Fourteen years of hydro-biogeochemical monitoring in a Mediterranean catchment

E. Vazquez, V. Acuña, J. Artigas, S. Bernal, E. Ejarque, A. Gaudes, I. Ylla, E. Martí, E. Mas-Martí, A. Guarch, I. Muñoz, A. Romaní, S. Sabater, F. Sabater, D. Von Schiller and A. Butturini

Vierzehn Jahre hydro-biogeochemischer Beobachtungen in einem mediterranen Einzugsgebiet

1 Introduction

Hydrology in areas under Mediterranean climate is heavily influenced by the contrasted seasonal precipitation regime. Annual precipitation in these areas ranges from 200 to 1000 $L \cdot m^{-2}$, and the precipitation events are subject to strong seasonality and high interannual variability (Gasith & Resh, 1999). Mediterranean regions experiment water stress deficit during extended time periods, resulting in periodical low flows, and even flow cessation. Therefore, these temporary rivers are characterized by cycles of dry-wet periods and by complex hydrological dynamics that in turn influence biotic communities, inorganic nutrients and organic matter processing (Larned et al., 2010) and countless other ecological factors (Steward et al., 2012).

Therefore, Fuirosos catchment is an exceptional area in an otherwise severely human-impacted Mediterranean zone. Being an almost undisturbed stream, Fuirosos is an attractive hydrological system for long-term ecological research that led it to become a reference site for fluvial ecology in Mediterranean regions.

Zusammenfassung

Die Abflusssysteme mediterraner Einzugsgebiete sind in starkem Maße von der Saisonalität der Niederschläge beeinflusst und zeigen daher Perioden mit Niederwasserführung bzw. gänzlich fehlendem Oberflächenabfluss. Der Fuirosos-Fluss zeigt intermittierende Verhältnisse, die seit 1998 beobachtet werden. Er liegt nahe Barcelona (Spanien) und ist nahezu anthropogen unbeeinflusst. Daher wird er oft als Testgebiet für biogeochemische und flussökologische Untersuchungen herangezogen. Diese konzentrieren sich oft auf den Einfluss von Trocken-Feuchte-Zyklen auf andere fluviatile Prozesse. Der Beitrag bietet einen Überblick über die Forschungsaktivitäten am Fuirosos-Fluss und unterstreicht die Wichtigkeit der Unterscheidung zwischen Feucht- und Trockenperioden in mediterranen Einzugsgebieten.

Schlagworte: Biogeochemie, Flussökologie, Hydrologie, mediterranes Einzugsgebiet, Langzeitbeobachtungen.

Summary

Fluvial systems in Mediterranean areas are subject to strong precipitation seasonality, characterized by a low flow period, and, in severe conditions, the complete disruption of surface flow continuum. The Fuirosos is a Mediterranean intermittent stream that has been monitored since 1998. It is located near Barcelona (Spain) in a catchment almost untouched by anthropic activity. Thus it has become a target for many studies on biogeochemistry and fluvial ecology. Some of these studies especially emphasize the role of the dry-wet cycling and its influence on other aspects of fluvial processes.

This text provides a wide overview of the research conducted in Fuirosos catchment and highlights the relevance of the alternation of hydrological periods in Mediterranean systems.

Key words: Biogeochemistry, fluvial ecology, hydrology, Mediterranean catchment, long-term monitoring.

Research in Fuirosos has been approached on two main aspects, biogeochemical and ecological, always with a strong background reliance on hydrology due to the particularities of the Mediterranean climate that cause a yearly dry-wet cycle. The objective of this article is to present an overview of the main hydrological and biogeochemical studies conducted during the last 14 years.

2 Catchment description

Fuirosos is a small tributary of the la Tordera river located 60 km from Barcelona (North-East Spain; 41°,41',51" N, 2°34'40"E). It drains a forested catchment of 15 km^2. Although surrounded by several villages, industrial, agricultural and resort areas, the catchment is part of a protected natural area mostly covered by forest (90 % of total area) and agriculture fields which had been gradually abandoned during the last 50 years. However, pasture is acquiring relevance recently.

