ECOSYSTEM FUNCTIONING OF TEMPORARY RIVERS

Joana Isabel Caeiro Condeço Rosado

Tese apresentada à Universidade de Évora
para obtenção do Grau de Doutor em Biologia

ORIENTADORES: Maria Manuela Morais
Klement Tockner

ÉVORA, NOVEMBRO DE 2012

INSTITUTO DE INVESTIGAÇÃO E FORMAÇÃO AVANÇADA

UNIVERSIDADE DE ÉVORA

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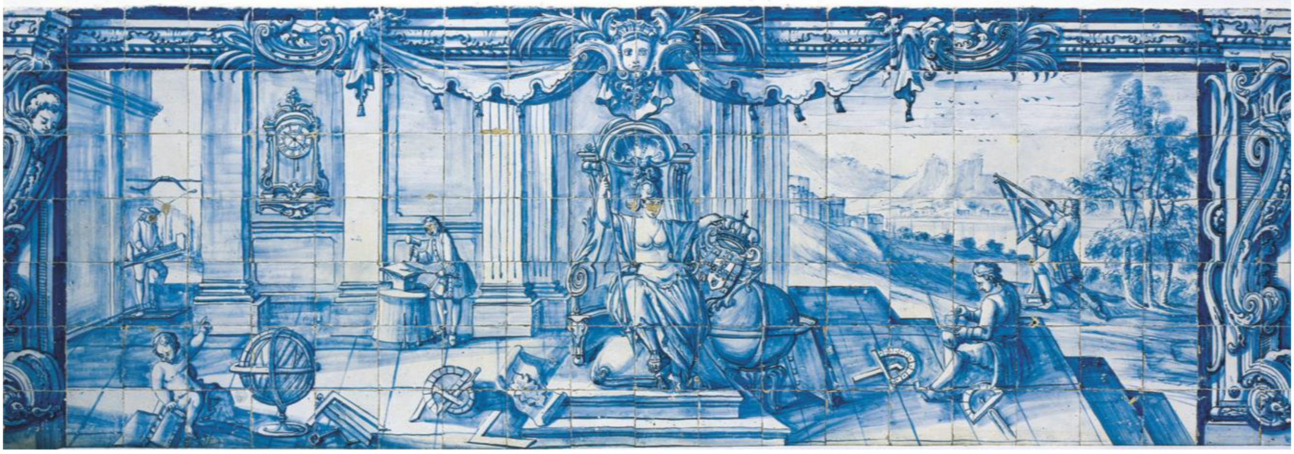

INSTITUTO DE INVESTIGAÇÃO E FORMAÇÃO AVANÇADA

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“To all my family and friends, for all the time I didn’t spend with them…” (M.H. Novais)

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I dedicate this thesis to my wonderful little stars, aunt Quina *and grandmother* Jacinta

who passed away this year.

Funcionamento de ecossistemas de rios temporários

Resumo

O presente estudo abrange questões relevantes sobre o funcionamento de rios temporários. São abordados diferentes tópicos tais como a problemática da escassez de água particularmente na bacia Mediterrânica, a biodiversidade aquática e ripícola, a dinâmica de nutrientes e fatores fundamentais para a gestão e conservação de rios temporários Mediterrânicos. O principal objetivo é estudar alguns dos processos que ocorrem ao nível da bacia de drenagem e galeria ripícola associada, fazendo sempre a ligação dos resultados obtidos com a importância de uma correta gestão da bacia hidrográfica. Os resultados obtidos demonstraram uma necessidade urgente de implementação de estratégias de gestão adequadas ao nível das bacias hidrográficas de forma a reduzir a vulnerabilidade dos rios temporários. A tese pretende acima de tudo adicionar informação sobre rios temporários dada a sua importante representatividade a nível mundial.

Palavras-chave: rios temporários, disponibilidade de água, biodiversidade de água doce, dinâmica de nutrientes, gestão e conservação de bacias hidrográficas

Número de palavras: 133

Ecosystem functioning of temporary rivers

Abstract

This research intended to address some relevant issues concerning the functioning of temporary rivers. It will be approached different topics such as water scarcity particularly in the Mediterranean basin, aquatic and riparian biodiversity, nutrients dynamics and key factors in the management and conservation of temporary Mediterranean streams. The main aim is to study some of the processes that occur within the river basin and subjacent riparian gallery, always linking the obtained data with the importance of a correct river basin management. The results showed an urgent need to implement suitable management strategies at river basin level to reduce the vulnerability of temporary rivers. This thesis intends most of all to increase the knowledge on temporary rivers given their important worldwide representativity.

Key words: temporary rivers, water availability, freshwater biodiversity, nutrient dynamics, management and conservation of river basins

Word Count: 121 words

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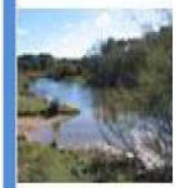

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Chapter 1

General introduction

Chapter 1

1.1 The pivotal role of freshwater ecosystems

Freshwater ecosystems represent around 3% of Earth's water, of which only a small fraction is in the form of lakes and ponds, rivers and streams, reservoirs, wetlands, and groundwater. This small portion of available freshwater is shared by the Earth's 7 billion people (CIA, 2012), highly dependent on freshwater for agriculture, industry, recreation, tourism, and municipal use. The rapid population growth over the past centuries has raised concerns related to the increasing demand for natural resources, which is sometimes faster than their rate of regeneration, and the subsequent negative impact in the environment and humans. Most freshwater ecosystems are threatened mainly due to habitat degradation, overexploitation, pollution, species invasion and global warming. Considering the actual trends, equity in water use for agriculture, industry and human consumption represents a major challenge for the 21st century (Tundisi, 2003; UN-Water, 2006). Currently, the water scarcity constitutes a key hazard to biosphere and humankind (Tisdell, 1991).

Climatic change will have significant impacts on the spatial distribution and availability of the hydrological resources, on water quality, and on the risk of occurrence of droughts and floods (UNEP, 2010). Human-caused perturbations that increase water scarcity will promote the physical uniformity of aquatic ecosystems and lead to a decrease in the biological diversity. The increasing human pressure on water resources together with the effects of climate change, will probably affect the hydrological, the geomorphological, and the ecological status of rivers worldwide (Sabater & Tockner, 2010). Hence, the hydrological systems have been the focus of an increasing consciousness, particularly in respect to the definition of water management strategies and political decisions. Currently, in Europe, different countries are implementing the Water Framework Directive (WFD, Directive 2000/60/EC; Council of the European Communities, 2000), which makes an ecosystem approach as a support of life, assessing the status of running waters, using both physical-chemical and biological indicators (i.e., benthic invertebrates, macrophytes, phytobenthos and fish fauna). However, the management of aquatic resources and the availability of water are complex issues and of huge strategic importance for sustainable development.

1.2 The mediterranean climate rivers[1]

Mediterranean ecosystems are amongst the most intensely utilized ecosystems by man, and for the longest periods of time (Williams, 2006). The anthropogenic perturbations, together with the strong ecological constraints, make mediterranean-type ecosystems especially reactive to

[1] Mediterranean is written with "M" when referring to the Mediterranean basin, and with "m" when referring to climate. This applies to the entire thesis.

management practices as well as to environmental alterations. One of the most characteristic features of mediterranean regions is the occurrence of temporary rivers. The temporary designation includes *intermittent streams,* which have flow during a certain time but it ceases occasionally/seasonally, *ephemeral streams,* which have flow only during and immediately after periods of rainfall or snowmelt, and *episodic streams,* which have flow only during very short periods of heavy rainfall).

While permanent rivers may be found in regions with a relative high and predictable rainfall, temporary rivers are located in regions with low and irregular rainfall and without strong connections to major aquifers, being mainly dependent on rainfall (e.g. Larned *et al*., 2010; Vidal-Abarca, 1990). Temporary streams have been described as more representative worldwide than considerably researched systems with permanent flow (Williams, 1988; Tooth, 2000). The estimation of the total length and discharge of temporary rivers is very rough: they represent about half of the total river length in Australia (Williams, 1983) and South Africa (Uys & O'Keeffe, 1997); at least 3 200 000 km of temporary rivers (60% of total river length) in the United States (Nadeau & Rains, 2007); at least 43% of Greece is drained by temporary rivers (Tzoraki & Nikolaidis, 2007); almost 50% of the 2700 km-long Tagliamento River network (NE Italy) (Doering *et al*., 2007) and nearly all running waters in Arctic and Antarctic regions (Vicent & Howard-Williams, 1986). In Portugal, the preliminary studies indicate that they can represent about half of the total river length (Morais *et al*., *in preparation*).

River flow alterations affect humans, especially in relation to water supply, hydropower generation, and flooding, but also affect ecosystems and its habitat suitability for freshwater-dependent biota (Poff & Zimmerman, 2010). One important consequence of flow regime alteration is the impact on aquatic and terrestrial biota living in the river (Bond *et al*., 2010), on riparian vegetation (Stromberg *et al*., 2005), and it can trigger a sequence of cascading effects that eventually affects the community structure and ecosystem functioning (Sabater & Tockner, 2010). The estimation of changes in rivers seasonality, interannual variability, low and high flows, floods and droughts is required to understand the impact of climate change on humans and freshwater ecosystems (Döll & Schmied, 2012). Hence, the knowledge concerning changing flow regimes is an overriding issue for assessing climate change risks linked to freshwaters ecosystems. Since temporary streams can occupy a huge part of river network in many catchments throughout the world, their true extent is most probably underestimated Larned *et al*., 2010). Thereby, any changes in the duration and extent of drying can generate a flow regime alteration, riparian degradation and lead to the loss of refugia habitats and biodiversity. Indeed, climate change is projected to exacerbate the extent of river intermittency in mediterranean streams (Milly *et al*., 2005; IPCC, 2007). Clearly, every changes in flow regimes will have a direct impact on the structure and function of aquatic ecosystems (Sabater & Tockner, 2010), on aquatic communities and processes (e.g. Boulton, 2003; Lake, 2003), and can affect the density, composition, and dominance patterns of riparian vegetation (Poff & Zimmerman, 2010). Overall, a change in the flow regime alters the relative proportion of input, storage, transfer, and transformation of organic matter and nutrients, and therefore affects the capacity of river networks to produce and transform material and energy (Sabater & Tockner, 2010). The effective conservation of the biodiversity in the mediterranean will require an increased focus on global anthropogenic interferences and their synergistic effects, which even if known, are poorly understood (Underwood *et al.*, 2009).

1.3 Temporary rivers undergo characteristic environmental and biotic cycles

Temporary rivers and streams naturally cease to flow and dry during a certain period. They expand and contract over time in response either to the seasonal flow regime (Stanley *et al.*, 1997; Gasith & Resh, 1999; Doering *et al.*, 2007), either driven by rainfall runoff and water table fluctuations, or by ice- and snowmelt runoff (Stanley & Grimm, 1997; Ward & Tockner, 2001). During maximum contraction, the entire riverbed may become dry. This leads to a temporary loss of aquatic habitats (Lake, 2003). Dry riverbeds are not confined to the headwaters reaches. They can be found in mid-reaches and lowlands, whenever there is a loss of connectivity in river networks (Fig. 1). Many arid and semiarid rivers can be dry over most of their length, and for extended times, apart from the potential presence of perennial, isolated pools (Hamilton *et al.*, 2005).

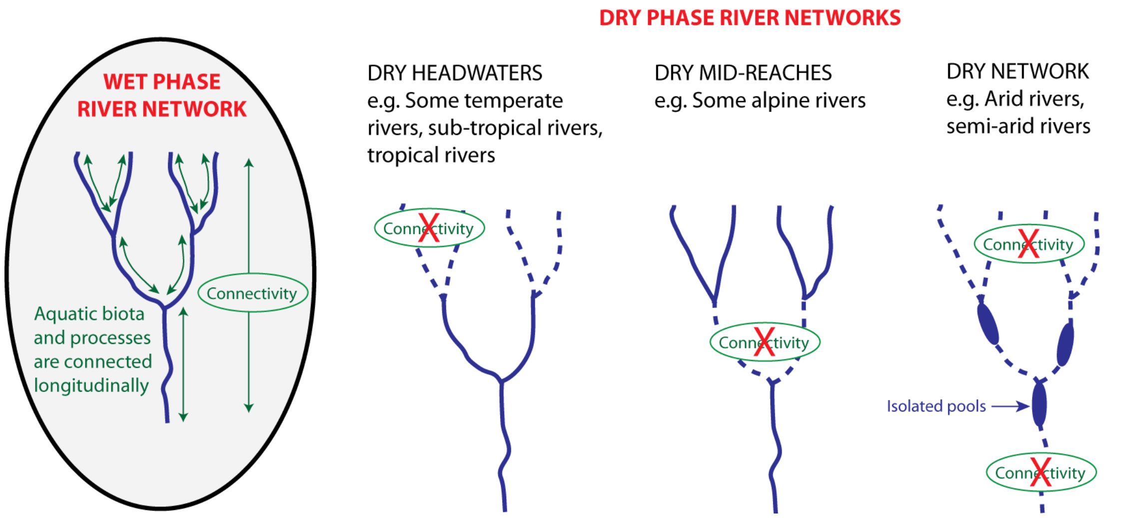

Figure 1. Examples of drying in temporary river basins, and how it interferes in river network connectivity (Steward *et al.*, 2012).

Following flow cessation, the remaining isolated pools undergo several stages until they eventually dry completely. During that period, pools develop specific physical, chemical, and biological characteristics and properties (Smith & Pearson, 1987). Although the drying process may be gradual, the cessation of flow may cause an abrupt loss of habitats, a major alteration of physicochemical conditions in pools, and the fragmentation of the entire river network (Fig. 2a, b, c). Therefore, ecological responses to drying can either be gradual or abrupt (Boulton, 2003; Lake, 2003).

Figure 2. Different phases of Mediterranean temporary rivers: Pardiela Stream (SE Portugal) detail of: summer pool (a), dry riverbed (b), riverbed before flood event (c) and during flood event (d); and Tagliamento River (NE Italy) detail of main channel (e) and pool in vegetated islands (f).

The large variability of climate conditions that are typical for Mediterranean streams may influence the hydrological regime and the input and retention of organic matter (Sabater *et al.*, 2001). Thus, climate variability may result in significant accumulations of organic matter during low flow and to a huge downstream transport during first flood events (Acuña *et al.*, 2004). Indeed, water flow is the most critical force that controls organic matter accumulation and transport in temporary streams (Acuña *et al*., 2004, 2005). The expansion and contraction cycles also lead to "booms" and "bust" periods for both aquatic and terrestrial ecosystem processes and biotic communities such as water birds, fish, and plants (Jenkins & Boulton, 2003). Larned *et al.* (2010) suggested a simple model whereas the aquatic biodiversity of temporary rivers increases with water level, with a subsequent increasing of the proportion of available aquatic habitats and resulting increase in diversity. In their model, the response of terrestrial biodiversity to changes in water level is approximately the opposite of the aquatic response, indicating the linking between aquatic ecosystems, their adjacent terrestrial environments, and the underlying relation of habitat availability and biodiversity maintenance (Larned *et al.,* 2010).

1.4 The importance of dry riverbeds

The dry beds of temporary rivers are an essential part of river landscapes. They are important as seed and egg banks for aquatic biota, as focus of an intense biological diversity of aquatic, amphibious and terrestrial biota, as dispersal corridors, as temporal ecotones between the aquatic and the terrestrial phase (Sabater & Tockner, 2010) and as sites for the accumulation and processing of organic matter and nutrients (e.g. Steward *et al*., 2012). Nevertheless, dry riverbeds have been largely overlooked in the past years (Larned *et al*., 2010), and described as 'biologically inactive, dry channels' (Stanley *et al*., 1997). Frequently they are used for cattle pasture, gravel and sediment extraction, or as recreation places, with large negative consequences in river functioning (Fig.3; Gómez *et al*., 2005). Nevertheless, recent research contradicts this initial assumption and emphasizes the important societal and ecological values of dry riverbeds (Steward *et al*., 2012).

During the dry period, the invertebrate assemblages become'terrestrial', with a shift from an aquatic-dominated assemblage to a terrestrial-dominated (Steward *et al*., 2012). The drying causes the death of many aquatic organisms such as invertebrates and fish (Matthews & Marsh-Matthews, 2003), particularly of those which do not have desiccation-resistant stages or the ability to move to water refugia (Pringle, 1997; Steward *et al*., 2012). Therefore, the duration of the dry period is a vital factor for aquatic biota. Larned *et al.* (2007) observed that with the increasing duration of the dry period the invertebrate richness decreased linearly while the density decreased exponentially. Overall, it is imperative that dry riverbeds are recognized and fully integrated into river management and legislation, which requires suitable monitoring programs.

Figure 3. The cultural significance of dry riverbeds: cattle pasture (a, b), recreation place (c) and sediment extraction/vehicles crossing (d). Photos b) and c) by M. Morais.

1.5 General purpose of the present research

The present research intends to address relevant issues concerning the functioning of temporary rivers ecosystems. It includes key topics such as water scarcity, biodiversity, and ecosystem functioning. The main aim is to study relevant processes within the riverbed and along the riparian corridor, linking the science with an improvement of river basin management. Particular emphasis is given to temporary ecosystems, including their hydrology and ecology as well as current river basin management approaches. Temporary streams are very sensitive to anthropogenic and natural pressures that may modify their hydrology and ecology. Therefore, improvement knowledge is required.

1.6 Thesis framework

This thesis is structured in seven chapters (Fig. 4). Most chapters are based on the analysis of field data collection in Pardiela stream (Guadiana River catchment; SE Portugal). A research reported in *chapter 5* includes data from the River Tagliamento (NE Italy). The thesis includes information of three published papers (*chapters 2* and *3*) and a book chapter (*chapter 6*). The other articles have been submitted or are accepted for publication in a peer reviewed journal (*chapters 4 and 5*). The structure and original content were maintained in the essential. Some of the rules concerning the formatting standard of each publication were revised in this thesis.

Chapter 2 addresses the topic of water scarcity. It is based on two review articles already published: 1) an article regarding the particular aspects of climate change and water scarcity in the mediterranean regions, and 2) an article concerning the strategies for coping with water scarcity in mediterranean regions, comparing with the actual situation in semiarid regions.

Chapter 3 constitutes an important contribution to the limited knowledge of dipterans in Portugal. It allowed the discovery of a new species to science (*Homoneura alata* sp.), the description and illustration for the first time of *Rachispoda ibérica* Roháček female, and the recording of several other new species for Portugal, the Iberian Peninsula and Europe. In the context of a growing awareness of the importance of biodiversity in freshwaters ecosystems, it is expected that this work will help to fill the existent gap in the knowledge of Diptera taxonomy.

Chapter 4 includes a submitted article on floating organic material as an important mass dispersal vector for terrestrial arthropods along the river course. The most important characteristics of temporary streams are the alternation between the dry and wet periods. After the dry period, the first flush floods have a major role in the transport of organic matter and biota downstream and may constitute critical habitats, refugia, and food resources for arthropods assemblage inhabiting the dry riverbed.

Chapter 5 consists of: 1) an article accepted for publication, with the results obtained from sediment sampling and experimental inundation simulations (Tagliamento River, Italy), and 2) an article submitted for publication with data from different type of inputs (allochthonous and autochthonous) to stream channel (Pardiela Stream, Portugal). This chapter confirms the significant role that riparian areas play as potential key energy sources to the aquatic system and downstream areas.

