirosos, with a special emphasis on how hydrology shapes the composition, traits and functioning of biota and its impact on the degradation of organic matter. Almost all studies highlighted the role of hydrology. Thus, the hydrological fragmentation of the stream continuum, induced by drying, impacts on the biota, inhibiting microbial diversity resulting in the proliferation of a few strains of beta-Proteobacteria and Actinobacteria (Fazi *et al.*, 2013). Simultaneously, leaf-packs colonization experiments evidenced how high floods reduced the biomass of protozoa on organic substrata (Gaudes *et al.*, 2009). Similarly, at traits level, worm-shaped body and active locomotor structures conferred higher resilience in the face of natural hydrological disturbances (i.e., floods and droughts). Further upstream small permanent pools are refuges for meiofauna that can eventually repopulate downstream reaches (Gaudes *et al.*, 2010).

In the context of community composition, drying determined the collapse of autotrophic communities (Timoner *et al.*, 2012) and favored an increase of ammonium oxidizer bacteria and archaea in dry and aerobic sediments (Merbt *et al.*, 2016). Changes in elemental composition of biofilm were also reported. Thus, C/P in biofilm increased dramatically, from 80 to 300. C/N ratio in biofilms changed slightly, from 10 to 16 (Timoner *et al.*, 2012). This finding challenged the hypothesis that Fuirosos would be N-limited during drying. Simultaneously, in biofilms, contents of polysaccharide, amino acid, and lipids increased during drying. However, exoenzymatic activity measurements implied that while polysaccharides were assimilated by bacteria, peptides were not (Timoner *et al.*, 2012). Therefore, according to these results, microbial heterotrophs were constrained to use the organic matter source of the lowest quality (polysaccharides, providing only C). On the other hand, little is known as to whether these stoichiometric changes in biofilm translated to consumers. However, a stoichiometric increase on the C/P ratio in aquatic detritivores has been observed during a laboratory experiment that simulated dry and warm conditions (Mas-Marti *et al.*, 2015).

Hydrology is also a useful tool for exploring in-situ microbiota functions and microbiota-biogeochemistry links. For instance, during drying, it is relatively straightforward to quantify the surface-hyporheic hydrological connectivity without interference from other hydrological inputs (i.e., from hillslope or groundwater). This situation allows us to perform mass balances and explore how water biogeochemistry and the microbial community composition/functioning change at the surface-hyporheic interface and, in parallel, to establish relationships among them. Thus, as surface water infiltrates the hyporheic zone, the hyporheic microbial community increases in abundance, in the proportion of living cells and in exoenzymatic activities. Concurrently, nutrients and DOC concentration decrease. Moreover, in the hyporheic zone, DOM becomes less aromatic, indicating that humic substances are bioavailable for microbiota (Harjung *et al.*, 2019). This study, together with previous ones (Vazquez *et al.*, 2007; Harjung, 2018) evidenced that the hyporheic zone might be a relevant compartment for total ecosystem respiration. However, at present it is not possible to quantify this contribution.

Lastly, but no less importantly, there is a fundamental functional descriptor that is not apparently related to hydrology: leaf decomposition rates. Here, temperature seemed to be the main driver. Fungi (related to lignin degradation) were more important in spring, whereas in summer, water quality changes seemed to favor bacteria (related to hemicellulose and cellulose degradation) (Mora-Gómez *et al.*, 2015, 2016).

Research at Fuirosos: what is next?

As is usual, advances stimulate new questions and doubts and reveal more evident gaps. For instance, a lot of research in IRES has focused on drying to the exclusion of rewetting. Rewetting, due to its erratic nature, is difficult to capture and sample. Further, rewetting is extremely variable in its magnitude. So, in addition to the difficulty of sampling, rewetting episodes can be markedly different from each other, while drying scenarios are always (more or less) identical (although the duration of the drought can be variable; see previous section). Duration and intensity of rewetting can be highly diverse and we know little about how this intrinsic hydrological variability influences solute mobilization/leaching, in-stream nutrient retention, biofilm recolonization or benthic fauna diversity/density.

In addition to rewetting, there are another two interesting aspects that, in my opinion, need additional work: a) the contribution of the hyporheic zone to total fluvial metabolism and; b) long-term changes.