Fuirosos soil is mainly underlain by leucogranite and granodiorite bedrock. At the top of the ridge there is a formation of sericitic schists and in the western catchment edge there is a formation of silicic slates, lidites and limestones. In the catchment lower area, along the river banks, gravel and sand become prominent and fluvial runoff recharges the Tordera aquifer. The stream main stem is 10 km long with a small reservoir roughly located in the middle of the stream length (Figure 1).

The catchment is covered mostly by perennial cork oak (*Quercus suber*) and pine tree (*Pinus halepensis*). Deciduous woodland of chestnut (*Castanea sativa*), hazel (*Corylus avellana*) and oak (*Quercus pubescens*) predominate in the valley head. The riparian vegetation is dominated by plane tree (*Platanus hispanica*) and Alder *(Alnus glutinosa)*.

Climate is typically Mediterranean. Air temperature ranges from –2 °C to 28 °C, and precipitation mostly falls in autumn and spring with occasional summer storms. Average annual precipitation ranges widely from less that 550 mm to more than 750 mm.

3 Research in Fuirosos

Although the focus here is on hydrology and biogeochemical research, ecology topics has been another research line. The different research topics have been on different spatial scales (catchment, riparian-stream interactions, reach and sub-reach), and different space scales also with special attention to the drying-rewetting cycles. The methodological approaches to the different research projects include long-term monitoring, short-term experiments and hydro-biogeochemical modelling.

3.1 Hydrology

Stream basal flow discharge ranges between 0 and 25 L s^{-1}. During storms discharge increased frequently up to 500 L s^{-1}

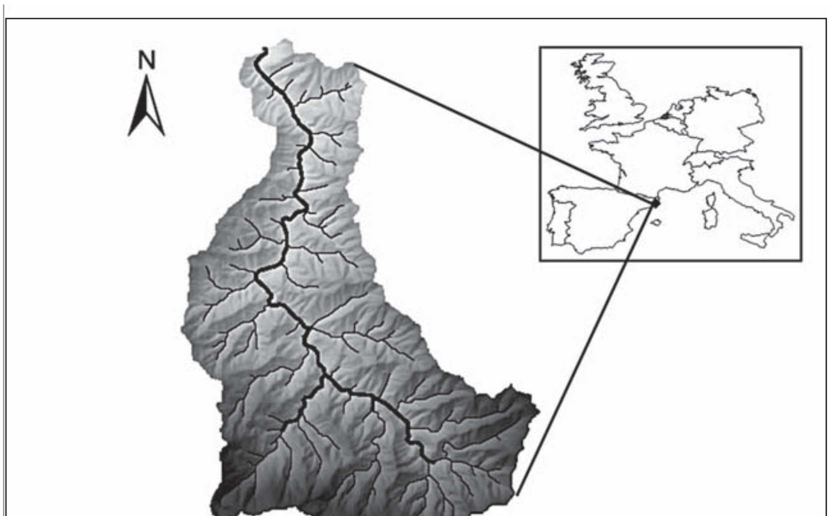

Figure 1: Geographical location of Fuirosos catchment
Abbildung 1: Geografische Lage des Fuirosos-Flussgebiets

and only during extreme events it exceeds 1000 L s^{-1}. Storm episodes covered 10–15 % of the time but contributed to more than 60 % of the annual water export.

Although annual precipitation is relatively high under Mediterranean climate, the high monthly and inter-annual variability cause the occurrence of two hydrological windows over an annual scale: the flowing window and the dry window. During the period of 1999–2012, the flowing window comprised 80 % of the time, while the remaining 20 % corresponded to the drought/dry window (see Figure 2).

The dry window is observed in summer and its span presents high variability in the monitored period, including two years when the main stream channel did not dry (water flowed the whole year) (see Figure 3). When the severity of the dry window is high enough, a third brief window with its own hydrological particularities can be observed, usually referred to as the dry-wet hydrological transition. During this third brief period, in contrast with the dry and flow windows, the stream-riparian interface becomes a very dynamic hydrological compartment, experiencing a wide expansion and follow-up contraction due to reversed water fluxes from the stream into the riparian zone, where biogeochemical processes are amplified.

During the flowing window, stream runoff is positively related with the intensity of precipitation events. On the other hand, this relationship is not observed during the dry period, when similar precipitation inputs generate very low runoff inputs due to low soil humidity (BUTTURINI et al., 2003).