Chapter 6 presents the results of the effects of climate change in a temporary river catchment from southern Portugal. One of the major problems associated with the dry period in temporary catchments is the decrease in water quality, which increases the vulnerability of rivers, both in terms of water quality and ecosystem biodiversity. An important implication of climate change is that it substantially can affect the efforts for a truly sustainable approach of river management in these regions, which are particularly sensitive to anthropogenic pressures.

Chapter 7 presents a summarized overview of the main results of this research and some specific questions to be approach in future studies.

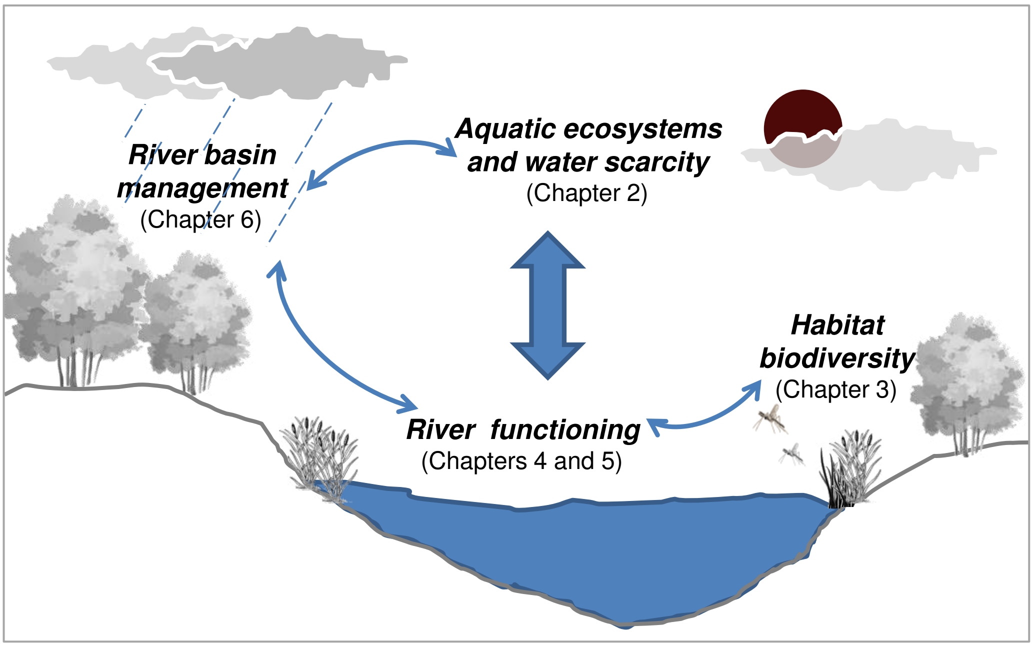

Figure 4. Illustration of the link between the themes discussed in each chapter of the thesis. *Chapter 2* is an overall approach to the theme climate change and water scarcity. *Chapters 4*, *5* and *6* include different themes concerning river functioning and management, and *chapter 3* is a contribution to the knowledge of insect biodiversity.

A number of specific research questions were addressed to each chapter, which can be summarized in the following table:

Table 1. General overview of the major chapters with research questions and main outputs.

	General theme	Research questions | Main outputs
Chapter 2	Main problems concerning the water scarcity in the mediterranean regions	✓*How will climate change and the overexploitation of natural resources affect water availability and biodiversity in mediterranean regions?* ✓*Which strategies are already being applied in order to attenuate the effects of water scarcity? Which other measures can also be adopted?*
		Rosado, J. & Morais, M. (2010) Climate change and water scarcity: from a global scale to particular aspects in mediterranean region (Portugal). In: Sens, M.L. & Mondardo, R.I. (eds.).*Experiences from Brazil, Portugal and Germany*. pp. 15-27. Science and Technology for Environmental Studies, Federal University of Santa Catarina, Florianópolis. **Rosado, J.** & Morais, M. (2010) Strategies for the management of water scarcity in semi-arid and mediterranean climate regions. *Sustentabilidade em Debate*, **1**, 31-46.

	General theme	Research questions | Main outputs
Chapter 3	The importance of temporary streams biodiversity	✓*Considering that dipterans are the most common insects emerging at the beginning of the dry period, and their importance from the environment and human perspective, how limited is the actual knowledge of dipterans in temporary streams biodiversity?*
		Carles-Tolrá, M. & **Rosado, J.** (2009) Some dipterans from Portugal captured by emergency traps (Insecta, Diptera). *Boletín Sociedad Entomológica Aragonesa,* **44**, 343-348.
Chapter 4	Effects of first flood event in dry riverbed	✓*How important are coarse particulate organic matter accumulations (CPOM) in dry riverbed and flood drift deposits as habitat for terrestrial arthropod assemblages?* ✓*How does the arthropod composition change in drift deposits?*
		Rosado, J., Morais, M. & Tockner, K. (submitted to *River Research and Applications*) Mass dispersal of terrestrial organisms during first flood events in a temporary stream.
Chapter 5	The seasonal inundation dynamics and ecosystem functioning	✓ *What are the main potential sources of nutrients in temporary streams? How do first flood events interfere in their annual variation?* ✓*How does the inundation dynamics and temperature influence the release of nutrients and organic matter from sediments in floodplains?* ✓ *What is the effect of first flood events in dried leaf litter?* ✓*What is the role of riparian areas along temporary streams?*
		Ostojić, A., **Rosado, J.**, Miliša, M., Morais, M. & Tockner, K. (2013) Release of nutrients and organic matter from river floodplain habitats: simulating seasonal inundation dynamics. Wetlands, **33** (5), 847-859. **Rosado, J.**, Morais, M., Guilherme, P., Lillebø, A. & Tockner, K. (submitted to *River Research and Applications*) The effect of different nutrient sources and first flood event on system functioning in a Mediterranean temporary stream (SE Portugal).
Chapter 6	Temporary rivers management	✓ *Is there already evidence of an increasing variation in long-term patterns of air temperature and precipitation in southern Portugal that could be due to climate change?* ✓ *What is the best modelling approach to track and predict the presence of dry riverbed reaches in temporary river basins?* ✓ *Which would be the best suitable strategies for the assessment and management of temporary river basins?*
		Rosado, J., Morais, M., Serafim, A., Pedro, A., Silva, H., Potes, M., Brito, D., Salgado, R., Neves, R., Lillebø, A., Chambel, A., Pires, V., Pinto Gomes, C. & Pinto, P. (2012) Key factors in the management

General theme		Research questions | Main outputs
		and conservation of temporary mediterranean streams: a case study of the Pardiela river, southern Portugal. In: Boon, M.P.J. & Raven, P.J. (eds.) *River Conservation and Management*. pp. 273-283. Wiley-Blackwell, Oxford.

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Chapter 2

Main problems concerning water scarcity in the mediterranean regions

Chapter 2

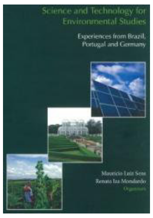
Summary

Water is vital to all life forms. In the 21st century, the water scarcity is a major hazard to humankind survival, as its protection depends on the preservation of the entire biosphere. The growing emissions of greenhouse gases, from burning fossil fuels, are causing global warming and subsequent climate change. The predicted changes in precipitation regimes may cause a decrease in water availability and quality, increasing seasonal and spatial asymmetries and interfering with biological cycles and biodiversity. This will influence both, environment and society, extremely dependent on water availability. As a result, climatic change scenarios have been object of an increasing consciousness, especially in what respects to management strategies and political decisions concerning hydrological systems. Furthermore, the increased water consumption and consequent contamination of aquatic ecosystems, urbanization, agricultural intensification, and land degradation have led to a decrease in water quality and availability. The management of aquatic resources and the availability of water constitute a complex issue of a huge strategic importance for a sustainable development.

In order to make an overview on the main problems concerning water scarcity in the mediterranean regions, this chapter is based on two review articles already published: 2.1) an article regarding the particular aspects of climate change and water scarcity in the mediterranean regions, and 2.2) an article concerning the strategies for the management of water scarcity in mediterranean regions, comparing with the present situation in semiarid regions.

Further articles on this subject from author:

Morais, M.M., Pedro, A., **Rosado, J.** & Pinto, P. (2009) Temporary Rivers: from excess to scarcity. In: Duarte, L.M.G. & Pinto, P. (eds.) *Sustainable Development: Energy, Environment and Natural Disasters*. pp. 37-49. Fundação Luís de Molina, Évora.



Science and Technology for Environmental Studies

Experiences from Brazil, Portugal and Germany

Sens, M.L. & Mondardo, R.I. (eds.) / Federal University of Santa Catarina,

Florianópolis, Brasil, 2010, Pages 15-27

2.1 Climate change and water scarcity: from a global scale to particular aspects in Mediterranean region (Portugal)

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Abstract

Climate change is the key environmental problem that our planet faces today. The growing emissions of greenhouse gases from burning fossil fuels are causing global warming and subsequent climate change. This will influence both, environment and society, extremely dependent on water availability. Changes in precipitation regimes may cause a decrease in water availability and quality, increasing seasonal and spatial asymmetries and interfering with biological cycles and biodiversity. The decrease in water availability is particularly important in catchments with temporary tributaries, where most of the streams are directly dependent of precipitation to maintain their superficial flow. It is predicted that in a near future, the Mediterranean regions will face serious problems of water scarcity. Considering the foreseen climate change predictions to Mediterranean, the perpetuation of this type of systems will mostly depend on fitting politics and on the sustainable use of water resources.

Key words: biodiversity, climate change, drought, Mediterranean region, water scarcity

2.1.1 Introduction

In the 21st century the scarcity of water is a reality, constituting a major hazard to biosphere and humankind (Tisdell, 1991). Currently, there has been a significant increase in arid and semiarid areas, due to desertification and climatic changes. However, water scarcity is not confined to arid and semiarid areas; it also occurs in mediterranean climate regions, where most tributaries of large rivers catchments are temporary. By definition, temporary streams are generally characterized by the interruption of the superficial flow or a total loss of water, during the dry period, and the occurrence of flash floods, during the wet period (Gasith & Resh, 1999).

Climatic change might have significant impacts in the spatial distribution and availability of the hydrological resources, in water quality and in the risk of occurrence of extreme events such droughts and floods. The impacts of economic and social activities can intensify pressures on water supplies, increasing the amount of affluent pollutants to water bodies (Cunha *et al.*, 2002). As a result, climatic change scenarios have been object of an increasing consciousness, especially in what respects to management strategies and political decisions concerning the hydrological systems. The understanding and prediction of the boundary between the changes in the hydrological systems and consequences to human society is the basis for the sustainable use of water. This review intends to summarize the particular aspects of climate change and water scarcity, giving particular emphasis to the Mediterranean basin.

2.1.2 Climate change at a planet extend

Climate change is the main environmental problem that our planet faces today. The growing emissions of greenhouse gases from burning fossil fuels are causing global warming and subsequent climate change. Direct observations and modeling indicate that since the 1970s that the tropical belt is increasing (UNEP, 2010). The observed rate of expansion over the last decade has already exceeded climate model projections for the entire 21st century (Yohe *et al.*, 2007). The southwestern part of North America may already switch from a sporadic to a perennial drought climate (MacDonald *et al.*, 2008). Southeastern Australia has experienced the lack of water for almost a decade (Isaac & Turton, 2009). Other regions expected to suffer persistent drought and water scarcity in future years include southern and northern Africa, the Mediterranean basin, much of west Asia, a wide group through central Asia and the Indian subcontinent (UNEP, 2010).

The global mean surface air temperature is continuing to increase (Fig. 1). The years 2000-2009 constituted the warmest decade since records for global temperatures were established, in the mid-19th century (UNEP, 2010). According to analyses of the Goddard Institute for Space Studies, the warmest year recorded remains 2005 (GISS, 2009). Actual models predict that as the world consumes more fossil fuel, greenhouse gas concentrations will continue to rise and Earth's average surface temperature will rise with them. Based on a range of possible emission scenarios, average surface temperatures can raise between 2°C and 6°C by the end of the 21st century (Yohe *et al.*, 2007).

Overall, global tendencies show that thet future impacts of climate change must be integrated not only in the management policies of water resources, but also concerning the legislation to reduce greenhouse gas emissions, as considered in the Kyoto Protocol (UNFCCC, 1998).

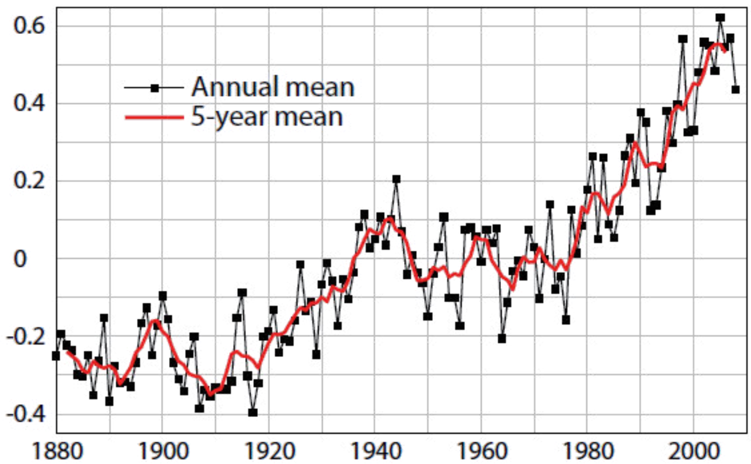

Figure 1. Global surface air temperature variation between 1951 and 1980 (adapted from GISS, 2009).

2.1.3 Global water scarcity

Water is an essential resource to sustain life but its access is not easy for millions of people for reasons that go beyond the physical resources. Water scarcity, defined in terms of the access water resources, affects one in three people on every continent of the globe (WHO, 2009) and is a considerable limitation to agriculture in many parts of the world. In some places water is abundant but the lack of infrastructures or restricted access makes it difficult to obtain (economic scarcity). In the other hand, in some places, people's demands go beyond the natural resources availability and the access to water cannot be guaranteed to everyone (physical scarcity; Molden *et al.*, 2007). A fifth of the world's people live in areas of physical water scarcity, where the water availability is not sufficient to everyone's demands. Actually, about 1.6 billion people live in basins that face economic scarcity (Molden *et al.*, 2007). This has further implications in human health since without water a healthy and clean living environment cannot be maintained (WHO, 2009). The situation is getting worse as water exploitation increases together with the increasing of population, urbanization, and domestic and industrial uses.

2.1.4 The mediterranean regions

All over the world, there are five regions with mediterranean climate. They are located between 30º-45º N and S of the Equator in the Mediterranean basin, California, Chile, South Africa and Australia (the South-West and South; Fig. 2). All these areas represent from 1% to 4% of the earth total surface (Mooney, 1982). The largest area comprises the Mediterranean Basin, which has given the climate its name. Besides the discrepancies among scientists concerning the description and delimitation of the extension of mediterranean climates (Nahal, 1981), it is defined in terms of precipitation (Di Castri, 1973) and temperature (Aschmann, 1973), and is characterized by a high seasonality, with hot/dry summers and cool/wet winters (Gasith & Resh, 1999).

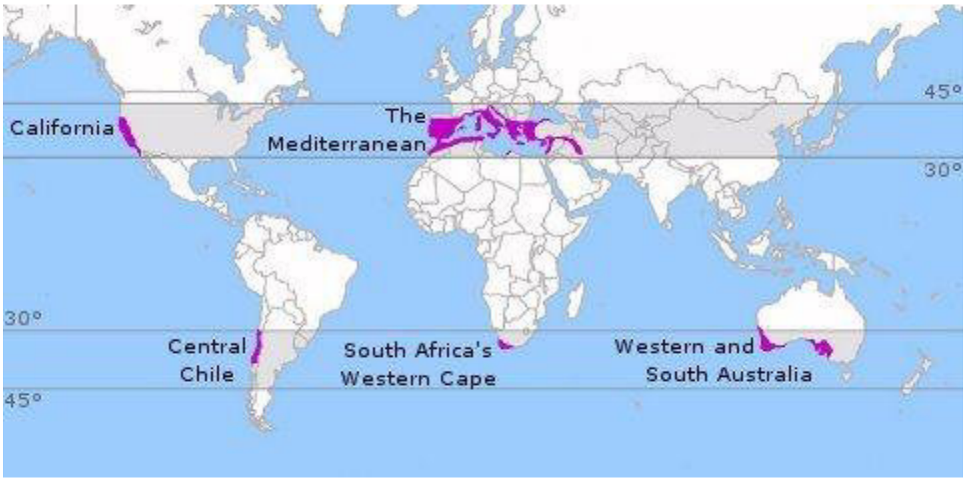

Figure 2. Map of the distribution of mediterranean climate over the world.

The Mediterranean basin is one of the world's richest places considering animal and plant biodiversity. It is particularly distinguished for its high biodiversity (Cuttelod *et al.*, 2008), being recognized as one of the first 25 Global Biodiversity Hotspots (Myers *et al.*, 2000). Nevertheless, urbanization, pollution and overexploitation of natural resources are leading to an increasing in the high risk of extinction of a large number of species. The International Union for Conservation of Nature (IUCN) is coordinating a process to evaluate the conservation status of some taxonomic groups. Some of them have been assessed at the global level (amphibians, birds, mammals and reptiles), while others have been evaluated regionally (cartilaginous fishes, cetaceans, crabs and crayfish, endemic freshwater fishes and Odonata (dragonflies and damselflies). The results confirmed that there is already a worrying number of species classified as Critically Endangered, Endangered or Vulnerable, especially endemic freshwater fishes, mammals and amphibians (Tab. 1). In general, the proportion of threatened species in the Mediterranean basin (those classified as Critically Endangered, Endangered or Vulnerable), at the global or at the regional level, is about one fifth (19%) and about 1% of the species are already extinct in the region (Cuttelod *et al.*, 2008).

Mediterranean ecosystems are amongst the most intensely utilized by man (Williams, 2000). The anthropogenic interferences have strong ecological constraints in mediterranean-type ecosystems. The use of water for agriculture and industry is high, and is predicted to have an increase of 50% until 2025, which will lead to an increase of temporary rivers (Tockner & Stanford, 2002). Recent studies suggest that, by the end of the 21st century, the Mediterranean will experiment a more severe aridity, in terms of water stress and desertification, than earlier estimated (Gao & Giorgi, 2008; Yohe *et al.*, 2007). The last highest resolution projections showed a substantial northward expansion of dry and semiarid regimes in the region (Gao & Giorgi, 2008). This implies a retreat of temperate oceanic and continental climate regime, which will involve a predictable shift in cover vegetation (Iglesias *et al.*, 2007). Occurrences of what are now considered high-temperature edges can raise up to 200-500 percent until the end of the century (Diffenbaugh *et al.*, 2007).

Table 1. Numbers of species from Mediterranean basin countries assigned to each IUCN Red List category, by taxonomic group. Assessments carried out between 2004 and 2008 by IUCN and partners. Data Deficient means that there is not enough information to assign the species to a category; does not imply that the species is not threatened (adapted from Cuttelod *et al.*, 2008).

IUCN Red List Categories	Amphibians[1]	Birds[1]	Cartilaginous fishes[2]	Crabs and Crayfish[2,3]	Endemic Freshwater fishes[1,4]	Mammals[1]	Dragonflies[2,4]	Reptiles[1]
Extinct[5]	1	1	0	0	8	2	4	0
Critically Endangered	4	6	13	0	45	5	5	14
Endangered	13	9	8	3	46	15	13	22
Vulnerable	16	13	9	2	51	27	13	11
Near Threatened	17	29	13	4	10	20	27	36
Least Concern	63	543	10	5	52	231	96	253
Data Deficient	1	0	18	0	41	30	6	19
TOTAL	**115**	**601**	**71**	**14**	**253**	**330**	**164**	**355**
Endemic	71 (62%)	16 (3%)	4 (6%)	7 (50%)	253 (100%)	87 (26%)	23 (14%)	170 (48%)

Legend: (1) Species assessed at the global level; (2) Species assessed at the regional level; (3) Preliminary data; still to be confirmed by the IUCN Red List Authority; (4) Only the species occurring in river basins flowing into the Mediterranean Sea and adjacent Atlantic waters were included; (5) "Extinct" includes the categories Extinct, Extinct in the Wild and Regionally Extinct.