The role of the hyporheic zone and interstitial riparian zone in processing organic matter has been tested in several field works (see Harjung *et al.*, 2019 and further references therein). However, it is hard to upscale these measurements to estimate the relevance of the hyporheic contribution to ecosystem respiration at the reach scale (see Acuña *et al.*, 2004). Here, CO_2 concentration/fluxes measurements under dry streambed conditions but with a water-saturated hyporheic zone might supply useful information.

Lastly, I must mention the temporal dimension. To date, the study with the longest-run data set is that of Sanpera-Calbet *et al.* (2016), who analyzed 10 years of POM inputs in the stream. The relevance of this study consists of the suggestion that a global climatic phenomenon (El Niño, in this case), that acts at interannual intervals, might be relevant in the fluvial carbon cycle at relatively short timescales. This study should stimulate further analysis, in the near future, of the available long-term data set and motivate continuation of the hydro-biogeochemical monitoring.

As to "what is next?", data generated at Fuirosos have furnished scores of published papers and more than 10 completed PhD theses. The most productive period was 2010 to 2013, with 30 papers. Since then, the publication rate has decreased gradually to just two papers in 2018. This trend reveals that research at Fuirosos is slowly diminishing and is no longer attracting researchers. There is no doubt that several years ago Fuirosos was crowded with limnologists: full of people going up and down collecting water samples, performing nutrient additions, plugging piezometers, scraping stones or collecting decayed leaves. Now, silence dominates and memories of these activities emerge only when old abandoned tubes, bags or boxes are found and removed. Is this depletion of activity a sign that Fuirosos is no longer of interest? Is research into IRES generally declining? The answers to these two questions are, respectively, "probably yes" and "probably no". Scientists and the general public are aware that climate change is neither the only stressor nor the most urgent for IRES (see the previous section). Therefore, it is understandable that those studies that focus on direct human impact (all types of contamination, water withdrawal, derivation or channelization, land use changes, wildfires) and on potential attenuation strategies (management, restoration, decontamination, water recycling, repopulation) are gaining relevance. Fuirosos, in this respect, has lost its appeal. Perhaps this is good news because it might imply that this small stream is not suffering such a dramatic human induced alteration as happens to the vast majority of rivers and streams that surround us.

CONCLUSIONS AND FINAL REMARKS

This work, apart from the last few lines at section 3.1, does not focus on water management in intermittent streams nor not does it make claims about the need to protect and save these unique ecosystems. Hundreds of articles and several books efficiently stress these needs. However, I cannot omit that while I was writing this text, the European commission reported that, "There are no water bodies in Spain that have had reference conditions established for all relevant hydromorphological or all relevant physicochemical quality elements." (http://ec.europa.eu/environment/water/water-framework/impl_reports.htm#fourth). The message is clear. In consequence, if local water authorities are interested in filling this gap and reassuring the EU, they can easily contact people who can provide this information from small intermittent reference headwaters and some names of those people are included in the reference list at the end this work.

At Fuirosos, almost 20 years of research have clearly demonstrated how far the hydrological regime shapes the entire stream ecosystem structure and functioning at all observational scales. From a neutral standpoint, this is not a revolutionary discovery. That said, the research at Fuirosos, is, in my opinion, a wonderfully instructive example of research activity that has accumulated evidence within an established scientific matrix (Kuhn, 1963). This reflection does not mean that I underestimate 20 years of research. On the contrary! I am fully convinced that research at Fuirosos has helped to close small fissures in our knowledge and create the basis for developing a new way to conceive lotic systems and, accordingly, a different way to study them. This is obviously not exclusive to research at Fuirosos but can be extended to most research in IRES around the world. Maybe a symptom of these changes is perceptible in the language currently being used. Terms such as "patchiness", "discontinuities, "heterogeneities", "fragmentation" or "contraction" are now commonplace in papers that report results from IRES. All these expressions reflect the perception of streams/rivers as turbulent and restless systems. This view, in my opinion, counterbalances the peacefulness of the concept of the river continuum (Vannote *et al.*, 1980), grounded in the study of permanent headwater streams/rivers, that has profoundly inspired fluvial ecologists over the last 40 years.

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