3.2 Inorganic solutes and organic matter biogeochemistry

Coupled to the hydrological monitoring, there is a continuous monitoring of solutes including chloride, sulphate, DOC, nitrate, and ammonium.

The annual nitrate export is 21.4 ± 9.3 kg·km^{-2} yr^{-1}. Between 52 and 87 % of the annual nitrate export was originated by storm episodes.

Precipitation is the main input of dissolved inorganic nitrogen in the Fuirosos catchment. The total annual input from precipitation is 411 kg·m^{-2}·yr^{-1}, of which a 45.7 % is in form of N-NO_3 (the rest is N-NH_4). Nitrate concentration in surface water ranges from 0.01 to 3 mg·L^{-1} with a clear seasonal pattern with minima in late spring/summer and maxima in winter (BUTTURINI et al., 2008; SABATER et al, 2003). The main cause for seasonal differences in DIN concentration is the higher biological demand during the growing season months. In riparian groundwater nitrate concentration near the stream zone (0.01 mg·L^{-1}) is lower than in stream water, but it increases towards the hill slope up to 3 mg·L^{-1}.

The contribution of storms to nitrate export in stream water is important, ranging from 52 to 87 % of the total annual export through stormflow. The contribution of large storm episodes greatly increased the quantity of exported nitrate (Figure 4, panel a). Overall, the remarkable increases in nitrate concentration during the hydrological year are observed mainly during precipitation events, and during

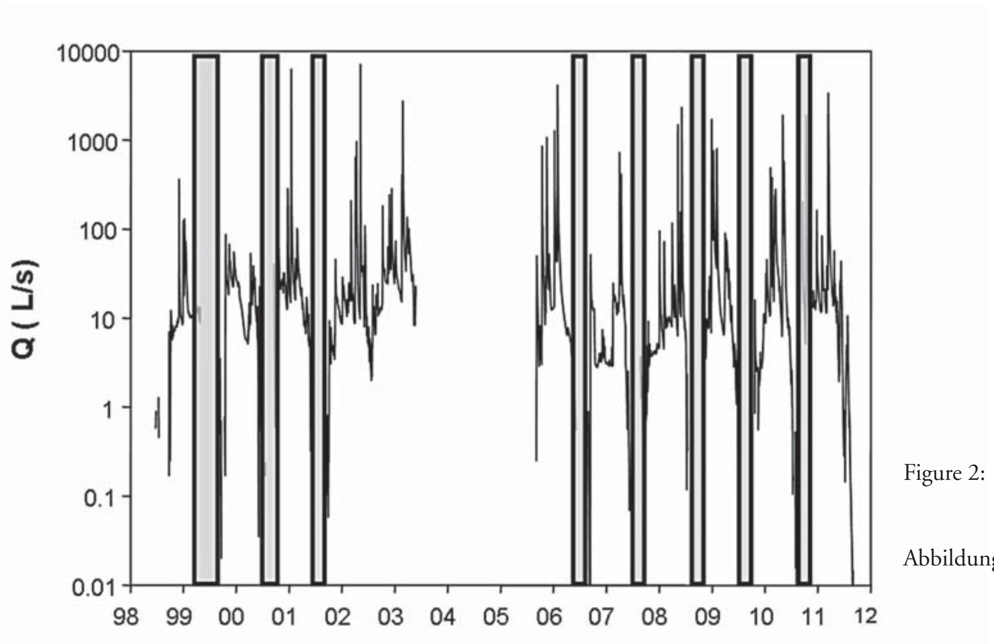

Figure 2: Discharge in Fuirosos main channel for the period 1998–2012. Grey areas mark the dry window

Abbildung 2: Abfluss des Fuirosos-Hauptkanals für den Zeitraum 1998–2012. Trockenperiode grau hinterlegt