Bladé & Díez (2010), using different precipitation databases - E-OBS and CRU TS3.0, calculated annual precipitation tendencies for the Iberian Peninsula, for the time series 1950-2006 and 1960-2006 (Fig. 3). Obtained data show negative tendencies in the most part of Iberian Peninsula from 1960-2008, together with an overall decreasing of precipitation in the entire Mediterranean, especially in northwest Africa, Italia, Balkan region and Turkey. As Mediterranean rivers discharge is related to rainfall patterns, climate change will inevitably have a negative impact on them. Models predictions show that the Mediterranean basin will be affected more than any other European area. While permanent rivers may be found in areas with a relative high and predictable rainfall pattern, ephemeral rivers are located in areas with low and irregular rainfall and without connection to main aquifers, being higly dependent on rainfall. As a result, permanency or temporality are mainly functions of precipitation, microclimate patterns and freatic level (Bonada *et al.*, 2003; Vidal-Abarca, 1990). Since intermittent and ephemeral streams can occupy a huge part of channel length in many catchments, their true extent is underestimated by most the available hydrologic data (Larned *et al.*, 2010). Additionally, human actions that create flow regime alterations may increase the intermittency of streams and droughts occurrence.

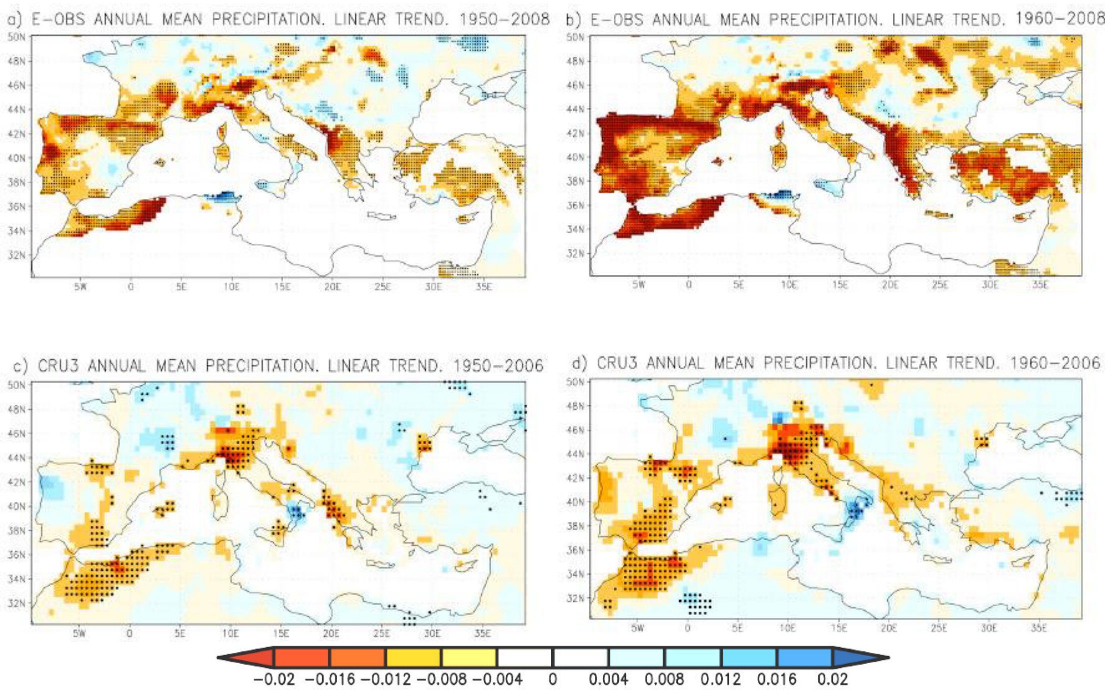

Figure 3. Mean annual precipitation tendencies (mm/day/year) obtained from E-OBS and CRU TS 3.0. databases, to time series 1950-2006 (left, 2008 to E-OBS) and 1960-2006 (right, 2008 to E-OBS). Black dots shows significant tendencies with 95% confidence level ($p<0.05$), Mann-Kendall test. White regions show areas without enough available data (adapted from Bladé & Díez, 2010).

Drought is one of the major natural hazards, resulting in significant economic, social, and environmental costs. By definition, drought is a normal recurring climatic feature and its frequency, duration, severity and extent may vary in space and time (Lake, 2008). In Europe, for instance, water shortage is an important problem in many regions but despite the increasing awareness of this hazard, the drought policies are only weakly developed (Vogt & Somma, 2000). Nevertheless, the survival of Mediterranean ecosystems will definitely depend on fitting politics and on sustainable water uses.

2.1.5 Droughts in Portugal

Due to its location, Portugal is vulnerable to the occurrence of droughts, and so this phenomenon is not considered as an extreme event but as an endemic characteristic of its climate (Afonso, 2007). Portugal has an average annual precipitation between 800-1000 mm similar to most of EU Member States, with a well-defined seasonal variability. During the the wet period (from autumn to spring) it rains around 70-80% of the total annual precipitation (Afonso, 2007). The temporal precipitation variability within the years frequently leads to severe problems of water scarcity in some regions during the dry period, where the average runoff can be less than 10% of the average annual runoff (Afonso, 2007). Meteorological data indicates that the

Portuguese climate suffered, throughout the 21st century, an evolution characterized by changes on the average temperature. Indeed, in the last 70 years Portugal has experienced several droughts (Tab. 2).

Table 2. Droughts in Portugal in the last 70 years (adapted from Afonso, 2007).

Data	Implications
1944-1945	2 years duration, affecting the whole country
1953-1954	2 years duration, affecting 50% of the country
1975-1976	1,5 years duration, affecting 40% of the country
1981-1983	2,5 years duration, affecting 90% of the country
1992-1993	2 years duration, affecting the whole country
2004-2006	2 years duration, affecting the whole country

During the 2004-2006 droughts were established new organizational efforts to cope with its impacts at a national level. The management efforts also led to the development of new methodologies, actions, and public participation, strengthening future lacks in drought management (Afonso, 2007). This droughts affected rivers, agricultural productions and population. The water level of the reservoirs decreased and made the water distribution to the population harder. In many parts of the country, January of 2005 was the driest month in last the 100 years (IM, 2005). The impact of this drought was remarkably clear in the satellite images (http://earthobservatory.nasa.gov). During those droughts Portugal spent about 300 million Euros, from which 23.2 million was in urban water supply (Kraemer, 2007). During this period, several reservoirs in the south Portugal (e.g. Funcho and Arade in Algarve) had a significant decrease in the water level (Kraemer, 2007). Several streams from southern Portugal remained dry during almost the entire hydrological year, only exhibiting flow at the time of the first flood event.

2.1.6 Final remarks

Several regions of Europe and, in particular, the Mediterranean basin will be negatively affected by climate change. The patterns of occurrence of extreme events like droughts may increase, intensifying the already existing water scarcity problems. Public water supply systems in Europe provide a service at a low cost, which is an advantage to consumers but does not foster the decrease in consumption. In such circumstances, the economic impact of droughts on public water supply is best estimated by applying restriction measures on water use or interruptions in the supply. According to Kraemer (2007), around 50 million inhabitants were affected during the 2004–2006 droughts in Portugal, and restrictions have led to a decreasing in water consumption of 10% average. In the Mediterranean region, the predicted lower and more irregular rainfall patterns and higher air temperatures (Bolle, 2003), will have consequences in the water availability of surface and aquifer systems. Furthermore, the increasing growth of sectors such as agriculture and/or tourism will intensify the water demand (Gleick, 1993). Nevertheless, the increasing global demand for food should always be a priority for security reasons. Even though some water savings in agriculture can be expected, additional water storages may be required (e.g. cisterns, long-distance water transfers between countries, artificial recharge of aquifers; Morais *et al.*, 2009). Even though water resources usages and storage were key topics, as it is directly related to human survival, the maintenance of ecological resources should never be neglected.

In summary, changes in precipitation regimes may cause a decrease in water availability and quality, increasing seasonal and spatial asymmetries, interfering with biological cycles and biodiversity. Even in the Mediterranean basin, typically covered by vegetation adapted to dry and warm conditions, species richness can decline (Gitay *et al.*, 2002). The impacts of climate change on sea level might also affect groundwater levels, thus influencing the water resources availability (Chen *et al.*, 2004). The decrease in water availability should be particularly important in catchments with temporary tributaries, where most of the streams are directly dependent of precipitation to maintain their superficial flow. Considering the foreseen climate change predictions to the Mediterranean and that in temporary streams catchments most tributaires rapidly dry after the superficial flow interruption (Rosado *et al.*, *submitted*), the survival of this type of systems will depend on fitting politics and on the sustainable use of water resources.

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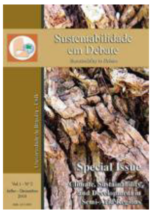

Sustentabilidade em Debate

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2.2 Strategies for the management of water scarcity in semiarid and mediterranean climate regions (*Estratégias de gestão da água em situação de escassez: regiões semiáridas e mediterrâneas*)

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Extended abstract

At the beginning of the 21st century, the shortage of water is irrefutable, constituting a major threat to biosphere and humankind. As water plays an important role in human health and nutrition, by performing different functions in industry and in energy production, the pressures associated with the increased water consumption are a constant source of conflict. The poor spatial and temporal distribution of water causes social imbalances that affect human health and generate global conflicts (Ragab & Hamdy, 2004). Furthermore, the increased water consumption and consequent contamination of aquatic ecosystems, urbanization, agricultural intensification and land degradation have led to a decrease in water quality and quantity. This associated with global warming and climate change is constantly increasing pressures on water resources (Vörösmarty *et al.*, 2000; Kundzewicz *et al.*, 2007; Bates *et al.*, 2008). The management of aquatic resources and the availability of water constitute a complex issue of a huge strategic importance for a sustainable development. Some nations, particularly in Europe, have already implemented new laws and regulations to protect water sources (Council of the European Communities, 2000). Moreover, in the context of climate changes, it becomes necessary to develop strategies that promote the availability of water. A correct management of water resources requires a distinct change in the behavior of institutions and individuals. It is estimated that climate change has already lead to a 20% increase in global water scarcity, posing a threat to the future of humankind (IPCC, 2007; UNEP, 2010). Countries that already experience water shortage will be the most affected with the additional problems arising from climate change (Kundzewicz *et al.*, 2007; Bates *et al.*, 2008). It is expected that the increase of average temperature and consequent changes in extreme values of precipitation and

temperature, will affect the availability of water by changes in rainfall distribution, soil moisture, melting of polar ice, flow of rivers and groundwater (e.g. Bates *et al*., 2008; WWAP, 2009). It is estimated that in 2025, 3.4 billion people could be subject to water shortage, which will lead to the worsening of regional and social inequalities (Calzolaio, 2009).

The main objective of this review is to present and discuss strategies for the water management in semiarid and mediterranean climate regions. Based on the available literature were presented different techniques that improve the availability of water and allow its sustainable use, such as cisterns, dams, groundwater reservoirs and surface water diversions. Rain harvesting trought cisterns is increasing its importance as an option to augmenting water sources availability. It is a practice that extends back to pre-biblical times (Pereira *et al*., 2002) and it still being applied nowadays in different countries as China ("1-2-1" program; Cook *et al*., 2000) and Brazil ("One Million Rainwater Harvesting Programme - P1MC"; ASA, 2010). Diverting surface waters into e.g. nearby basins, lagoons, ditches or injection wells to recharge aquifers, are other technique used to deal with the natural variability. This practice is being applied in different regions from arid and semiarid, throughout the Middle East and Mediterranean regions (UNESCO, 2006). The construction of reservoirs has been commonly the answer to the growing water demand for hydropower, irrigation, human supplies, fishing and recreation, as well as to lower the impacts and risks from high-intensity events such as floods and droughts (UNESCO, 2006). Their construction is vital to grant water availability, but it has a considerable impact on the Earth's ecosystems and landscapes, with consequent interference in the hydrological cycle. Despite the benefits that population obtains from reservoirs, there is a recurrent debate about how to prevent/reduce the social and environmental consequences that come from building reservoirs (e.g. the ongoing National Programme of High Hydroelectric Potential Reservoirs in Portugal). Recent studies developed in the semiarid regions of northeastern Brazil point out to the need to store water mainly in underground dams, with ancient techniques used by small farmers (Carvalho *et al*., 2009). The underground dams are built within the streambed of rivers in alluvial areas. They are constructed perpendicular to the river, in order to retain moisture in the soil, increase agricultural productivity and facilitate the exploitation of small and medium-sized farms, especially those that do not have water for use in conventional irrigation (Silva & Porto, 1982). The underground dams have main advantages such as the accumulation of water with reduced evaporation, lower risk of salinity (if properly exploited) (Brito *et al*., 1989). The treateament of wastewater can be considered as a "new" water feature to add to its overall availability. It can be used for irrigation and other purposes rather than public supply, thus contributing to a decrease in the water demand (Crook, 1998). However, irrigation with untreated wastewater can be hazardous to human health, since it may contain pathogenic bacteria, viruses, unwanted organisms, heavy metals and organic contaminants (UNEP, 2010). In this sense, its use should be made with caution, and only after treatment and the implementation of monitoring programs to ensure that the water do not represent a risk to human, animal and environmental health. In addition, other techniques more expensive, such as water transferring between river basins, desalination of seawater, and recharging of aquifers, are also referred since they may often be required. The transferring of water from one river basin or aquifer to another basin has been used as a method to overtake water constrains, particularly in arid and semiarid regions. Is frequent in areas where agricultural demands have exceeded the existing water resources. There are many long-distance schemes in different areas, some of them recently constructed. An example is the Ganges-Brahmaputra-Meghna system (UNESCO 2006), to overlap the problem related to recurring droughts and floods through both India and Bangladesh. Another example is the water transfer system of the River Sao Francisco in Brazil, which includes the construction of two set of canals and dams that will link hundreds of kilometers in the semiarid area (Hauschild & Dóll, 2000). Desalination is used mainly in water-scarce coastal arid and semiarid areas, which are located inland, where the only available water source is saline or brackish groundwater. While offering a high cost per m^3 when compared with other techniques, the process is effective to provide drinking water in regions where water availability is already or is becoming limited.

Overall, the reduced ecological resilience, caused by the degradation of ecosystems and increased droughts, strengthen the social and environmental vulnerability, creating conflicts concerning freshwater and food, particularly in semi-arid regions, where the lack of water is a constant. The key challenge of water managers is to optimize ecosystem resilience in response to anthropogenic and natural disturbances and protect this resilience within a catchment level and throughout life-support systems. The semiarid regions, due to their characteristics, will naturally suffer more with water scarcity. Thereby, these regions, with particular emphasis on the northeast region Brazil, China and some semarid regions in India, have seen the implementation of different low cost techniques to capture rainwater. Regarding the Mediterranean basin, all future scenarios provide an increase in temperature associated with a decrease in the precipitation. This future trend will have major impacts on aquatic ecosystems, extremely vulnerable in terms of biodiversity. Thereby, prevention strategies and new technologies that enhance the existing natural water resources and reduce its demand are part of the solution.

Key words: management of aquatic ecosystems, mediterranean climate regions, semiarid climate regions, water use, water scarcity

2.2.1 Introdução

Á água é um bem essencial indispensável à vida. Tem um papel importante na saúde humana e alimentação, desempenhando diferentes funções na indústria e na produção de energia. As pressões associadas ao aumento do consumo de água são uma constante fonte de conflito. A deficiente distribuição espacial e temporal da água provoca desequilíbrios sociais, que vão afetar a saúde humana e a gerar conflitos globais (Ragab & Hamdy, 2004). Os conflitos relacionados com a água remontam à antiguidade, sendo possível identificar a existência de competição por este importante recurso em todos os períodos da história da humanidade (Gleick, 1998). Apesar da sua importância, só recentemente a água recebeu o seu valor apropriado. O valor económico da água é um dos aspetos mais importantes da gestão dos recursos hídricos. Compete a todos os países assegurar a sua adequada disponibilidade e garantir que, quando utilizada para abastecimento ou para outros fins, seja usada corretamente e com o valor adequado. As políticas respeitantes à economia da água devem garantir uma melhor eficiência na sua utilização, integrando simultaneamente o desenvolvimento social e a sustentabilidade ambiental. Não obstante, a comercialização da água e os serviços relacionados com esta, continuam a aumentar. Os conflitos associados ao uso dos recursos hídricos tendem a concentrar-se em bacias hidrográficas transfronteiriças, especialmente quando combinados com uma baixa disponibilidade de água (Halle, 2009). O principal objetivo da gestão da água é definir estratégias que conduzam a uma maior disponibilidade e melhoria da sua qualidade, à produção de alimentos e à diminuição da pobreza, ao mesmo tempo que minimizam os impactos negativos na saúde humana e no ambiente (Drechsel *et al.*, 2009).

O crescente consumo de água e a consequente contaminação dos ecossistemas aquáticos, o aumento da urbanização, a intensificação agrícola e a degradação dos solos, têm conduzido a uma diminuição na sua qualidade e quantidade. Adicionalmente, o aquecimento global associado às alterações climáticas verificadas nos últimos anos está a intensificar a pressão sobre os recursos hídricos (Vörösmarty *et al.*, 2000; Kundzewicz *et al.*, 2007; Bates *et al.*, 2008). No sudoeste da Austrália a disponibilidade de água está a diminuir sensivelmente há uma década (Isaac & Turton, 2009). Prevê-se que a escassez da água aumente nos próximos anos na bacia do Mediterrâneo, em grande parte da Ásia Ocidental e Central e no subcontinente indiano (Kundzewicz *et al.*, 2007; Bates *et al.*, 2008; Isaac & Turton, 2009). Estima-se que as alterações climáticas já conduziram a cerca de 20% no aumento global da escassez da água, constituindo uma ameaça para o futuro da humanidade (IPCC, 2007; UNEP, 2010). Os países que já sofrem com a escassez serão os mais afetados com os problemas adicionais decorrentes do efeito das alterações climáticas (Kundzewicz *et al.*, 2007; Bates *et al.*, 2008). É expectável que o aumento da temperatura média e consequentes alterações nos valores extremos de precipitação e de temperatura, afetem a disponibilidade de água através de alterações na distribuição da precipitação, da humidade do solo, do degelo das calotes polares e do escoamento de rios e de águas subterrâneas (p. ex. Bates *et al.*, 2008; WWAP, 2009). Uma vez que a água doce circula no nosso planeta através do ciclo da água, o volume disponível permanecerá igual, consequentemente, se a exploração e degradação da água continuar a aumentar, prevê-se uma diminuição mundial na sua disponibilidade *per capita*. Estima-se que em 2025, 3.4 mil milhões de pessoas poderão ficar sujeitas a situação de escassez de água, facto que conduzirá ao agravamento das desigualdades regionais e sociais (Calzolaio, 2009).