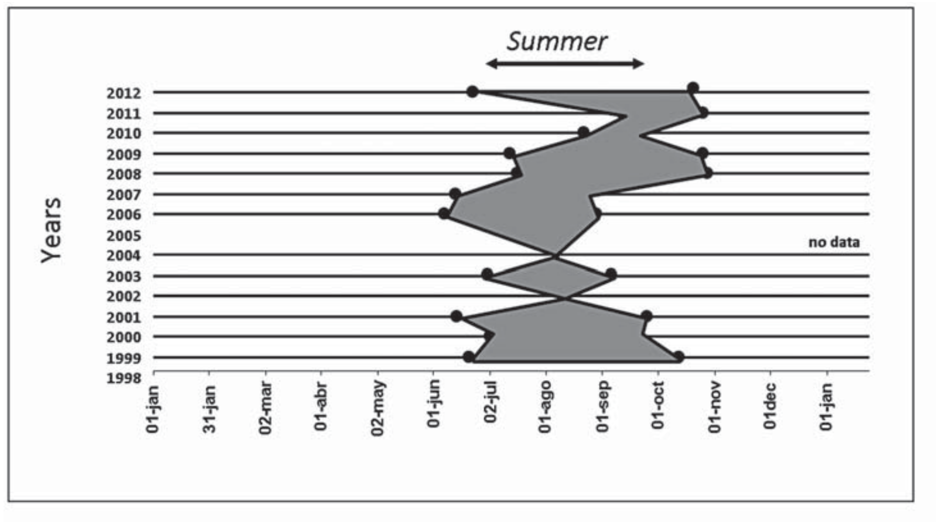

Figure 3: Temporal localization of the dry window from 1998 to 2012. Note that there is no data corresponding to year 2005. The grey area marks the span of the dry period

Abbildung 3: Zeitlicher Verlauf der Trockenphasen zwischen 1998 und 2012. Keine Daten für 2005. Die graue Fläche zeigt die Spanne der Trockenphase

the dry-wet hydrological transition due to inputs into stream water originated by the reconnection between deep groundwater and the upper unsaturated soil layer (BUTTURINI et al., 2003; BERNAL et al., 2005).

Data collected between 1998 and 2001 allowed the estimation of DOC export as 180.7 ± 43.8 kg·km^{-2} yr^{-1}. In stream water, during baseflow conditions, the average DOC concentration varies seasonally, being 3 mg·L^{-1} in winter and spring, and rising to 4–8 mg·L^{-1} in summer and autumn. During intense precipitation events DOC concentration can increase to 3.5 times the pre-flood concentration. DOC hysteretic responses to stormflow show a high diversity which can not be explained by the concatenation of wet, dry and hydrological transition periods (BUTTURINI et al., 2008).

The hydrologic transition window is an important disruption that hinders the determination of a pattern in DOC dynamics. While similar intensities of precipitation events happen during spring and winter under the same antecedent moisture conditions, DOC concentration reaches the highest values during this hydrologic window (Figure 4, panel b). Thus, DOC export/concentration is not driven by geochemical factors exclusively, but also by the accumulation of leaf litter and debris in the riparian strip and streambed during summer (0.45 kg D Wm^{-2}) (ACUÑA et al., 2004).

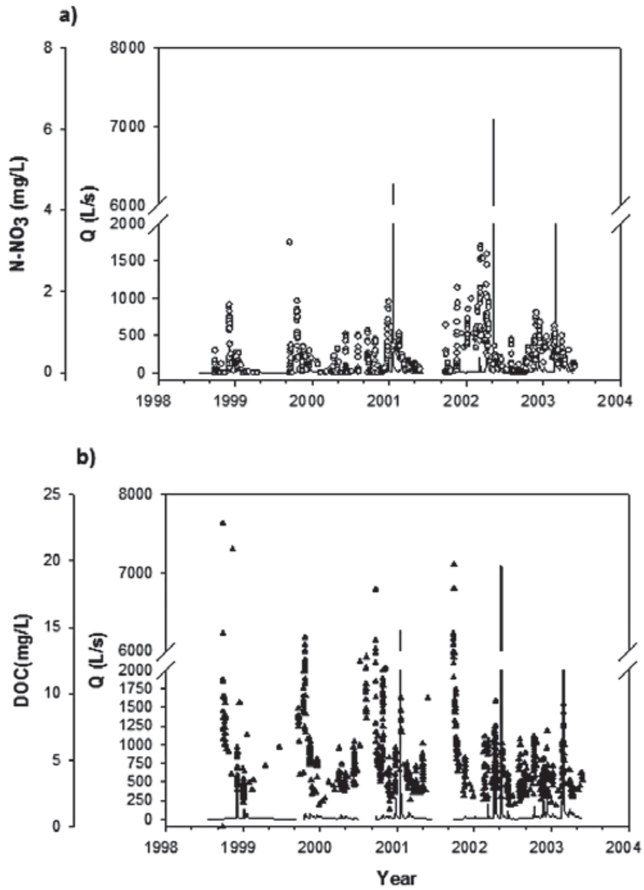

Figure 4: Nitrate (panel a) and DOC (panel b) concentration dynamics for the period 1998–2004. The highest concentration DOC values appear immediately after the dry period while nitrate concentration follows more closely the discharge pattern