O principal objetivo deste trabalho é apresentar e discutir a gestão da água em regiões semiáridas e mediterrâneas ameaçadas pela escassez, apresentando estratégias para uma gestão sustentável da água e da biodiversidade. Nesse sentido, com base numa análise da literatura disponível para o tema em análise, são apresentadas diferentes técnicas que permitem a utilização sustentável da água (cisternas, açudes e barragens subterrâneas, desvio de água superficial, tratamento de águas poluídas). Adicionalmente referem-se outras técnicas mais dispendiosas, mas muitas vezes necessárias, tais como a transferência de água entre bacias, a dessalinização da água do mar, e a recarga de aquíferos.

2.2.2 Regiões de clima semiárido e mediterrâneo

As regiões com clima árido e/ou semiárido cobrem cerca de um terço da superfície de terra. As regiões semiáridas são caracterizadas por um clima seco, no qual a evapotranspiração potencial é superior à precipitação anual. Estes climas estendem-se entre as latitudes 20-35°, a norte e a sul do Equador, e em grandes regiões continentais, frequentemente rodeadas por montanhas (Lohrnann *et al.*, 1993). Existem duas variantes no clima semiárido, um clima semiárido quente (p.ex. Tijuana-México e região nordeste do Brasil), e um clima semiárido frio (p.ex. Punta Arenas-Chile). Devido a processos de desertificação e às alterações climáticas, atualmente tem-se assistido a um aumento progressivo das áreas de clima árido e semiárido (Schlesinger *et al.*, 1990).

O clima mediterrâneo é do tipo temperado, com uma estação seca no verão muito bem definida. As regiões com clima mediterrâneo apresentam uma reduzida representatividade à escala planetária (menos de 4% da superfície total da terra; Mooney, 1982). O clima mediterrâneo é caracterizado por uma elevada sazonalidade, com verões secos e quentes, e invernos frios e húmidos (Lohrnann *et al.*, 1993). Ocorre entre as latitudes 30°- 45° a norte e a sul do Equador (Fig. 1), existindo na Europa meridional, na Califórnia, no Chile, no sudoeste da África e no sudoeste da Austrália (Aschmann, 1973). Apesar da sua baixa representatividade, as regiões de clima mediterrâneo incluem zonas de elevada diversidade (*hotspots*) (Cuttelod *et al.*, 2008), assumindo um papel mundial relevante em termos de preservação e proteção da sua biodiversidade (Underwood *et al.*, 2009). Esta característica é particularmente importante nos ecossistemas aquáticos interiores, uma vez que a maioria dos rios é temporária, ficando extremamente vulneráveis às alterações climáticas e a pressões humanas que conduzam a uma diminuição no escoamento superficial.

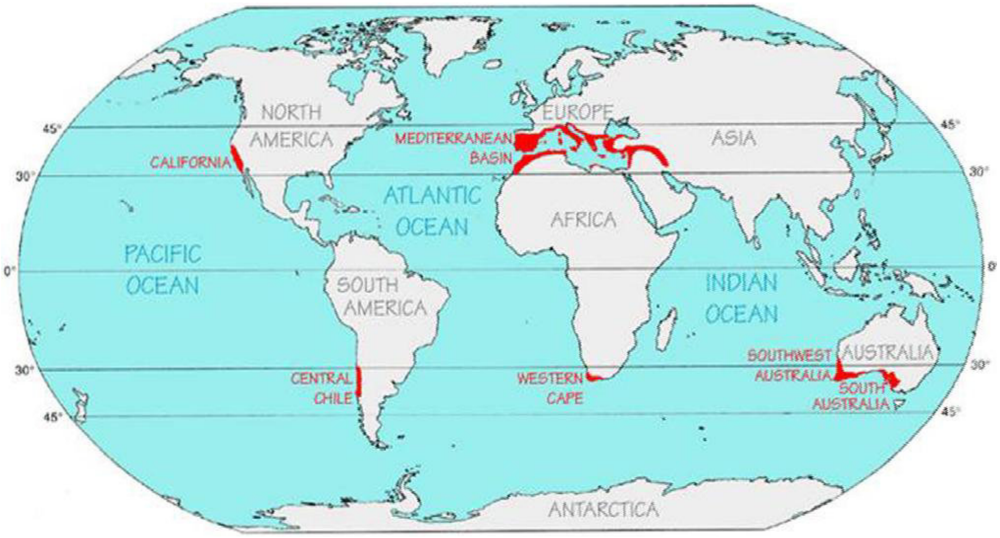

Figure 1. Distribuição das regiões de clima mediterrâneo (adaptado de Di Castri, 1981).

2.2.3 A disponibilidade dos recursos hídricos e a crescente escassez da água

2.2.3.1 Regiões de clima semiárido

A água doce e os ecossistemas associados não estão distribuídos de igual forma na superfície terrestre. Apesar de em termos globais a água existente no planeta ser suficiente para suportar toda a humanidade, a sua distribuição díspar conduz a desequilíbrios sociais e disponibilidades distintas. A carência de água é um problema frequente nas regiões semiáridas, onde não é suficiente para sustentar a produção agrícola para a população rural (Mvungi *et al*., 2005). O acesso à água potável é problemático, tornando-se ainda mais crítico durante períodos de seca. Nestas regiões, somente a população urbana (ou grande parte dela) tem acesso a um sistema de abastecimento público (Hauschild & Döll, 2000). Adicionalmente, na maioria dos casos os sistemas de abastecimento público apresentam problemas na gestão do consumo, o que conduz a gastos relativamente elevados de água, não compatíveis com a sua existência (Hauschild & Döll, 2000). Em algumas regiões a indústria e o turismo são importantes consumidores de água, competindo com o sector agrícola, prevendo-se que se não forem tomadas medidas adequadas esta situação possa vir a agravar-se. Nas regiões semiáridas, onde a escassez de água é quase uma questão endémica, a água subterrânea tem um papel fundamental no uso doméstico e na irrigação. Contudo, a utilização de água subterrânea e a falta de um planeamento adequado conduzem sérios problemas relacionados com a sustentabilidade do seu uso intensivo (UNESCO, 2006).

A construção e gestão adequada de infraestruturas para abastecimento das populações constituem a base necessária para a manutenção da qualidade da água. Simultaneamente é necessária uma gestão adequada das necessidades de forma a garantir um desenvolvimento sustentável para estas regiões. De acordo com dados de 2006, o índice de exploração de água é de 83% na Tunísia, 92% no Egipto, 169% em Gaza, 644% na Líbia, 50% na Síria, 25% no

Líbano, 20% na Argélia e cerca de 40% em Marrocos (Pearce, 1996). O Brasil possui a maior região semiárida do mundo, com cerca de um milhão de quilómetros quadrados (50% do território do Nordeste e parte do Norte de Minas Gerais), sendo uma das mais densamente habitadas (Pearce, 1996). De forma a aumentar a disponibilidade de água nesta região, está atualmente em construção o grande empreendimento de transferência de água do rio São Francisco. Todavia, não é consensual o resultado desta opção, prevendo-se um aumento da escassez mesmo após a transferência de água entre bacias (Hauschild & Dóll, 2000; Tundizi, 2003).

2.2.3.2 Regiões de clima mediterrâneo

As regiões de clima mediterrâneo incluem ecossistemas muito particulares com uma grande biodiversidade (zonas de *hotspots*), existindo contudo espécies em perigo. A região do Sudoeste da Austrália é a que apresenta maior diversidade, sendo também a mais frágil e a mais gravemente ameaçada (Pittock, 2003). Desde a antiguidade que os países das regiões com clima mediterrâneo sofrem com a falta de água, sobretudo durante o período seco de verão. Os recursos hídricos são limitados e a distribuição anual das precipitações determina que muitos rios desenvolvam descontinuidades espaciais e temporais no sistema de corrente, apresentando características temporárias.

A partir da segunda metade do século XX, a procura de água tem vindo a aumentar progressivamente (Vargas-Yáñez *et al.*, 2009). Em alguns países das regiões Mediterrânicas, o uso de água está a aproximar-se da capacidade máxima dos recursos disponíveis. O abastecimento de água começa a ficar ameaçado devido a uma exploração excessiva da água subterrânea, facto que conduz a intrusão salina e consequente perda de qualidade. Verifica-se igualmente uma sobre-exploração de recursos não renováveis que incluem água fóssil (Pereira & Paulo, 2004). A crescente urbanização tem sido a principal responsável pelo declínio na qualidade da água devido, principalmente, ao tratamento ineficiente das águas residuais aliado a uma má gestão dos resíduos sólidos (especialmente nas áreas mais pobres). A crescente desigualdade entre a disponibilidade e o consumo de água tem conduzido a situações de escassez, aumento de poluição e consequente aumento das pressões ambientais, a que acresce a competição entre os diferentes sectores de atividade económica. A agravar este cenário todas as projeções futuras preveem que a região Mediterrânica se torne uma região muito sensível, com aumento de temperatura, diminuição de precipitação e de escoamento. Prevê-se que por volta do ano 2025, a disponibilidade de água *per capita* nestas regiões se reduza para menos 50% do nível atual (Ragab & Hamdy, 2004), estimando-se igualmente uma expansão das zonas de clima semiáridos e árido (Kundzewicz *et al.*, 2007; Gao & Giorgi 2008). As implicações decorrentes poderão incluir alterações na cobertura vegetal com repercussões significativas na agricultura (Iglesias *et al.*, 2007) e produção de alimento.

2.2.4 Estratégias de gestão para prevenir a variação natural da água

No sentido de desenvolver uma nova abordagem para a gestão da água nas regiões semiáridas e mediterrâneas é necessário alterar a legislação atual, basicamente centrada na gestão do abastecimento e não na gestão das necessidades. Em termos globais, e considerando a problemática da escassez de água, as estratégias de gestão deverão ser aplicadas nos diferentes sectores. Dentro dos sectores mais importante inclui-se: (1) o abastecimento público a populações, onde pelo menos um terço do volume de água se perde nas redes de distribuição ou é rejeitada por mau manuseamento; (2) a indústria, onde muitas empresas utilizam volumes de água que excedem as suas necessidades; (3) a irrigação onde se estima que metade do volume de água gasto no sistema não é realmente utilizado no campo. Por outro lado, a gestão dos recursos hídricos implica um conjunto de ações estratégicas de planeamento que deverão ser consideradas ao nível da bacia hidrográfica, sempre incluindo a participação pública e as organizações institucionais.

A compreensão e a previsão das complexas interações entre a hidrologia e a dinâmica do sistema, constituem a base para a gestão e reabilitação de qualquer sistema aquático, perfeitamente integrada nos requisitos da atual Directiva 2000/60/CE do Parlamento Europeu e do Conselho que estabelece o quadro da ação comunitária no domínio da política da água, para a Europa. Conhecida por Diretiva Quadro da Água (Council of the European Communities, 2000), é considerada um dos exemplos mais recentes em termos de legislação ambiental do Mundo, uma vez que é centrada na proteção dos ecossistemas e da água como meio de suporte de vida. Assim, os países da zona euro assumiram o compromisso de mudar as estratégias tradicionais da oferta, o que requer a criação de infraestruturas em larga escala. No âmbito da Directiva Quadro da Água, os estados membros deverão desenvolver Planos de Bacia que incluam as componentes: (1) gestão de bacias hidrográficas; (2) classificação do estado ecológico e do estado químico das massas de água com vista à recuperação de todas aquelas classificadas abaixo de Bom; (3) avaliação dos custos da água; (4) consulta pública de forma a encorajar a participação ativa de todas as partes interessadas na implementação dos Planos de Bacia; (5) política integrada dos diferentes sectores que lidam com a gestão da água, tais como a energia, os transportes, a agricultura, a pesca, a política regional e o turismo.

À escala global, a gestão do uso da água surge como um assunto prioritário, sobretudo nas regiões onde ela é um recurso escasso. Deve ser orientada para o seu uso racional, através: do controle da poluição nas reservas de água; do armazenamento em depósitos - como é o caso das cisternas, dos açudes e das barragens subterrâneas; do desvio de água superficial para bacias próximas, lagoas e diques; e do tratamento de águas poluídas. Muitas destas técnicas são antigas não necessitando de grandes investimentos nem infraestruturas, devendo ser reabilitadas no sentido de aumentar a disponibilidade de água em regiões carenciadas e que normalmente surgem associadas à existência de maiores índices de pobreza. Adicionalmente existem técnicas mais caras, mas muitas vezes necessárias, tais como a transferência de água entre bacias, a dessalinização da água do mar e a recarga de aquíferos

(UNESCO, 2006). Em regiões com aparente abundância de água, mas com graves problemas de poluição, tais como a Austrália, a Europa e a América do Norte, assiste-se também à implementação destas técnicas associadas a práticas de gestão mais sustentáveis. Pretende-se assim remediar qualquer perturbação no balanço hídrico e permitir que possa ser aduzida e armazenada para suprimir as necessidades decorrentes de variações sazonais (SIWI/WHO, 2005). Porém, nestas regiões, os impactos decorrentes do desenvolvimento humano têm sido mais severos do que os anteriormente previstos (UNEP, 2010). Os ecossistemas aquáticos têm-se degradado a níveis abaixo do ponto de resiliência (definida como o limite para a recuperação natural após um episódio perturbador), com decréscimo na disponibilidade de água. É atualmente reconhecida a nível mundial a importância de preservar os ecossistemas aquáticos acima do nível de resiliência de forma a não comprometer no futuro, a disponibilidade de água, a biodiversidade global e a biosfera como um todo (UN-Water, 2007).

2.2.4.1 Armazenamento de água da chuva em cisternas

O armazenamento da água da chuva tem assumido uma importância renovada, sendo considerado como uma oportunidade para aumentar a disponibilidade de água. Intercetar e recolher a água da chuva onde ela cai é uma prática que remonta aos tempos bíblicos (Pereira *et al.*, 2002). Foi utilizada há 8000 anos no Sul da Ásia (Pandey *et al.*, 2003); há 4000 anos na Palestina e na Grécia; e há 2000 anos era utilizada nas residências romanas, onde cisternas e pátios pavimentados captavam chuva que abastecia as cidades através de aquedutos.

Nos anos 90, a China desenvolveu o Programa 1-2-1, “uma área de terra, duas cisternas e uma área de captação de água de chuva” (Cook *et al.*, 2000), pretendendo desta forma disponibilizar água potável para o desenvolvimento sustentável de populações em áreas onde a chuva representa o único recurso de água. Tal aconteceu com grande êxito no estado de Gansu, que apresentava uma forte contaminação das águas subterrâneas, constituindo a chuva a única fonte de água possível. Na China até o final de 2003, foram construídas 2,5 milhões de cisternas, beneficiando 1,1 milhão de famílias no fornecimento de água potável (Gnadlinger, 2001). Recentemente na Índia, o armazenamento de água da chuva é largamente utilizado para recarga de aquíferos, efetuado a taxas superiores comparativamente com as obtidas em condições de recarga natural (UNESCO, 2000; Mahnot *et al.*, 2003). Esta técnica de baixo custo representa uma vantagem acrescida uma vez que pode ser desenvolvida e mantida através de programas individuais e comunitários.

No nordeste brasileiro, caracterizado por apresentar carência de água e prolongados períodos de seca, em 2003 foi lançado o “Programa de Mobilização Social para a Convivência com o Semiárido – Um Milhão de Cisternas Rurais (P1MC; Fig. 2)”, pela Articulação do Semiárido (ASA). O principal objetivo da P1MC é beneficiar cerca de 5 milhões de pessoas em todo o Semiárido, fornecendo água potável por meio da construção de 1 milhão de cisternas a partir da captação de água de chuva precipitada nos telhados das residências. Atualmente o P1MC já beneficiou 1,5 milhões de pessoas com a construção de 300 mil cisternas a que corresponde 4.800.000 m^3 de água disponível para as famílias do Semiárido brasileiro (Bezerra & Gama da Silva, 2010).

Figura 2. Cisterna rural em Afogados da Ingazeira (Bacia do Rio Pajeú – Nordeste brasileiro)[1].

2.2.4.2 Desvios de água

O desvio de água de superfície para bacias próximas, lagoas, diques, poços de armazenamento ou poços de injeção para recarrega de aquíferos, são técnicas usadas para fazer face à variabilidade natural nos escoamentos. Reduzem as perdas por evaporação, potenciando a obtenção de água com melhor qualidade. Esta prática tem sido aplicada em diferentes regiões do planeta, desde as regiões áridas e semiáridas até ao Médio Oriente e regiões Mediterrâneas (UNESCO, 2006). Como exemplo refira-se o escoamento de barrancos "*wadis*" - linhas de água que apenas apresentam caudal superficial durante a ocorrência de fortes precipitações – que de outro modo se evaporaria ou escoaria diretamente para o mar (UNESCO, 2006). A água infiltra-se para uma zona subterrânea de aluvião, permanecendo disponível por períodos mais longos sem perdas por evaporação. Em regiões mais húmidas, tais como na América do Norte e norte da Europa, os desvios de água para zonas subterrâneas são usados como meio para armazenar e manter ecossistemas subterrâneos dependentes do escoamento superficial e também como forma de reduzir o tratamento da água necessário para o abastecimento público, captado a jusante das zonas de recarga. Os programas de recarga de aquíferos, alguns incluindo injeção de águas residuais tratadas, têm sido implementados tanto em países desenvolvidos como em países em desenvolvimento (p. ex. Austrália, China, Índia, Quénia, México, Oman, Paquistão, África do Sul e EUA) (UNESCO, 2006).

[1] Fotografias: M. Morais

2.2.4.3 Reservatórios

A construção de barragens para a criação de reservatórios de água tem sido usada como resposta à crescente necessidade de água para a energia, a irrigação, o consumo humano, a pesca e as práticas recreativas, assim como uma forma de segurança, para diminuir os impactos e riscos de eventos de intensidade extrema tais como as inundações e as secas (UNESCO, 2006). A criação de reservatórios é essencial para proporcionar disponibilidade de água quando e onde é necessária (Fig. 3). Todavia, todo o processo de construção acarreta impactos consideráveis nos ecossistemas e na paisagem, com consequente interferência no ciclo hidrológico. Basta pensar que o sistema lótico, caracterizado por apresentar um escoamento horizontal que determina toda a sua organização funcional, passa a apresentar características lênticas, muito mais dependentes do eixo vertical de penetração da luz na organização funcional do ecossistema. Apesar dos benefícios imediatos que as populações favorecidas obtêm dos reservatórios, existe uma polémica recorrente sobre as consequências sociais e ambientais que advêm da construção das barragens (p. ex. Programa Nacional de Barragens Hidroeléctricas em Portugal). No Brasil, a construção de grandes barragens tem criado um grupo social denominado "desalojados de barragens" que apresentam grandes dificuldades de integração nos locais para onde são deslocados, contribuindo para o aumento das desigualdades sociais. Recentemente, de forma a minimizar os impactos ambientais negativos provenientes destas construções, as barragens têm sido modificadas, assegurando um caudal estável calculado em função das necessidades das comunidades biológicas e dos habitats situados a jusante (caudal ecológico). Quando tal equilíbrio é conseguido, os resultados são substanciais em termos de preservação dos ecossistemas e da biodiversidade a jusante.

Figura 3. Alqueva, o maior reservatório de Portugal e da Europa, com 90 km de extensão (Rio Guadiana, sul de Portugal)[2].

[2] Fotografia: A. Serafim

2.2.4.4 Barragens bubterrâneas

Estudos recentes desenvolvidos em regiões do Semiárido do nordeste brasileiro apontam para a necessidade de armazenar água principalmente no subsolo, aproveitando as técnicas antigas usadas pelos pequenos agricultores (Carvalho *et al.*, 2009). As barragens subterrâneas são obras construídas no leito de rios, em aluvião (Fig. 4). São construídas perpendiculares ao leito do rio, com o objetivo de reter a água no subsolo. A função é reter humidade no solo de forma a incrementar a produtividade agrícola e viabilizar a exploração de pequenas e médias propriedades rurais, principalmente as que não dispõem de água para uso em irrigação convencional (Silva & Porto, 1982). As principais vantagens são: acumulação de água com reduzida evaporação; menor risco de salinização, quando bem explorada; uma maior disponibilidade de água para eventual produção agrícola (Brito *et al.*, 1989). No entanto, realça-se a necessidade de se proceder a uma monitorização continuada da qualidade da água e do nível de salinidade do solo, de forma a evitar-se a degradação do solo e o aumento da sua salinidade.

Figura 4. Barragem subterrânea (Bacia do Rio Pajeú –Nordeste brasileiro)[1].

2.2.4.5 Águas residuais como recurso adicional

A água residual tratada pode ser considerada como um "novo" recurso de água a adicionar à disponibilidade global de uma região. Pode ser utilizada para a irrigação ou para outras finalidades que não incluam o abastecimento público, contribuindo para uma melhor gestão da água (Crook, 1998). Não obstante, a irrigação com água residual não tratada pode representar um risco para a saúde pública, uma vez que pode conter bactérias patogénicas, vírus, organismos indesejáveis, metais pesados e contaminantes orgânicos (UNEP, 2010). Neste sentido a sua utilização deverá ser feita com muita prudência, só após tratamento e implementação de programas de monitorização que nos garantam que aquela água apresenta os requisitos mínimos em termos de qualidade para o fim a que se destina, não representando um risco para a saúde humana, animal e ambiental.

2.2.5 Estratégias de gestão da água para aumentar a disponibilidade de água

Os países das regiões semiáridas e mediterrâneas estão a utilizar os seus recursos de água com uma intensidade crescente. A agravar esta situação, os cenários de alterações climáticas preveem diminuições acentuadas de precipitação (Bates *et al.*, 2008), facto que conduzirá gradualmente a crises nacionais à medida que as reservas superficiais e subterrâneas diminuam e os lagos, zonas húmidas e rios sequem ou se degradem. Como consequência irá assistir-se a uma redução do recurso água por habitante, tanto em termos da disponibilidade como de captação. Nesse sentido, torna-se imperativo desenvolver novas técnicas e implementar estratégias de gestão que aumentem a disponibilidade de água, evitando a depleção deste recurso e a degradação dos ecossistemas associados.

2.2.5.1 Transferência de água entre bacias

A transferência da água de uma bacia hidrográfica de um rio ou de um aquífero, para outra, tem sido utilizada como um método para resolver problemas de tensão política relacionada com a escassez da água, particularmente usual em regiões áridas e semiáridas (Fig. 5). É frequente em áreas onde as necessidades da agricultura excederam os recursos de água existentes. Há já alguns sistemas de transferência de longa distância entre diferentes áreas, algumas delas recentemente construídas. Um exemplo é o sistema de Ganges-Brahmaputra-Meghna (UNESCO, 2006), construído para fazer face aos problemas recorrentes de seca e inundações na Índia e Bangladesh. Outro exemplo é o sistema de transferência de água do rio São Francisco no Brasil, que prevê a construção de dois conjuntos de canais e barragens que ligam centenas de quilômetros de rios na região do semiárido (Hauschild & Döll, 2000). Em termos globais, todas as experiências desenvolvidas têm demonstrado que embora a transferência da água entre bacias pareça dar uma resposta viável em termos técnicos e hidrológicos, é necessário considerar avaliar todos os impactos sociais e ambientais, antes de se iniciar qualquer processo de construção que implicará grandes alterações com enormes perdas em termos ambientais e de biodiversidade (Ballestero, 2004).

2.2.5.2 Dessalinização

A dessalinização inclui qualquer processo que remova o excesso do sal e de outros sais dissolvidos na água. É um processo usado principalmente em zonas costeiras de regiões áridas e semiáridas que apresentam escassez e onde as únicas fontes de água disponível são a água do mar ou a água subterrânea com características salobras. Embora apresentando um custo elevado por metro cúbico quando comparado com outras técnicas, representa o processo com eficiência de custo mais baixo para fornecer água para consumo humano em regiões onde a disponibilidade da água já é ou está a tornar-se limitada. Awerbuch (2004) e Schiffler (2004) referem que em termos de aplicação global, a capacidade de dessalinização representa um dos avanços e desafios mais recentes. De acordo com a Associação Internacional de Dessalinização (AID), aproximadamente 53% da dessalinização global ocorre no Médio Oriente, seguido da América do Norte (16%), Europa (13%), Ásia (11%) e África (6%). A América Central e América do Sul representam menos de 2% do volume global (UNESCO, 2006).

Figura 5. Construção de canais de transferência de água do Rio São Francisco para a região do nordeste brasileiro[1].

O Programa "Água Doce" é um programa para dessalinização de água salobra, desenvolvido pelo Ministério do Meio Ambiente brasileiro que visa garantir o abastecimento de água potável a populações rurais do Semiárido que vivem em áreas com graves problemas de desertificação. Este programa pretende tratar água retirada do solo com alto teor de sais, prevendo-se que nos próximos 10 anos, 2,3 milhões de pessoas (25% da população que vive em zonas rurais) da região do nordeste brasileiro possa beneficiar de água potável (Ministério do Meio Ambiente, 2010).

2.2.6 Gestão da água e da biodiversidade em equilíbrio com o ambiente

A agricultura, a indústria e os efluentes de águas residuais não tratadas, estão a contribuir para o aumento da degradação dos ecossistemas aquáticos superficiais e subterrâneos, (UNESCO, 2006; UN-Water, 2006, 2007). As regiões Mediterrânicas são importantes zonas de diversidade (*hot-spots*), onde já existem espécies ameaçadas, facto que indica perda de biodiversidade (Myers, 2000). Este é um indicador importante que revela baixa resiliência e consequente degradação dos ecossistemas (Underwood *et al.*, 2009). A nível global, a reduzida resiliência ecológica, provocada pela degradação dos ecossistemas e pelo aumento das secas, conduzem ao aumento da vulnerabilidade ambiental e social devido à perda de meios de subsistência. Criam-se condições para o estabelecimento de conflitos entre a preservação dos ecossistemas e a produção de alimentos, situação particularmente evidente nas regiões semiáridas onde a escassez da água é uma constante.

O novo desafio dos responsáveis pela gestão ambiental reside na otimização da resiliência dos ecossistemas em resposta a perturbações naturais e antropogénicas, que por sua vez deverão ser protegidos ao nível local através da implementação de planos de bacia que contemplem programas e sistemas sustentáveis de suporte à vida. Tendo em conta que os sistemas aquáticos têm uma interação permanente e dinâmica com as suas bacias de drenagem, é fundamental que se conheçam as interações entre estas e os sistemas aquáticos. Por outro lado, é imprescindível que se faça um esforço para compreender as interações entre os elementos naturais (físicos, químicos e biológicos), económicos e sociais, dada a sua interdependência. A interação entre diferentes componentes, muitas vezes com interesses opostos, deverá conduzir à formação de parcerias que viabilizem programas de recuperação e de conservação de uma forma integrada e sustentável. O conceito de desenvolvimento sustentável, no sentido em que atende as necessidades do presente sem comprometer a necessidades das gerações futuras (Salati *et al.*, 2006), é cada vez mais aceite, sendo contudo implementado com alguma dificuldade devido a interesses económicos e políticos. Indiscutivelmente, para a manutenção de um desenvolvimento sustentável, a nível local e regional, é necessário que sejam preservados os recursos hídricos tanto em quantidade como em qualidade.

2.2.7 Considerações Finais

O aquecimento global e a problemática das alterações climáticas causam mudanças, variabilidade e incertezas adicionais no que diz respeito à disponibilidade de água (Bates *et al.*, 2008; Kundzewicz *et al.*, 2007). O crescimento populacional nas regiões semiáridas e mediterrânias e os recentes eventos de seca têm contribuído para o aumento das pressões nos ecossistemas aquáticos, facto que requer novas abordagens no planeamento e na gestão da água. A implementação de estratégias de prevenção da escassez da água e a aplicação de novas tecnologias que permitam aumentar a disponibilidade de água, reduzindo a procura, poderão representar parte da solução. A criação de reservatórios de água, a construção de desvios que canalizam a água de regiões onde ela é abundante para outras com escassez e a extração de água dos aquíferos, representam parte das estratégias em desenvolvimento com a finalidade de disponibilizar água para onde e quando for necessária. Atualmente e no futuro, para captar água é necessário recorrer a processos simples e inovadores que promovam a utilização de fontes naturais como a água da chuva, tal é o caso das cisternas e das barragens subterrâneas. Por outro lado, no contexto das alterações climáticas torna-se necessário desenvolver estratégias de adaptação e de mitigação que promovam o aumento da disponibilidade da água. Todavia, as novas técnicas de gestão da água requerem uma alteração no padrão de comportamento das instituições e dos indivíduos. Alguns países têm implementadas leis e regulamentações para proteção e reabilitação dos ecossistemas aquáticos, adaptando técnicas que contemplam a utilização do conhecimento local. A gestão do recurso água é uma matéria complexa de enorme importância estratégica para o desenvolvimento sustentável (UNDP, 2006) que interfere em quase todos os aspetos da sociedade e economia, principalmente na saúde, na produção de alimento e segurança, no abastecimento público, no saneamento básico, na energia, na indústria e no ambiente.

A maioria dos ecossistemas de água doce estão ameaçados sobretudo devido à sobre exploração, à poluição, e ao aquecimento global. Considerando estas tendências, a equidade na utilização da água para a agricultura, para a indústria e para o consumo humano, representa um dos grandes desafios para o século 21^{st} (Tundisi, 2003; UNESCO, 2006). As regiões semiáridas, devido às suas características específicas, naturalmente sofrerão mais com a escassez. Assim, nestas regiões, com especial destaque para a região do nordeste brasileiro, da China semiárida e de algumas regiões na Índia, têm-se assistido à implementação de diferentes técnicas de baixo custo para capturar a água das chuvas. No que se refere à região Mediterrânica, todos os cenários de evolução futura preveem um aumento da temperatura associado a uma diminuição da precipitação e do escoamento. Esta tendência trará graves impactos, tanto em termos sociais como ambientais uma vez que estas regiões se apresentam extremamente vulneráveis em termos de biodiversidade. Neste sentido, interessa implementar técnicas simples e de baixo custo utilizadas nas regiões semiáridas, muitas das quais com tradições centenárias na própria história do Mediterrâneo, como é o caso das cisternas (Fig. 6).

Figura 6. Cisterna da vila de Monsaraz, séculos XIV-XV (sul de Portugal) [1].

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Chapter 3

The importance of temporary streams biodiversity

Chapter 3

Summary

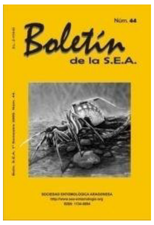
In the south of Portugal, the summer season is characterized by low rainfall and high air temperatures, which cause the disruption of rivers surface flow into fragmented pools. During this dry period, the remaining pools and surroundings become important in the survival of biological communities, acting as a refuge for both aquatic and terrestrial biota. With the beginning of the dry period, several aquatic insects emerge and continue their life in the adult phase. Diptera is a very large and widespread order of insects, with about 150000 species described. Dipterans are quite common taxa that can be seen emerging during this period. They are very important from the environment and human perspective, especially in the medical field.

This chapter includes an article that constitutes a great contribution to increase the limited knowledge of dipterans in Portugal. It allowed the discovery of a new species to science (*Homoneura alata* sp.), the description and illustration for the first time of *Rachispoda ibérica* Roháček female, and the report of several other species for Portugal, the Iberian Peninsula and Europe. Given the growing importance of freshwater biodiversity, this work helped to improve our knowledge concerning Diptera taxonomy in temporary ecosystems.

Other articles from the taxonomist expertise published with the obtained data:

Carles-Tolrá, M. (2009). *Athyroglossa ordinata* Becker: género y especie nuevos para Portugal (Diptera, Ephydridae). *Boletín Sociedad Entomológica Aragonesa* 45, 236.

Carles-Tolrá, M. (2009). *Homoneura alata* sp. n.: A new lauxaniid species from Portugal (Diptera: Lauxaniidae). *Heteropterus Revista de Entomología* 9(2), 97-100.



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3.1 Some dipterans from Portugal captured by emergency traps (Insecta, Diptera)
Algunos dípteros de Portugal capturados mediante trampas de emergencia (Insecta, Diptera)

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Extended abstract

Flies are a very large order of insects, with about 150 000 species described so far. It is a very important insect order from the perspective of environment and human, the latter in the medical field and economy, and thus of great importance in terms of knowledgment. The present work represents a great contribution to increase the limited knowledge of dipterans in Portugal.

The study was carried out in Pardiela stream, a temporary stream from southern Portugal. To capture the insects it were used emergence traps with an open base (50 x 50 cm), and a 500 μm mesh. The traps were placed in pairs over a reach of 750 m, placed with a distance of approximately 150 m from one another, taking into account the areas most likely to retain water during summer. Each pair of emergence traps was placed near the shoreline, at a height of 2 to 3 cm to allow the passage and movement of insects emerging from the water. The collection containers were filled with alcohol 96° and verified weekly. Sampling was conducted from April 2005 to September 2006. During this period, samples were collected monthly, sorted at the laboratory and kept in alcohol 70° for further study. The methodology used in the capture allowed the harvest of thousands of specimens from several families of dipterans. However, this study included only families with relevant interest. Thus, we studied a total of 512 specimens, of which were identified 74 species from 20 families. It allowed the discovery of a new species to science (*Homoneura alata* sp.), the description and illustration for the first time of *Rachispoda ibérica* Roháček female, and the report of several other new species for Portugal, the Iberian

Peninsula and Europe. In the context of the growing awareness of the importance of biodiversity, it is expected that this work will help to fill a gap on the knowledge of Diptera taxonomy in Portugal.

Key words: Diptera, emergence traps, faunistics, Portugal

3.1.1 Introducción

Los dípteros forman un orden muy grande de insectos, pues se han descrito unas 150 000 especies hasta ahora (Courtney *et al.*, 2009; Pape *et al.*, 2009). Este grupo de insectos incluye las conocidas moscas, mosquitos, tábanos, moscas de la carne, moscas de la fruta, moscas del vinagre, etc. Es uno de los órdenes más importantes de insectos desde el punto de vista ecológico y humano, este último en el campo de la medicina y economía, por lo tanto, es muy importante continuar desarrollando nuestro conocimiento. Recientemente, en Carles-Tolrá Hjorth-Andersen (2002) se publicó el número de especies conocidas en Portugal (en total 1941), observándose que el conocimiento que se tiene sobre los dípteros en este país es extremadamente bajo, sólo superando a Andorra e islas macaronésicas y Baleares. Afortunadamente, en los últimos años el conocimiento faunístico de los dípteros de Portugal ha aumentado algo con la adición de nuevas citas, pero sigue siendo comparativamente bajo. El trabajo que se presenta es una contribución para aumentar en lo posible el escaso conocimiento dipterológico de Portugal. Para ello se hizo un estudio de la fauna asociada a un pequeño arroyo.

3.1.2 Zona de estudio

El estudio se llevó a cabo en el arroyo Pardiela, que es de tipo mediterráneo y está situado en el sur de Portugal (Évora; lat. 38°38'N, long. 07°42'O). La cuenca de este arroyo cubre una superficie de 514 km^2 (Fig. 1), teniendo un desnivel que va desde los 505 m en la cabecera hasta los 169 m donde desemboca en el río Degebe (Gallart *et al.*, 2008). El Pardiela es un arroyo temporal caracterizado por un caudal altamente variable, según la estación del año. La temperatura media varía desde un máximo de 23 ºC en verano (Junio– Septiembre), hasta un mínimo de 9 ºC en invierno (Diciembre– Febrero) (Lillebø *et al.*, 2007). La precipitación media anual es aproximadamente de 600 mm, distribuida irregularmente a lo largo del año y entre diferentes años (Lillebø *et al.*, 2007). La pluviosidad se sucede estacionalmente, desde finales de otoño hasta principios de primavera y normalmente las tormentas fuertes causan desbordamientos y las consiguientes inundaciones.

3.1.3 Material y métodos

Para la captura del material se utilizaron 8 trampas de emergencia de forma piramidal (de 50 x 50 cm) con la base abierta y una malla blanca de 500 µm de luz. Las trampas se colocaron por parejas a lo largo de 750 m del curso del arroyo y de manera aleatoria. De cada pareja, una se coloco en tierra, en la orilla, y la otra en el agua, encima del nivel del agua (Fig. 1, 2). En el primero caso se colocaron a una altura de 2 a 3 cm. Ello permitió el paso y movimiento de los insectos y capturar los dípteros que emergieron del agua. Los recipientes de recogida furean llenos con alcohol 96 ° y verificados semanalmente. El muestreo se llevó a cabo desde abril de 2005 hasta septiembre de 2006. Durante este periodo de tiempo, las muestras se recogieron mensualmente y se conservaron en alcohol 70º para su posterior estudio.

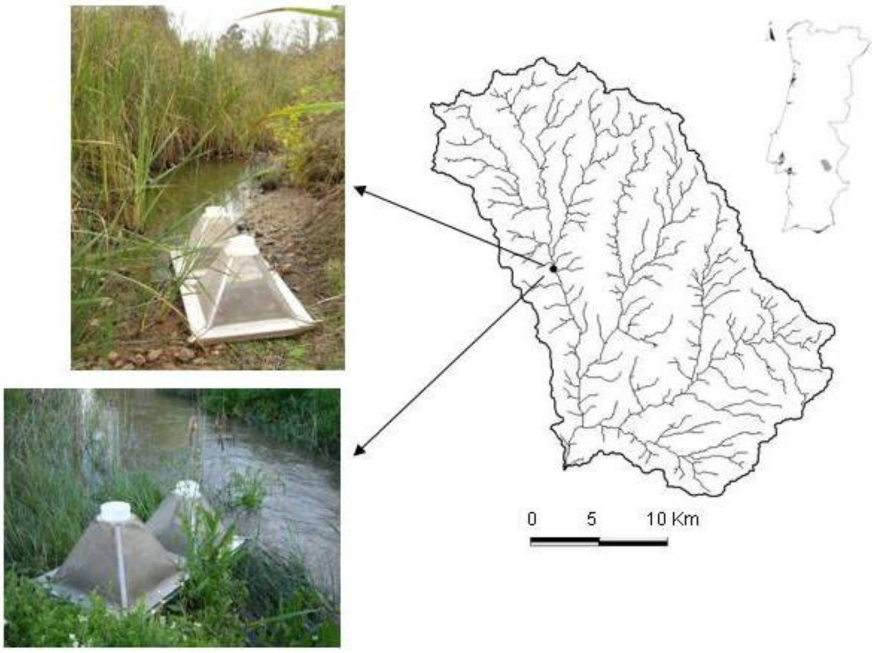

Figura 1. Localización del arroyo Pardiela y ubicación de dos parejas de trampas.

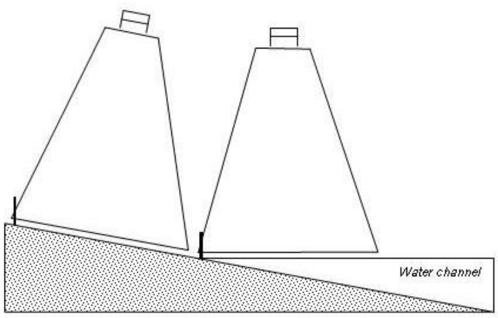

Figura 2. Detalle de la colocación de una pareja de trampas de emergencia mostrando su situación en la orilla del arroyo (adaptado de Paetzold & Tockner, 2005).