Abbildung 4: Konzentration von Nitrat (a) und DOC (gelöster organischer Kohlenstoff, b) von 1998 bis 2004. Hohe Konzentrationen von DOC treten nach Trockenperioden auf, der Konzentrationsverlauf von Nitrat folgt der Abflussganglinie

3.3 Links between hydrology and biogeochemistry

The intermittent hydrological regime in Fuirosos has allowed discerning biogeochemical "hot spots" and "hot epi-

During the dry-wet transition window, the re-establishment of the fluvial continuum is abrupt. It causes an increase in DOC concentration due to the mobilization of riparian zone reserves. Moreover, the shift of hydrological pathways from those observed during the wet window causes the homogenization of DOC properties and bioavailability (see Figure 5). Although DOC bioavailability is momentarily high, it quickly drops to the lower values found during the wet period. It is also during this period that the hydrological connection between surface water and the riparian-stream interface is greatly amplified. Thus, in this interface it can be observed a selective immobilization of DOC according to its molecular weight (VAZQUEZ et al., 2007).

Concerning inorganic nutrients, the DIN:SRP ratio shows that while during the whole wet period Fuirosos is a N-limited system, during the dry-wet transition this ratio is reversed and becomes P-limited for this brief time (Figure 6). The monthly addition of NH_4 and SRP over two years determined that uptake velocity (Vf), that is, the demand of a specific nutrient, was not related to their concentration. Usually the Vf-SRP was higher than Vf-NH_4 during the wet period. However, there was no seasonal pattern, and the peaks of demand ("hot episodes") occurred in every hydrologic period (dry, wet and transition) (Figure 7). On the other hand, Vf-SRP showed a negative exponential relationship with temperature when considering all hydrological periods and, although Vf-NH_4 did not present the same relationship, the ratio between Vf-NH_4 and Vf-SRP exponentially increased with temperature (VON SCHILLER et al., 2008, 2011).

Finally, hydrology strongly shapes the magnitude of fluvial metabolism. For instance, ecosystem respiration (ER) during 2001–2002 averaged 10 g O_2 m^{-2}·d^{-1}. However, during the dry-wet hydrological transition it increases up to 30 gO_2 m^{-2}·d^{-1} as a consequence of elevated benthic organic matter (BOM) accumulation during the preceding drought period (see Figure 8).

4 Conclusions and further research

In Fuirosos, the hydrologic regime influences DOC and NO_3 temporal dynamics. Although both solutes are flushed during storm episodes, the sequence of responses is difficult to categorize and model.

The periodical dry-wet hydrological transition strongly affects to distinct fluvial processes: i) N/SRP Redfield ratio; ii) DOC dynamics and qualitative characteristics; and iii) ecosystem metabolism.

Although there are already many studied topics on biogeochemistry and fluvial ecology in Fuirosos, there are several questions left unanswered. Thus it is necessary to maintain the temporal hydro-biogeochemical monitoring, the nutrient retention and fluvial metabolism estimates as long as possible. In the present, with the restart of livestock raising in close areas to the stream, the necessity for monitoring becomes stronger. The previous fertilization studies should provide an invaluable resource to evaluate the impact that these anthropic activities will have on stream biota.

The dry-wet phase shifting should be further explored on a longer temporal scale where it would be possible to exa-

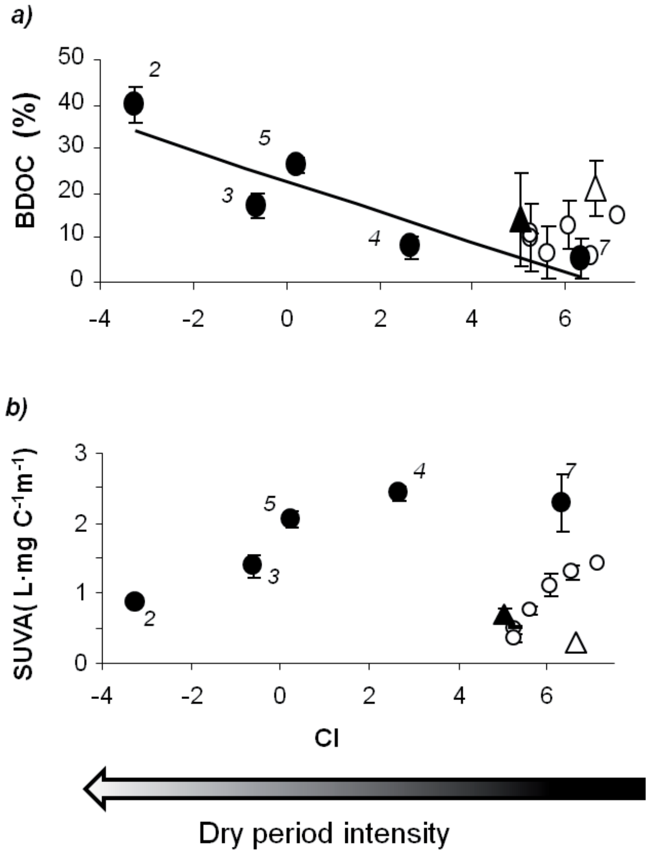

Figure 5: Changes in DOC according to drought intensity reflected by a Chemical Index (CI, see Vazquez et al. 2011 for further information). Panel a) shows changes BDOC (%) and panel b) changes in SUVA254 during the dry period (black dots) and the wet period (white dots). Triangles (white for wet and black for dry period) stand for riparian ground water

Abbildung 5: Änderungen im DOC bezüglich Trockenheit bzw. chemischem Index CI. (a) Prozentuelle Änderung von BDOC und (b) Änderungen von SUVA254 bei Trockenheit (schwarz punktiert) und feuchten Perioden (weiß punktiert). Dreiecke symbolisieren angrenzendes Grundwasser

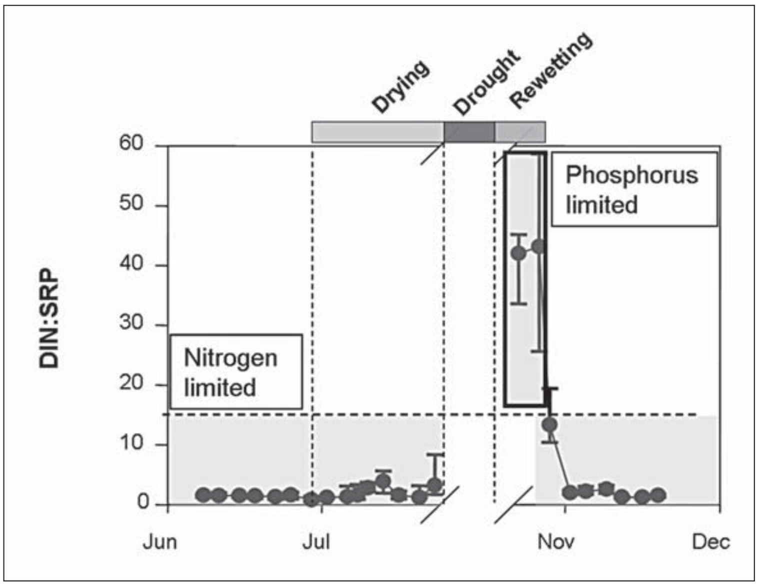

Figure 6: DIN:SRP relationship from June to December 2006. During the dry period, Fuirosos is nitrogen limited (DIN:SRP ratio is lower than Refield ratio), while during the hydrological transition the limiting nutrient is phosphorus

Abbildung 6: SRP-Beziehung Juni–Dezember 2006. Fuirosos ist während der Trockenperioden stickstofflimitiert, während der Übergangsphase phosphorlimitiert