3.1.4 Resultados

La metodología utilizada para la captura de material ha permitido coger miles de ejemplares de muchas familias de dípteros. Sin embargo, en este trabajo se incluye sólo una parte de ellas, ya que se han estudiado únicamente aquellas familias (y ejemplares sueltos de algunas familias) de interés para el primer autor (MC-T). Aún así, en total se han estudiado 512 ejemplares, de los cuales se han identificado 74 especies pertenecientes a 20 familias. Es de destacar que se ha obtenido 1 especie nueva para la ciencia y se describe e ilustra por primera vez la hembra de *Rachispoda ibérica* Roháček (Sphaeroceridae). Asimismo, se aumenta la distribución de varios taxones a diferentes niveles geográficopolíticos: de Europa, de la Península Ibérica, de país y de distrito, tal como se puede comprobar en la relación de especies que se presenta a continuación.

Relación de especies

Para la clasificación taxonómica se ha seguido la dada por Carles-Tolrá Hjorth-Andersen (2002), salvo la familia Otitidae ya que actualmente esta familia se incluye en los Ulidiidae como una subfamilia. Para cada captura se indica la fecha y la proporción de sexos, que se ha separado mediante una barra inclinada (machos/hembras).

CHAOBORIDAE

Chaoborus flavicans (Meigen, 1830)
21.5.2005 0/3, 15.7.2005 3/1, 16.12.2005 0/1, 14.6.2006 1/0. Género y especie nuevos para Portugal.

DIXIDAE

Dixa nebulosa Meigen, 1830
4.5.2006 0/1. Especie nueva para la Península Ibérica.

Dixella attica (Pandazis, 1933)
4.5.2006 1/0. Especie nueva para Portugal continental.

KEROPLATIDAE

Macrocera pusilla Meigen, 1830
11.8.2006 1/0. Especie nueva para Portugal.

BOMBYLIIDAE

Cononedys scutellata (Meigen, 1835)
15.7.2005 0/1. Género y especie nuevos para el distrito de Évora.

Petrorossia hespera (Rossi, 1790)
15.7.2005 0/1, 12.8.2005 0/1, 7.9.2006 1/0. Género y especie nuevos para el distrito de Évora.

*Thyridanthrax elegan*s (Wiedemann in Meigen, 1820)
15.7.2005 0/3.

Villa sp.
15.7.2005 2 ejemplares, 12.8.2005 1 ejemplar, 11.8.2006 1ejemplar, 7.9.2006 2 ejemplares. No se han podido identificar por estar en muy mal estado.

STRATIOMYIDAE

Sargus cuprarius (Linnaeus, 1758)
21.5.2005 0/1, 7.9.2006 1/0. Género y especie nuevos para Portugal.

LONCHOPTERIDAE

Lonchoptera bifurcata (Fallén, 1810)
20.4.2005 0/3. Género nuevo para el distrito de Évora. Especie nueva para Portugal continental.

Lonchoptera lutea Panzer, 1809
4.5.2006 0/1. Especie nueva para el distrito de Évora.

PHORIDAE

Phora edentata Schmitz, 1920
15.7.2005 1/0.

Phora limpida Schmitz, 1935
7.9.2006 1/0. Especie nueva para Portugal.

SYRPHIDAE

Eristalinus taeniops (Wiedemann, 1818)
12.8.2005 0/1.

Eristalis arbustorum (Linnaeus, 1758)
13.9.2005 1/0.

Eumerus sp.
12.8.2005 1 ejemplar, 13.9.2005 7 ejemplares, 4.5.2006 1ejemplar, 11.8.2006 1 ejemplar. De momento no se han identificado.

Helophilus trivittatus (Fabricius, 1805)
15.7.2005 0/1. Especie nueva para Portugal.

Myathropa florea (Linnaeus, 1758)
15.7.2005 1/0, 12.8.2005 1/1, 7.9.2006 1/0.

Paragus majoranae Rondani, 1857
16.6.2005 1/0.

Paragus quadrifasciatus Meigen, 1822
16.6.2005 1/0, 15.7.2005 0/1.

Spilomyia digitata (Rondani, 1865)
15.9.2005 0/1, 11.8.2006 0/1.

Spilomyia saltuum (Fabricius, 1794)
13.9.2005 1/0.

Syritta flaviventris Macquart, 1842
11.8.2006 0/1.

Syritta pipiens (Linnaeus, 1758)
14.7.2006 0/1.

ASTEIIDAE

Asteia amoena Meigen, 1830
14.7.2006 1/0. Género y especie nuevos para Portugal continental.

CAMILLIDAE

Camilla atrimana Strobl, 1910
16.6.2005 0/1. Género y especie nuevos para Portugal.

CONOPIDAE

Leopoldius anatolii Zimina, 1963
15.7.2005 0/1. Género nuevo para el distrito de Évora. Ejemplar muy interesante, pues hasta ahora esta especie estaba citada unicamente de la antigua Rusia, Oriente Medio y norte de Africa. Por lo tanto, esta captura representa la primera cita de esta especie para Europa.

Thecophora cinerascens (Meigen, 1804)
15.7.2005 1/0. Género nuevo para el distrito de Évora. Especie nueva para Portugal continental.

EPHYDRIDAE

Ochthera manicata (Fabricius, 1794)
4.5.2006 1/0. Género y especie nuevos para Portugal.

HELEOMYZIDAE

Oecothea fenestralis (Fallén, 1820)
11.8.2006 1/0, 7.9.2006 1/0. Género y especie nuevos para el distrito de Évora.

Suillia variegata (Loew, 1862)
11.8.2006 1/1, 7.9.2006 1/1. Género y especie nuevos para el distrito de Évora.

LAUXANIIDAE

Homoneura limnea (Becker, 1895)
13.9.2005 2/0. Género nuevo para Portugal. Especie nueva para la Península Ibérica.

Homoneura notata (Fallén, 1820)
13.9.2005 8/20, 14.7.2006 1/0, 7.9.2006 2/2, 11.8.2006 2/0. Especie nueva para Portugal.

Homoneura sp.n.
13.9.2005 4/3, 11.8.2006 0/1. Especie nueva para la ciencia que se describirá en un trabajo aparte.

Minettia fasciata (Fallén, 1826)
21.5.2005 0/1, 12.8.2005 3/0, 13.9.2005 0/1, 11.8.2006 1/4,
7.9.2006 1/1. Género y especie nuevos para el distrito de Évora.

Minettia graeca Papp, 1981
14.7.2006 1/1, 11.8.2006 2/1, 7.9.2006 3/1. Especie nueva para Portugal.

Minettia inusta (Meigen, 1826)
13.9.2005 0/1, 7.9.2006 1/1. Especie nueva para Portugal.

Minettia subvittata (Loew, 1847)
15.7.2005 1/2, 12.8.2005 1/0, 13.9.2005 3/1, 11.8.2006 2/0,
7.9.2006 3/1. Especie nueva para Portugal.

Minettia tetrachaeta (Loew, 1873)
13.9.2005 1/1. Especie nueva para la Península Ibérica. Es importante resaltar que falta confirmar que el ejemplar macho pertenece realmente a esta especie.

Sapromyzosoma drahamensis (Villeneuve, 1921)
12.8.2005 1/0, 13.9.2005 0/1. Género nuevo para el distrito de Évora. Especie nueva para Portugal.

OPOMYZIDAE

Geomyza majuscula (Loew, 1864)
21.5.2005 1/0, 11.8.2006 0/2. Género nuevo para el distrito de Évora. Especie nueva para Portugal.

Geomyza tripunctata Fallén, 1823
5.4.2006 0/1. Especie nueva para el distrito de Évora.

SEPSIDAE

Nemopoda nitidula (Fallén, 1820)
14.6.2006 2/6. Género y especie nuevos para el distrito de Évora.

Sepsis punctum (Fabricius, 1794)
14.6.2006 1/0. Género y especie nuevos para el distrito de Evora.
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Sepsis thoracica (Robineau-Desvoidy, 1830)
11.8.2006 1/0. Especie nueva para Evora.

Themira minor (Haliday, 1833)
15.7.2005 1/0. Género y especie nuevos para Portugal continental.

SPHAEROCERIDAE

Coproica lugubris (Haliday, 1836)
15.7.2005 1/0. Género y especie nuevos para Portugal continental.

Leptocera caenosa (Rondani, 1880)
14.6.2006 1/0. Género nuevo para el distrito de Évora. Especie nueva para Portugal continental.

Leptocera nigra Olivier, 1813
14.7.2006 4/1, 11.8.2006 0/1, 7.9.2006 11/5. Especie nueva para el distrito de Évora.

Opacifrons coxata (Stenhammar, 1855)
21.5.2005 0/1, 4.5.2006 6/0. Género y especie nuevos para el distrito de Évora.

Pullimosina heteroneura (Haliday, 1836)
12.8.2005 0/1, 14.7.2006 0/1, 11.8.2006 1/0. Género y especie nuevos para el distrito de Évora.

Rachispoda brevior (Roháček, 1991)
15.7.2005 1/2, 12.8.2005 1/2, 7.9.2006 0/2. Especie nueva para Portugal.

Rachispoda iberica (Roháček, 1991)
15.7.2005 1/1, 14.7.2006 1/0, 11.8.2006 3/2, 7.9.2006 2/1.

Capturas muy interesantes, pues de esta especie se conocían únicamente dos machos, que fueron capturados en España. Por lo tanto, la hembra se describe a continuación por primera vez. No obstante, la descripción coincide basicamente con la del macho dada por Roháček (1991: 146), por lo tanto se describe únicamente la genitalia. Para ello, se han separado dos abdómenes y, después de haberlos aclarado con KOH, se han diseccionado y fotografiado las partes que interesaban. Cada genitalia se halla guardada dentro de su respectivo abdomen en un microvial con alcohol (70º).

Genitalia (Fig. 3-8) marrón. Terguito 7 (Fig. 3) corto y ancho, con pelos posteriores. Terguito 8 (Fig. 3, 4) dividido en dos escleritos laterales, cada uno con cerdas largas posteriores, ventralmente con un pequeño esclerito curvado hacia dentro. Terguito 10 (Fig. 3) simple, ancho, con 1 par de pelos dorsales. Esternito 7 (Fig. 4, 5) semiovalado, con pelos posteriores cortos y largos y con una mancha marrón oscura corta y transversal en el centro. Esternito 8 (Fig. 4, 6) con forma de X, con una diminuta cresta marrón oscura en la intersección (se ve muy bien de lado), extremos posteriores algo más dilatados y cada uno con 2 diminutos pelos por el lado interno. Esclerito interno (Fig. 7) diminuto, rectangular, posteriormente con una pequeña mancha marrón oscura en el medio. Circulos membranosos (Fig. 7) cóncavos por el lado interno. Espermatecas (Fig. 7) negruzcas, con forma de higo. Esternito 10 (Fig. 8) con forma de muela, anteriormente con una escotadura claramente ancha y profunda, mitad posterior marron oscura y con un par de hileras laterales de cerdas robustas y cortas dirigidas hacia dentro. Cercos (Fig. 3) separados del terguito 10, cortos y con pelos cortos.

Longitud total: 2.4 – 2.7 mm.

Según Roháček (1991), *R. iberica* pertenece al grupo formado por *R. cryptochaeta* (Duda, 1918), *R. uniseta* (Roháček, 1991) y *R. duplex* (Roháček, 1991) en base principalmente a caracteres de la genitalia masculina. Desafortunadamente, la hembra de *R. uniseta* no se ha descrito todavia, pero a juzgar por los caracteres de la genitalia femenina, especialmente por la forma de los esternitos 7, 8 y 10, *R. iberica* está muy relacionada con *R. duplex*.

Como ya se ha comentado, *R. iberica* se conocía sólo de España, por lo tanto se cita ahora por primera vez de Portugal.

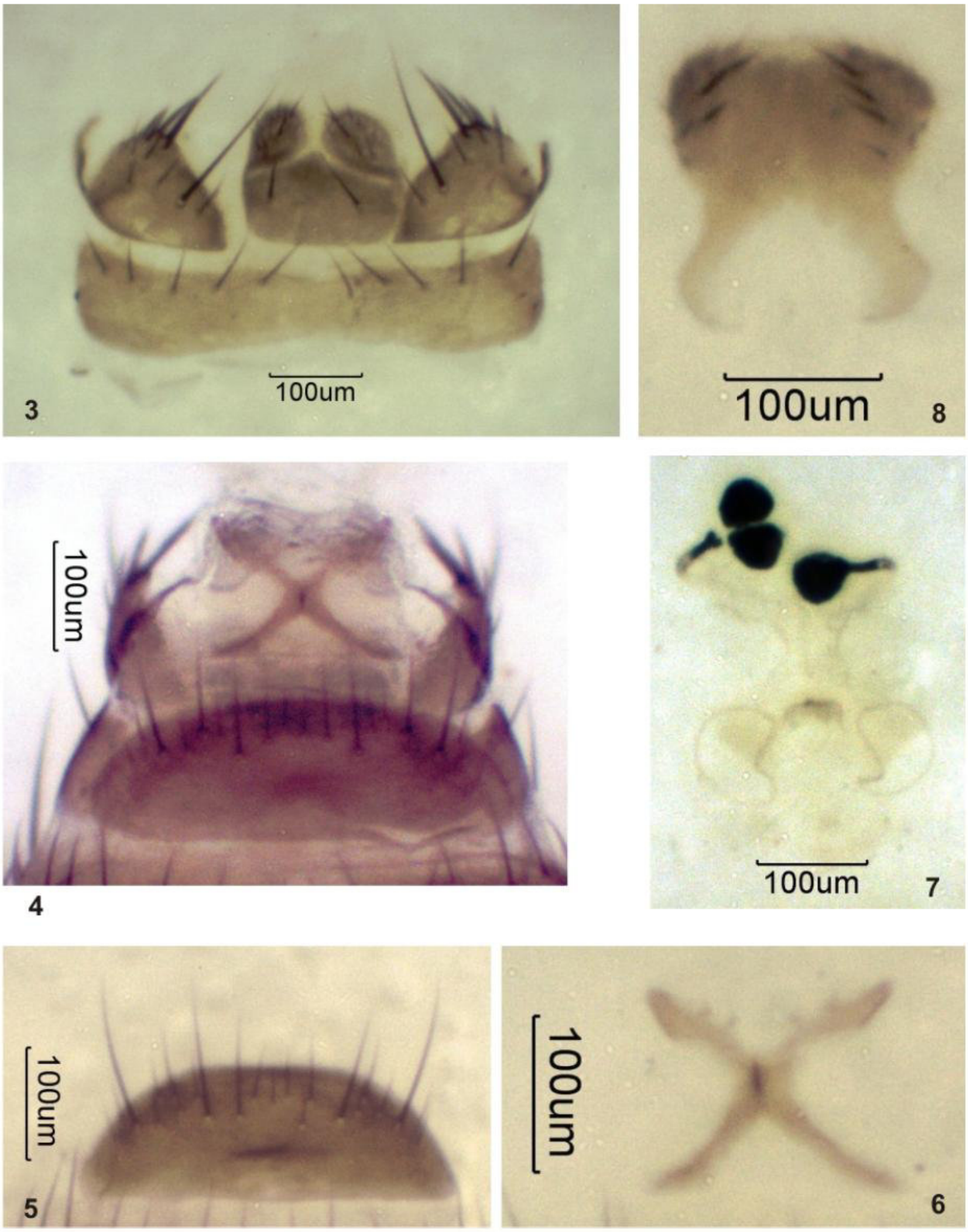

Figura 3-8. Genitalia de la hembra de *Rachispoda iberica* (Roháček): **3)** terguitos 7, 8, 10 y cercos en visión dorsal (aplanados con un cubreobjetos); **4)** esternitos 7,8 y terguito 8 en visión ventral; **5)** esternito 7 en visión ventral; **6)** esternito 8 en visión ventral; **7)** esclerito interno, círculos membranoso y espermatecas; **8)** esternito 10 en visión ventral.

Rachispoda kabuli (Papp, 1978)
11.8.2006 1/0. Especie nueva para el distrito de Évora.

Rachispoda lutosoidea (Duda, 1938)
21.5.2005 1/1, 16.6.2005 0/1, 15.7.2005 3/1. Género y especie nuevos para el distrito de Évora.

Rachispoda modesta (Duda, 1924)
15.7.2005 0/1. Especie nueva para el distrito de Évora.

TRIXOSCELIDIDAE

Trixoscelis obscurella (Fallén, 1823)
16.6.2005 0/1, 15.7.2005 1/0. Género nuevo para el distrito de Évora. Especie nueva para Portugal.

Trixoscelis psammophila Hackman, 1970
16.6.2005 7/9, 15.7.2005 19/44, 12.8.2005 2/1, 13.9.2005 23/50, 15.9.2005 21/17, 11.8.2006 0/2, 7.9.2006 3/7. Especie nueva para Portugal.

ULIDIIDAE

Herina gyrans (Loew, 1864)
7.9.2006 2/1. Género nuevo para el distrito de Évora. Especie nueva para Portugal.

SARCOPHAGIDAE

Apodacra seriemaculata Macquart, 1854
12.8.2005 1/0. Género y especie nuevos para Portugal.

Blaesoxipha plumicornis (Zetterstedt, 1859)
*16.6.2005 1/1, 15.*7.2005 2/0. Género y especie nuevos para Portugal.

Metopia argyrocephala (Meigen, 1824)
12.8.2005 4/0. Especie nueva para Portugal.

Metopia tshernovae Rohdendorf, 1955
12.8.2005 4/0. Especie nueva para la Península Ibérica.

Metopodia pilicornis Pandellé, 1895
15.7.2005 5/0, 12.8.2005 1/0. Género y especie nuevos para Portugal.

*Miltogramma rutila*ns Meigen, 1824
13.9.2005 1/0. Género nuevo para Portugal. Especie nueva para la Península Ibérica.

Protomiltogramma fasciata (Meigen, 1824)
12.8.2005 1/0. Género y especie nuevos para Portugal.

Pterella melanura (Meigen, 1824)
11.8.2006 1/0. Género y especie nuevos para Portugal.

Ravinia pernix (Harris, 1780)
16.6.2005 15/0, 15.7.2005 5/0, 12.8.2005 2/0, 14.6.2006 1/0.

Sarcophaga argyrostoma (Robineau-Desvoidy, 1830)
15.7.2005 2/0, 7.9.2006 1/0.

Sarcophaga crassipalpis Macquart, 1839
11.8.2006 1/0.

Sarcophaga lehmanni Mueller, 1922
12.8.2005 1/0. Especie nueva para Portugal.

Sarcophaga pandellei (Rohdendorf, 1937)
16.6.2005 2/0, 15.7.2005 5/0, 12.8.2005 2/0, 11.8.2006 1/0. Especie nueva para Portugal.

Sarcophaga portschinskyi (Rohdendorf, 1937)
4.5.2006 1/0, 7.9.2006 1/0. Especie nueva para Portugal.

Sarcophaga uncicurva Pandellé, 1896
15.7.2005 1/0. Especie nueva para Portugal continental.

Senotainia albifrons (Rondani, 1859)
12.8.2005 1/0. Especie nueva para Portugal.

Taxigramma heteroneura (Meigen, 1830)
16.6.2005 2/0, 15.7.2005 2/0, 12.8.2005 1/0. Género y especie nuevos para Portugal.

3.1.5 Conclusiones

Tras el estudio de un total de 512 ejemplares de dípteros pertenecientes a 20 familias, se han identificado 74 especies. Entre los resultados obtenidos se destacan las siguientes novedades: a) Una especie nueva para la ciencia cuya descripción se publicará en un trabajo aparte; b) Se describe e ilustra por primera vez la hembra de *Rachispoda iberica*; c) Una especie (*Leopoldius anatolii*) nueva para Europa; d) Cinco especies (*Dixa nebulosa*, *Homoneura limnea*, *Minettia tetrachaeta*, *Metopia tshem*ovae y *Miltogramma rutilans*) nuevas para la Península Ibérica; e) Una familia (Camillidae), 14 géneros y 30 especies nuevos para Portugal; f) Una familia (Asteiidae), tres géneros y siete especies nuevos para Portugal continental; y g) Nueve familias, 18 géneros y 16 especies nuevos para el distrito de Évora. Todas estas nuevas novedades confirman lo poco estudiado que está Portugal desde el punto de vista dipterológico.

3.1.6 Agradecimiento

Deseamos expresar nuestro más sincero agradecimiento a Thomas Pape (København) por la identificación de un ejemplar de cada uno de los siguientes géneros de la familia Sarcophagidae (*Apodacra* Macquart, *Blaesoxipha* Loew, *Metopia* Meigen, *Metopodia* Brauer & Bergenstamm, *Miltogramma* Meigen, *Protomiltogramma* Townsend, *Pterella* Robineau-Desvoidy, *Senotainia* Macquart y *Taxigramma* Perris), lo que ha permitido al primero author (MC-T) corroborar e identificar el resto de ejemplares de estos mismos géneros. Asimismo, muchas gracias a David K. Clements (Cardiff) por su ayuda en la identificación del ejemplar de *Leopoldius anatolii*, y a Jindrich Roháček (Opava) por confirmar que la hembra de *Rachispoda iberica* no había sido descrita hasta el presente. Esta investigación fue financiada por una beca de doctorado (SFRH/BD/18359/2004/41ZX), apoyado por la *Fundação para a Ciência e Tecnologia*, POPH (*Programa Operacional Potencial Humano*, QREN).

3.1.7 Referencias

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Chapter 4

Effects of first flood event in dry riverbed

Chapter 4

Summary

In southern Portugal, the typical temporality of the aquatic systems, with a recurrent dry period, turns the riverbed almost dry during summer. Dry riverbeds have been described as biologically inactive habitats, which have favored their abusive use by humans. Only recently, the ecological and economic value of dry riverbeds has been recognized. One of their particularities is the shifting between the dry and wet periods. During the dry period, there is an accumulation of large amounts of coarse particulate organic matter (CPOM), nutrients, contaminants; and terrestrial arthropods along the dry riverbed. However, with the first flush floods, there is a mass transfer of organic matter and terrestrial biota to downstream sections, by rafting or drifting on floating organic matter, which increases biota dispersion.

This chapter includes results from a pilot study in a temporary river basin (SE Portugal), concerning the floating organic material and associated terrestrial arthropods along the river longitudinal gradient. It discusses the importance of deposits as critical habitats, refugia, and food resources for terrestrial arthropod assemblages.

River Research and Applications

Submitted in November 2012

4.1 Mass dispersal of terrestrial organisms during first flush events in a temporary stream

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Abstract

Temporary streams expand and contract seasonally, forming a complex mosaic of aquatic, amphibic, and terrestrial habitats. We studied the terrestrial arthropod fauna of the dry riverbed as well as CPOM (Coarse Particulate Organic Matter) deposits during first flood events (Days 0, 5 and 10), from a total of 114 samples collected along the Pardiela stream (SE Portugal). During the dry period, large amounts of organic material accumulated at the bed surface, colonized by terrestrial arthropods (mean density: 13.3 ± 15.29 Ind. g DM (Dry Mass of CPOM)). Arthropod density peaked in fresh flood deposits (mean biomass: 35.8 ± 33.4 Ind. g DM), and subsequently decreased within time. Concurrently, the relative composition of the arthropod community changed from Day 0 to Day 10. The present results demonstrated that the dry riverbed of temporary streams serve as a critical habitat for terrestrial arthropods. During first flood events, large amounts of CPOM and associated terrestrial arthropods were transported downstream, and deposited along the channel margin. These deposits may constitute critical habitats, refugia, and food resources for terrestrial arthropod assemblages.

Keywords: first flood event, floating organic matter, temporary streams, terrestrial arthropods

4.1.1 Introduction

Temporary rivers are common on every continent and they are likely more representative than perennial rivers globally. They are predicted to increase in the spatial extent and the duration of the dry period due to water abstraction, climate change, and land-use alteration (Larned *et al*., 2010). In recent times, many perennial rivers have become temporary, including large rivers such as the Rio Grande (USA) and the Yellow river (China) (Ellis *et al*., 2001; Fu *et al*., 2004; Gleick, 2003; Makar *et al*., 2006). Temporary rivers expand, contract, and fragment seasonally, thereby forming a shifting mosaic of aquatic, amphibic, and terrestrial habitat types. However, temporary rivers have primarily been considered as aquatic (lotic) ecosystems (see Wishart 1990; Steward *et al*., 2012). Dry riverbeds have been described as biologically inactive habitats, which have favored their exploitation for direct human use. Only most recently, the ecological and economic values of dry riverbeds have been recognized (Steward *et al.,* 2012).

Dry riverbeds accumulate large amounts of coarse particulate organic matter (CPOM), nutrients and contaminants (e.g. Obermann *et al*., 2009, Tzoraki *et al*., 2007, Von Schiller *et al*., 2011), and they are colonized by abundant and diverse terrestrial invertebrate assemblages (Steward *et al*., 2011, 2012). During the onset of flow, a mass transfer of material and dispersal of terrestrial biota to downstream sections may occur (Jakobson *et al*., 2000; Corti & Datry, 2011). Rafting or drifting of terrestrial organisms on floating organic matter may be an effective, long-distance dispersal pathway that increases the likelihood of biota arriving in a suitable habitat (Robson *et al*., 2008). Therefore, it may be a fundamental mechanism for maintaining species and genetic diversity along temporary river corridors (Steward *et al*., 2012).

Flood-deposited clumps of intertwined plant material ("litter hovels"), created by flood events, accumulate arthropod species from the entire river network and, thereby, serve as integrator, and indicator, of the whole river corridor biodiversity (Mason & Macdonald, 1982). Flood deposits may also represent a unique, persistent habitat type, as well as a shelter and a food resource for local terrestrial communities. For example, Loeser *et al*. (2006) found a positive correlation between hovel size and the density and diversity of spiders.

In the present study, we sampled CPOM accumulations from the dry riverbed surface at the end of the summer period during three consecutive years, as well as fresh flood deposits of floating CPOM that became entangled at vegetation along the edge of the channel. Deposits were sampled immediately after flood recession, and 5 and 10 days afterwards (Fig. 1). The main questions were: (i) how important are CPOM accumulations at the surface of the dry riverbed and flood-related deposits as habitat for terrestrial arthropod assemblages, and (ii) how does the density, biomass, and composition of the arthropod assemblages change in flood deposits. Finally, we discussed the importance of rafting on floating organic matter as a potentially critical dispersal mode along (temporary) rivers.

4.1.2 Methods

4.1.2.1 Study area

The study was conducted in a 3rd order section of the Pardiela stream located in southern Portugal (38°38'N, 07°42'W; total catchment area: 514 km^2). Pardiela is a temporary stream that dries at the surface during summer (Fig. 1a, Fig. 2). Rainfall typically occurs from late autumn to early spring, during which frequent storms create flush flood events (detailed description in tempQsim-Consortium, 2006 and Lillebø *et al.*, 2007; Fig. 1b; Fig. 2).

Figure 1. Pardiela stream (SE Portugal): dry bed conditions in summer (a), first flood event (b), and coarse particulate organic matter deposits after flood recession (c, d).

Riparian vegetation is mainly dominated by sclerophyllous vegetation, with bare areas due to habitat degradation. *Tamarix africana* Poiret is very common along and within temporary riverbeds (Fig. 1c, d) as it can sustain extended dry periods and high discharge events (Biléu, 2008).

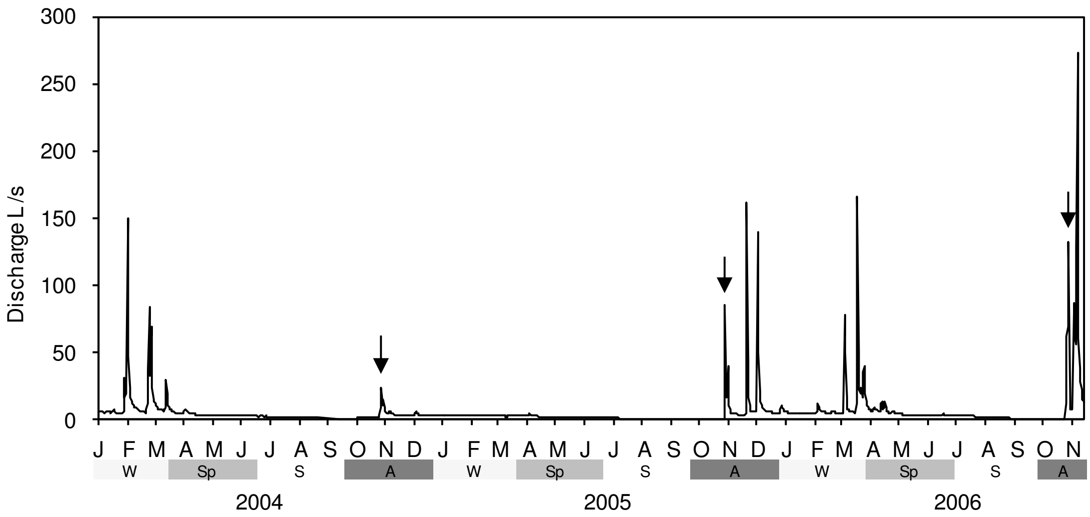

Figure 2. Hydrograph of the Pardiela stream (2004-2006). Arrows indicate the first flush event. W winter; Sp spring; S summer; A autumn. Data: SNIRH (2007).

4.1.2.2 *Sampling of CPOM deposits*

At the end of the dry season, OM deposits and their associated terrestrial arthropods were randomly sampled within the dry riverbed along a 250 meters lenght section. OM deposits were sampled within frames covering an area of 25 x 25 cm (in a total of 8 samples per year from 2004 to 2006). Samples were placed into plastic bags and processed in the laboratory. At the time of the first flood event, deposits were sampled immediately after flood recession, and 5 and 10 days afterwards. CPOM accumulations and associated terrestrial arthropods were sampled within frames of 25 x 25 cm and quickly transferred into plastic bags. Samples of drift deposits were collected along the margin of the river channel and around salt cedar stands that retained CPOM (Fig. 1c, d). Ten samples per date and year (from 2004 to 2006) were collected at random positions along the reach. In the laboratory, samples were processed within 24 hours of collection. All terrestrial organisms were counted using a dissecting microscope. Arthropods were stored in 96% alcohol and identified to order or family level. CPOM was dried at 40ºC in an oven, until constant weight, and expressed as g DW (Dry Weight). Arhtropod density and biomass were expressed as individuals or dry mass per g DM (Ind. gDM or g gDM) of CPOM to allow standardization.

4.1.2.3 *Data analysis*

Descriptive statistics were calculated for each sampling data and year. Differences between years and sampling dates were tested with the non-parametric Independent samples Kruskal-Wallis Test, and subsequent Pairwise Comparisons, as data failed to meet the assumptions of normal distribution. The Spearman's rho (ρ) was computed to analyze the effect of the amount of OM deposits on the biomass and density of arthropods. Outliers were removed before applying statistics tests. All statistical analyses were performed in PASW® Statistics 18.

4.1.3 Results

Until the end of the dry period, in average 5.71 ± 5.14 g DM of CPOM (surface area: 625 cm^2) accumulated at the surface of the riverbed. The mean density of arthropods colonizing CPOM deposits was 13.3 ± 15.3 Ind. g DM (maximum: 55 Ind. g DM), corresponding to an arthropod biomass of 0.05 ± 0.09 g per g DM CPOM (maximum: 0.43 g per g DM CPOM). Arthropod density and biomass were lower in 2004 (Fig. 3). Coleoptera (44.8 to 78.5% of total density; mainly Staphylinidae and Carabidae) and Arachnida (21.5 to 27.6%, mainly wolf spiders) dominated the arthropod assemblage. Psocoptera (<10.3%), Collembola (<6.9%) and Hymenoptera (<7.1%, mainly ants) were also common and important taxa of the dry streambed assemblage (cf. Fig. 4).

CPOM deposited during first flood events along the margins of the streambed mainly constituted of small branches (95.91 ± 6.26% DM). In addition, small amounts of leaves (1.71 ± 0.98% DM), cork (1.32 ± 5.74% DM), roots (0.78 ± 1.31% DM) and animal excrements (0.28±0.30% DM) were found. Deposits sampled immediately after the recession of the first flood event (Day 0) contained in average 35.8 ± 33.4 Ind. gDM (maximum: 156 Ind. g DM), corresponding to an arthropod biomass of 0.74 ± 1.30 g per g DM CPOM (maximum: 6.76 g per g DM CPOM). Arthropods density and biomass peaked in 2006 (Fig. 3). The relative composition of the arthropod assemblage was similar (at high taxonomic level) at dry riverbed when compared to Day 0 assemblage (Fig. 4), albeit density was always significantly lower in the dry riverbed (Tab. 1). Coleoptera (54.6 to 87.0 % of total density; mainly Staphylinidae and Carabidae) and Arachnida (9.4 to 26.6%, mainly wolf spiders) were predominant. Hymenoptera (<12.5 %; mainly ants) and Hemiptera (<8.0 %) were common taxa too (Fig. 4).

The density and biomass of arthropods decreased in the flood deposits until Day 10. At Day 5, deposits contained in average 17.2 ± 19.8 Ind. gDM. (maximum: 97 Ind. g DM), corresponding to an arthropod biomass of 0.33 ± 0.73 g per g DM CPOM (maximum: 3.68 g). At Day 10, deposits contained in average 6.9 ± 8.8 Ind. gDM. (maximum: 46 Ind. g DM), corresponding to an arthropod biomass of 0.05 ± 0.08 g per g DM CPOM (maximum: 0.32 g per g DM CPOM).

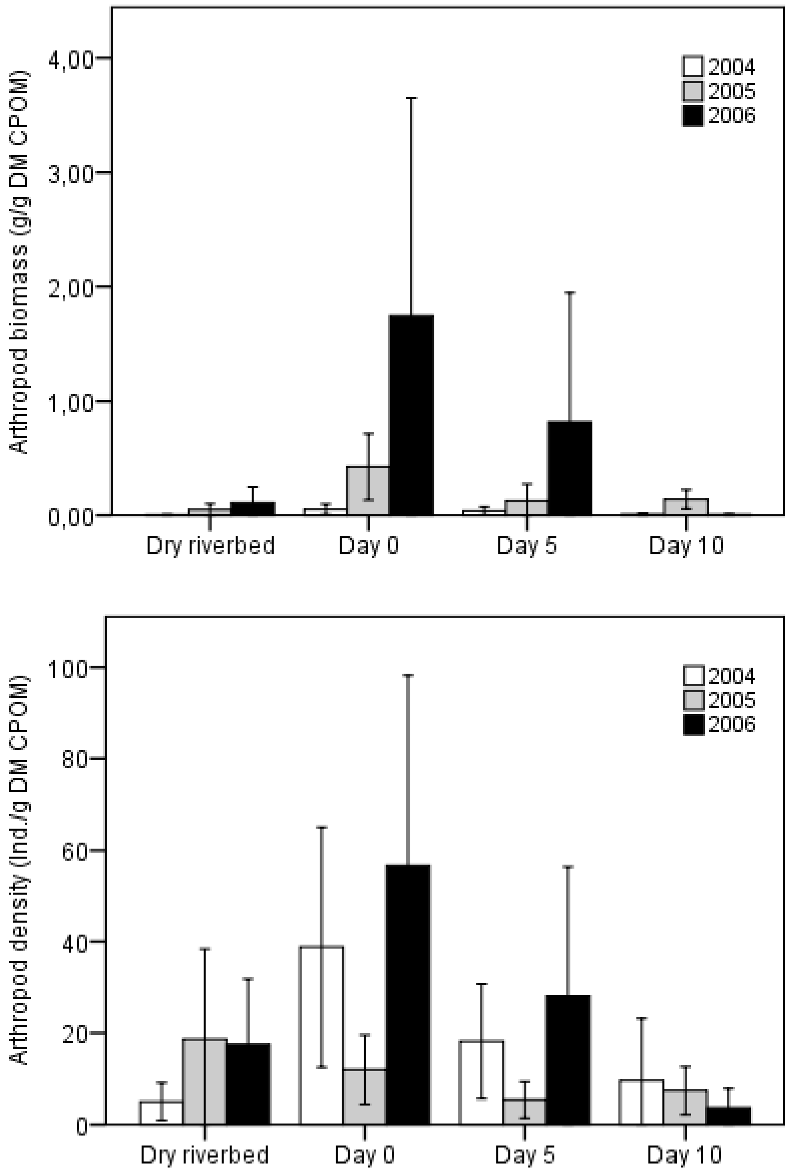

Figure 3. Mean arthropod biomass g dry mass CPOM (upper panel) and mean density Ind. g dry mass CPOM (lower panel) (Mean±SD; n=24 for "Dry riverbed"; n=30 each for "Day 0, Day 5 and Day 10").

The relative arthropod composition in the flood deposits changed within time. The number of taxa increased from Day 0 to Day 10. Coleoptera (16.7 to 80.4% of total density), Arachnida (8.9 to 59.4%), Hemiptera (<22%), Hymenoptera (<16.67%), Collembola (<16.67%) and Chilopoda (<11.11%) were the dominant groups (Fig. 4).