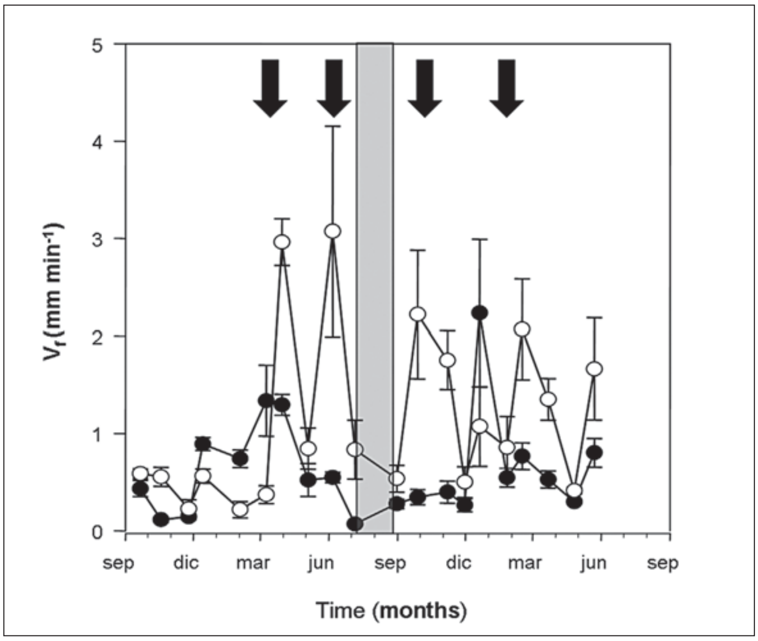

Figure 7: Nitrate (white dots) and phosphorus (black dots) velocity uptake (Vf). Arrows mark “hot moments” of nutrient uptake. There is no clear pattern in the increase of Vf values, indicating that hydrology is not the main driver of these processes

Abbildung 7: Nitrat- (weiß punktiert) und Phosphorentnahme (schwarz punktiert). Pfeile markieren „kritische Bereiche“ der Nährstoffentnahme

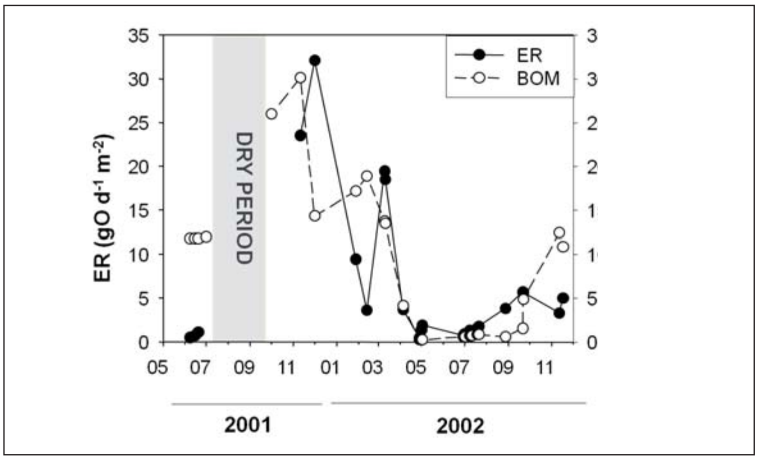

Figure 8: Ecosystem respiration (ER) (black dots) measured in Fuirosos between 2001 and 2002. The highest values correspond to moments where there is a high accumulation of benthic organic matter (BOM) (white dots)

Abbildung 8: Ökosystem-Veratmung (schwarz punktiert) im Fuirosos zwischen 2001 und 2002. Höchste Werte treten während der maximalen Rate benthischer Organismen auf (weiß punktiert) mine how the concatenation of dry periods and storm episodes with different degrees of severity might affect biogeochemical processes concerning dissolved organic matter.

With the recent changes in land use in Fuirosos catchment, the importance of these studies might become more relevant since the stream presented pristine conditions that will probably be altered, and information on the consequences of such activities will surely be useful for future management decisions.

Acknowledgments

This contribution has been partially founded by Ministerio de Economia y Competitividad (project CGL2011-30151-C02).

References

ACUÑA, V., A. GIORGI, I. MUÑOZ, U. UEHLINGER and S. SABATER (2004): Flow extremes and benthic matter shape the metabolism of a headwater Mediterranean stream. Freshwater Biology, 49: 960–971.

BERNAL, S., A. BUTTURINI and F. SABATER (2005): Seasonal Variations of Dissolved Nitrogen and DOC:DON Ratios in an Intermittent Mediterranean Stream. Biogeochemistry, 75(2), 351–372. doi:10.1007/s10533-005-1246-7.

BUTTURINI, A. (2003): Influences of the stream groundwater hydrology on nitrate concentration in unsaturated riparian area bounded by an intermittent Mediterranean stream. Water Resources Research, 39(4), 1–13. doi:10.1029/2001WR001260.

BUTTURINI, A., M. ALVAREZ, S. BERNAL, E. VAZQUEZ and F. SABATER (2008): Diversity and temporal sequences of forms of DOC and NO 3- discharge responses in an intermittent stream: Predictable or random succession? Journal of Geophysical Research, 113(G3), 1–10. doi:10.1029/2008JG000721.

GASITH, A. and V.H. RESH (1999): Streams in Mediterranean climate regions: Abiotic influences and biotic responses to predictable seasonal events. Annu rev Ecol Systems 30: 51–81.

LARNED, S.T., T. DATRY, D.B. ARSCOTT and K. TOCKNER (2010): Emerging concepts in temporary-river ecology. Freshwater Biology, 55: 717–738.

MCMAHON, T.A. and B.L. FINLAYSON (2003): Droughts and anti-droughts: The low flow hydrology of Australian rivers. Freshwater biology, 48: 1147–1160.

ROMANÍ, A.M., E. VÁZQUEZ and A. BUTTURINI (2006): Microbial availability and size fractionation of dissolved organic carbon after drought in an intermittent stream: biogeochemical link across the stream-riparian interface. Microbial ecology, 52(3), 501–12. doi:10.1007/s00248-006-9112-2.

SABATER, S., A. BUTTURINI, J.C. CLEMENT, T. BURT et al. (2003): Nitrogen removal by riparian buffers along a European climatic gradient: Patterns and factors of variation. Ecosystems, 6: 20–30.

STEWARD, A.L., D. VON SCHILLLER, K. TOCKNER, J.C. MARSHALL and S.E. BUNN (2012): When the river runs dry: human and ecological values of dry riverbeds. Ecol. Environ, 10(4): 202–204.

VON SCHILLER, D., E. MARTÍ, J.L. RIERA, M. RIBOT, A. ARGERICH, P. FONOLLÀ and F. SABATER (2008): Inter-annual, Annual, and Seasonal Variation of P and N Retention in a Perennial and an Intermittent Stream. Ecosystems, 11(5), 670–687. doi:10.1007/s10021-008-9150-3.

VON SCHILLER, D., V. ACUÑA, M. RIBOT, S. SABATER, X. TIMONER and K. TOCKNER (2011): Contraction, fragmentation and expansion dynamics determine nutrient availability in a Mediterranean forest stream. Aquatic Sciences, 73, 485–497. doi:10.1007/s00027-011-0195-6.

VÁZQUEZ, E., A.M. ROMANÍ, F. SABATER and A. BUTTURINI (2007): Effects of the Dry-Wet Hydrological Shift on Dissolved Organic Carbon Dynamics and Fate Across Stream-Riparian Interface in a Mediterranean Catchment. Ecosystems, 10(2), 239–251. doi:10.1007/s10021-007-9016-0.

VÁZQUEZ, E., S. AMALFITANO, S. FAZI and A. BUTTURINI (2011): Dissolved organic matter composition in a fragmented Mediterranean fluvial system under severe conditions. Biogeochemistry.

Address of authors

E. Vazquez, E. Ejarque, A.Gaudes, E.Mas-Martí, A. Guarch, I. Muñoz, F. Sabater and A. Butturini, University of Barcelona, dept. of Ecology, Barcelona, Catalonia, Spain.
V. Acuña, J. Artigas, S. Sabater and **D. Von Schiller**, Catalan Institute for Water Research, Girona, Catalonia, Spain.
I. Ylla, A. Romaní and S. Sabater, Institute of Aquatic Ecology, University of Girona, Girona, Catalonia, Spain.
S. Bernal and **E. Martí**, Biogeodynamics and Biodiversity Group, Centre for Advanced Studies of Blanes (CEAB-CSIC) Blanes, Catalonia, Spain.

Corresponding author

Andrea Butturini, Departament d'Ecologia, Universitat de Barcelona, Diagonal 643, 08028-Barcelona, Spain.
E-mail: abutturini@ub.edu
Tel. 34 934021507/Fax : 34 934111438