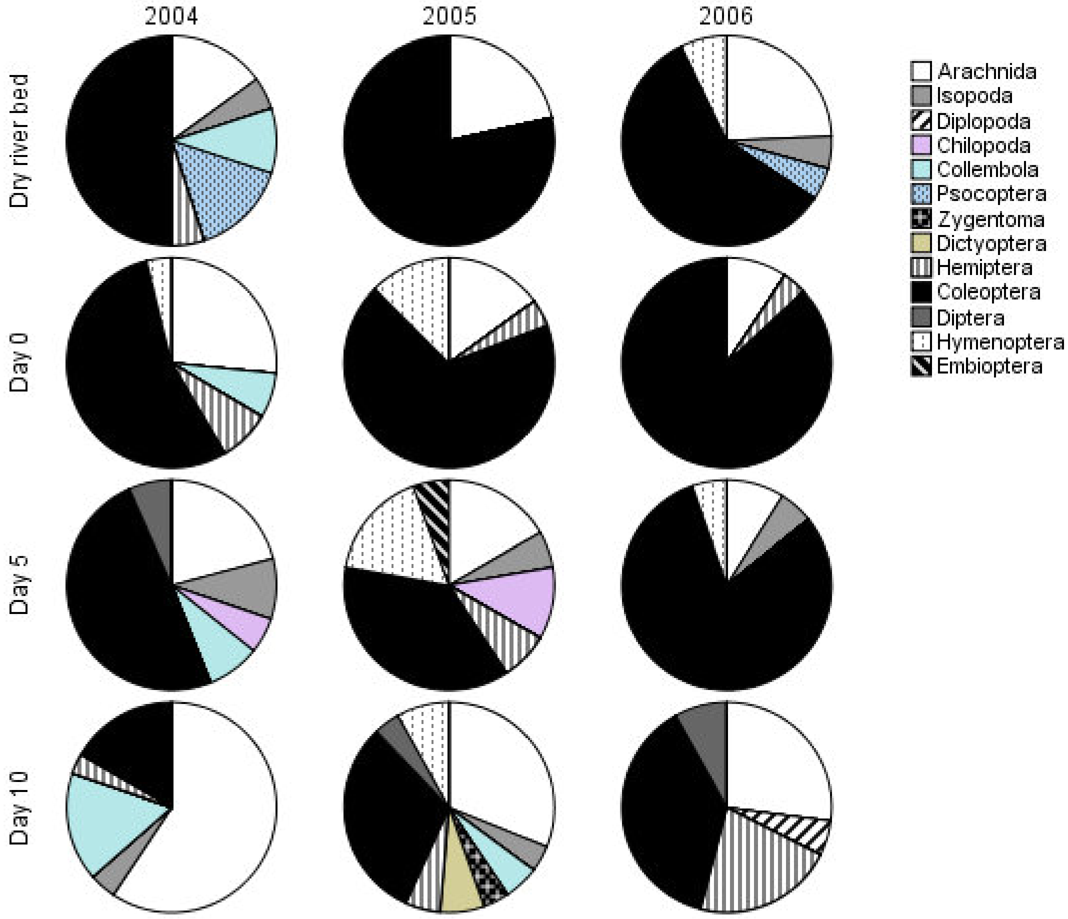

Figure 4. Relative composition (%) of the arthropod assemblages (pooled data for each date and year, 2005-2006; total n=114).

Results of the Kruskal-Wallis tests showed that total arthropods density was significantly different among sampling dates (H (3) = 29.094, p = 0.000, n = 113) but not among years (H(2) = 5.661, p = 0.059, n = 113). Arthropod density was significantly lower at i) the surface of the dry riverbed compared to Day 0 (t = -30.893, p = 0.004), ii) Day 10 compared to Day 5 (t = 24.233, p = 0.025) and iii) Day 10 compared to Day 0 (t = 44.797, p = 0.000) (Tab. 1).

The total biomass of arthropods was significantly different between sampling dates (days) (H(3) = 32.792, p = 0.000, n = 113) and years (H (2) = 23.687, p = 0.000, n = 113). Biomass was significantly lower at i) dry riverbed compared to Day 0 (t = -40.311, p = 0.000), ii) 2004 compared with 2005 (t = -30.908, p=0.000) and 2006 (t = -32.553, p = 0.000). Biomass was significantly higher at Day 0 compared with Day 10 (t = 43.124, p = 0.000) (Tab. 1).

Overall, Spearman correlations exhibited no significant relation between the size of CPOM deposits (expressed as DM) and arthropod biomass (ρ = -0.152, p = 0.431, n = 29) after first flood events (Day 0). Likewise, Spearman´s correlations exhibited no significant relation between the size of CPOM deposits (expressed as DM) and arthropod density (ρ= -0.334, p =

0.076, n = 29). However, there was a weak, albeit positive, correlation between the size of CPOM deposits (expressed as DM) and arthropod density in 2005 (ρ = 0.789, p = 0.007, n = 10) (Fig. 5).

Table 1. Pairwise comparisons (density and biomass) between dates (i.e., days) and years. Arthropods density was not significantly different between years. Significant differences marked in bold.

	Density			Biomass		
	Test Statistic	SE	Sig.	Test Statistic	SE	Sig.
Day 10-DRB	13.904	8.964	0.725	2.812	8.972	1.000
Day 10-Day 5	24.233	8.452	**0.025**	25.433	8.459	**0.016**
Day 10-Day 0	44.797	8.524	**0.000**	43.124	8.532	**0.000**
DRB-Day 5	-10.329	8.964	1.000	-22.621	8.972	0.070
DRB-Day 0	-30.893	9.033	**0.004**	-40.311	9.041	**0.000**
Day 5-Day 0	20.564	8.524	0.095	17.690	8.532	0.229
2004-2005	-	-	-	-30.908	7.516	**0.000**
2005-2006	-	-	**-**	-1.645	7.567	1.000
2004-2006	-	-	-	-32.553	7.567	**0.000**

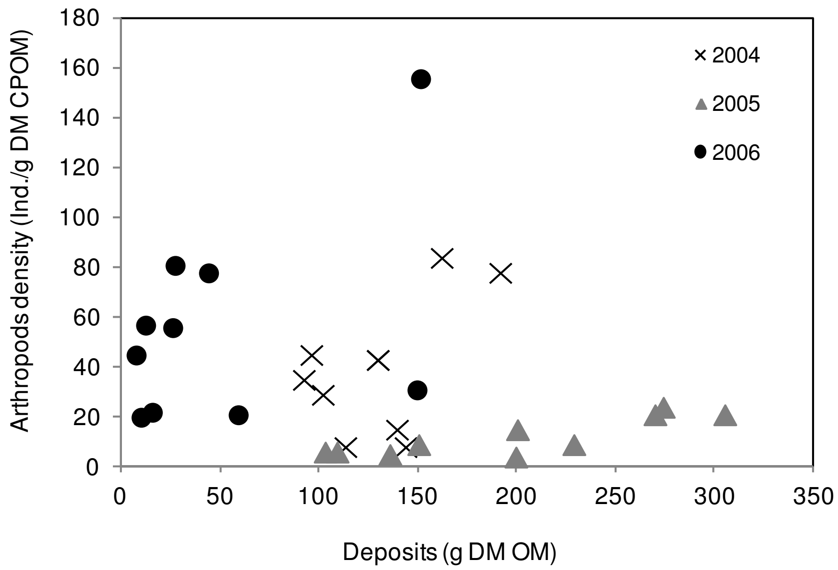

Figure 5. Organic matter deposits (g DM OM) and arthropods density (Ind./g DM CPOM) immediately after flow recession (Day 0, 2005-2006; n=30).

4.1.4 Discussion

Though initially described as biologically inactive habitats, the ecological and economic value of dry riverbeds is now admitted (Steward *et al.*, 2012). They provide habitat for a diverse terrestrial invertebrate community including various species of ants (Formicidae), beetles

(Coleoptera), and spiders (Arachnida) (Wishart 2000; Larned *et al*., 2007). The large amount of accumulated CPOM provides shelter to many arthropods inhabiting the dry riverbed (Steward *et al*., 2012) including ground beetles (Carabidae), rove beetles (Staphylinidae), and spiders. Along the fringing edge of remaining pools terrestrial predators feed on emerging and stranded aquatic invertebrates (Hering & Plachter, 1997; Batzer, 2004; Paetzold *et al*., 2005).

Flooding, acting as a “reset” period (Gasith & Resh 1999), affects the number of surface-active arthropod taxa (Crawford, 1991) present in dry riverbed. In fact, the first flush flood event affects arthropod assemblages, leading to their dislodgement and to the subsequent transportation downstream, mostly by rafting on floating organic matter.

Although the arthropod community had a very similar composition both at the surface of the dry riverbed and in fresh flood deposits (i.e., beetles and arachnids), the density of arthropods was significantly higher in organic matter flood deposits than at the surface of the dry riverbed. This is most likely the consequence of the dislodgement of arthropods not only from the upstream dry riverbed but also from lateral banks and small tributaries. Indeed, the density of arthropods peaked in fresh flood deposits, and subsequently decreased within time. At the same time, the relative composition of the arthropod community changed after the flood event (i.e., from Day 0 to Day 10). It demonstrated that the dry riverbed of temporary streams served as a critical habitat for terrestrial arthropods; and organic matter deposits may constitute critical habitats, refugia, and food resources for a diverse and abundant arthropod community.

Our results showed that the effect of floods varied among the different taxonomic groups. While some taxa have developed efficient strategies to survive flood events, such as many riparian beetles that can escape by flying or surviving in interstitial habitats (e.g. Zulka, 1994, Plachter & Reich, 1998; Bonn, 2000; Adis & Junk, 2002). Other arthropods such as spiders, depend on refugia above the water level to escape and survive flooding (Uetz, 1979; Bonn *et al*., 2002; Loeser *et al*., 2006). Mobile invertebrates may have a better chance in finding refugia than sessile ones (Gasith & Resh, 1999). However, many arthropods will not survive the downstream transfer during floods. Although the survival of many organisms depends on finding a refuge from the severe hydraulic stress, even the most effective instream refugia can become ineffective when flood intensity is too high (e. g. Gasith & Resh, 1999).

After the flood event, the composition and the density of the arthropod assemblages changed in the organic matter deposits. The density decreased while the number of taxa remained constant or increased in time. Even though the dominant orders remained the same, the OM deposits were colonized by predatory taxa such as spiders, chilopods, ants and some bugs, as well as by non-predatory taxa such as diplopoda and collembola. The change in the composition of the arthropod assemblages could be related to the availability of (aquatic) food sources (Hering & Plachter, 1997; Sanzone *et al*., 2003). Furthermore, the shifting in arthropods composition could be mostly due to casual movements across different habitats, not necessarily searching for food. Ants, for instance, are well known to have an opportunistic behavior and feed on stranded organism particularly after floods (Paetzold *et al*., 2008). Hence, they were expected to be abundant in flood deposits. However, only few individuals were captured. Furthmore, isopods, which were common along the edge of the river channel were almost completely absent in drift deposits.

A few days after the water level started to decline, seedlings germinated within the deposits (pers. observation). Stromberg *et al.* (1991), for instance, demonstrated that floods create habitat for seedlings of many riparian plant species. Similarly, Pettit *et al*. (2006) demonstrated the importance of wood debris piles for tree seedling establishment. Therefore, OM deposits not only promote seed germination but also increase the subsequent persistence of the riparian vegetation.

Floating OM is a mode to escape and survive floods. By providing important habitat and refugee, OM deposits may increase the opportunity of arthropods to survive flood-related disturbances and to colonize new habitats further downstream. Differences in the density and composition of arthropods after flood recession might be due to the colonization of the deposits through local communities, stimulated by the high availability of prey and food resources. Because habitat selection plays a key function in the survival and reproductive success of animals (Stearns, 1977), OM deposits may offer to arthropods a diversity of microhabitats that can mitigate the adverse physical conditions (e.g. humidity, Wise, 1993). Furthermore, Riechert & Gillespie (1986) observed that litter structure and complexity can influence species assemblages. Likewise, Loeser *et al.* (2006) observed that “litter hovels”, i.e., OM deposits attached to bushes and trees at different heights, provide refuge during floods, thereby acting as a key source for spiders after water level receded.

4.1.5 Conclusions

Floods are not only responsible for the transport of large amounts of organic matter (branches, leaves, etc) downstream, but also for an increased input of arthropods into water, most of them from terrestrial origin (Mason & Macdonald, 1982). It will affect the distribution of riparian arthropods such as spider and ground beetles along river corridors (Bonn *et al*., 2002). With the receding water level, the floating organic material accumulates along the river margins, providing refugia for organisms that try to escape the flood as well as serving as a resource for species searching for food (Wenninger & Fagan, 2000; Bonn *et al*., 2002). Braccia & Batzer (2001), for example, found that floating woody debris served as a ‘‘hot-spot’’ for both aquatic and terrestrial invertebrates. Loeser *et al*. (2006) documented the use of elevated litter hovels by spiders as refugia during floods as well as key resources when waters receded. Therefore, OM deposited along river shores and accumulated at vegetation stands could be of major importance to arthropods, whether they were transported downstream by floods or they belong to local communities.

Our results highlighted the importance of hydrological events in the transport of organic matter and biota. Periodic flooding during the wet period can be considered a natural disturbance that is fundamental to ecosystem functioning (Plachter & Reich, 1998; Ward, 1989). Human interference in riparian ecostystems through deforestation and channelization, among other activities, modifies the natural flow regime of rivers and the subsequent ecosystem biodiversity. OM deposits and pioneer vegetation can influence the composition and diversity of arthropod assemblages as well as the input of terrestrial invertebrates into streams during floods. Therefore, management practices that interfere with riparian corridors, lead to the loss of natural forests and may potentially change the food resources in streams.

The surface-active arthropods, denominated by Crawford (1991) as “temporary dwellers”, typically consisting of beetles, spiders and ants, play an essential ecological role, for example, as detritivores, herbivores, predators and parasites. Consequently, they influence nutrient cycling, the abundance of other invertebrates, and serve as prey for many vertebrates (e.g. Kim, 1993; Williams, 1993). Although arthropods dominate terrestrial ecosystems, both in terms of the number of species and individuals (Erwin, 1982; Gaston, 1991; Kremen *et al.*, 1993), they seem to be overlooked in monitoring and conservation practices. Since they inhabit the forest floor, they will suffer immediately the impact of flooding. As a result, studies that provide additional understanding on how hydrologic extremes affect biota may support management strategies for future sustainability and biotic integrity (e.g. Lundberg & Moberg, 2003). Therefore, more research is required to assess arthropods influence on ecosystems, and integrate them in the assessment of impacts restoration projects.

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Chapter 5

The seasonal inundation dynamics on ecosystem functioning

Chapter 5

Summary

A key challenge in ecology is to understand the effects of environmental heterogeneity on biotic assemblages and ecosystem processes. This relationship is particularly amenable to study in river floodplains due to its complex mosaic of aquatic, semi-aquatic, and terrestrial habitats. Although spatially distinct, these habitats are connected through water, carbon and nutrients, and thus ecosystem processes in one habitat type might have ramifications for others. In order to check the importance of hydrological processes in river floodplains, the first part of this chapter includes an article accepted for publication, with the results obtained from sediment sampling in River Tagliamento (Italy). Despite the natural variability, the Mediterranean rivers are also under the influence of anthropogenic disturbances such as pollution and habitat fragmentation, which can lead to nutrient enrichment, interfering in the entire river functioning. In these systems, evaluating the relative contribution of different nutrient input sources may provide an initial step to cope with factors that may cause surface water enrichment, through catchment runoff. The second part of this chapter presents different nutrient sources in Pardiela stream (Portugal) and how they are affected by first flood events. În both parts, it is confirmed the significant role that riparian areas play as potentially key energy sources for the aquatic system, especially during floodings.

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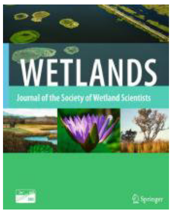

Wetlands

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5.1 Release of nutrients and organic matter from river floodplain habitats: simulating seasonal inundation dynamics

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Abstract

River floodplains are a complex mosaic of aquatic, semi-aquatic, and terrestrial habitats. While spatially distinct, these habitats are connected through water, carbon and nutrients, and thus ecosystem processes in one habitat type may have ramifications for others. In the laboratory, we studied the effects of inundation duration (12, 36 and 96 h) and water temperature (4, 12 and 25°C) on the release of nutrients and organic carbon from sediments of seven habitat types, and from leaves (*Populus nigra* L.), from the near-natural, braided, River Tagliamento in NE Italy. The relative content of POC, TN, and TP was similar in the sediment size fraction <2.0 mm across all habitat types, 9.3%-11.9% C, 0.007%-0.046% N, and 0.013%-0.019% P. Leaves contained a mean of 73% C, 0.86% N, and 0.06% P. Leaching released, on average, 0.017% C, 1.79% N, and 0.018% P of the respective element in the sediments. Leaching peaked during the first 12 hours of inundation at 12°C and 25°C, but was delayed at 4°C. Leaf litter was a key source for C and P, while sediments, especially those from terrestrial habitats, were an

important source for N; thereby emphasizing the unique role that each habitat plays in the floodplain mosaic.

Key words: ecosystem processes, leaching, leaf litter, nutrients, sediments, Tagliamento, wetlands

5.1.1 Introduction

A key challenge in ecology is understanding the effects of environmental heterogeneity on biotic assemblages and ecosystem processes (Stewart *et al.,* 2000; Cardinale *et al.,* 2002; Lovett *et al.,* 2005). The relationship between habitat heterogeneity and ecosystem processes is particularly amenable to study in river floodplains, because they are a shifting mosaic of aquatic and terrestrial habitat patches that differ in successional stage (i.e., age), frequency and duration of flooding and drying, organic matter and nutrient content, and biotic assemblages (Ward *et al.,* 2002; Stanford *et al.,* 2005; Langhans *et al.,* 2008; Döring *et al.,* 2011).

In river floodplains, as well as in forested headwater streams, leaf litter provides an important source of nutrients and organic matter (Fisher & Likens 1973; Cuffney, 1988). Langhans *et al.,* (2013) quantified the input, storage, and transfer of coarse particulate organic matter (CPOM), with leaf litter as the dominant fraction, in the Tagliamento River (Italy; present study floodplain). Aerial CPOM input was as high as 325 g AFDM m^{-2} y^{-1} at the edge of vegetated islands. CPOM storage at the sediment surface ranged from 2.8 to 562.4 g AFDM m^{-2} y^{-1}, with an area-weighted mean for the entire river floodplain of 154.6 g AFDM m^{-2} y^{-1}.

Ecosystem processes in river floodplains are mainly driven by hydrology. Primary productivity, nutrient uptake, and decomposition of leaf litter are controlled by the magnitude, frequency, duration, and timing of drying and rewetting (Junk *et al.,* 1989; Baldwin & Mitchell 2000; Tockner *et al.,* 2000; Anderson, 2005; Langhans *et al.,* 2006; Kobayashi *et al.,* 2009; Bruder *et al.,* 2011). The availability of nutrients in the underlying sediments is controlled by additional factors such as decomposition of organic matter, desorption of nutrients from sediments, and alteration of soil chemistry (Mitsch & Gosselink 2000 and references therein;; Smolders *et al.,* 2006). Flow and flood pulses (*sensu* Tockner *et al.,* 2000) lead to a rapid release of nutrients from previously deposited sediments and decomposing organic matter (Judson & Kauffman 1990; Naiman & Décamps, 1997; Xiong & Nilsson, 1997). In dryland rivers, flow extremes are considered to be the major drivers of the so-called "boom and bust" cycles of ecosystem processes, especially in systems with extensive floodplains (Bunn *et al.,* 2006). The pulsed release of nutrients and organic matter from rewetted sediments, following a dry period, is known as the so-called "Birch effect" (e.g. Birch, 1964; Jarvis *et al.,* 2007).

We conducted leaching experiments on sediments and leaves collected from different floodplain habitats within the Tagliamento River in north-east Italy (Tockner *et al.,* 2003). Leaching is the natural release of soluble chemicals out of biological tissues and soils. For example, the initial rapid weight loss of leaves is due to leaching, which is primarily a physical process (Polunin, 1982; Gessner & Schwoerbel 1989; Xiong & Nilsson 1997; Bärlocher, 2005). Leaching may account for a loss as high as one third of the original mass, depending on type of litter (Nykvist, 1963; Petersen & Cummins 1974; Blackburn & Petr 1979; Short *et al.,* 1980; Day, 1983; Gessner & Schwoerbel 1989; Xiong & Nilsson 1997). Leaf leachates are composed of soluble sugars, carbonic and amino acids, and phenolic substances (Nykvist, 1963; Suberkropp *et al.,* 1976; Polunin, 1984; Bärlocher, 2005), as well as nutrients such as phosphorus, potassium and nitrogen (Tukey, 1970; Jensen, 1974; Sanyal & De Datta 1991; Kaiser *et al.,* 2004).

We focused our simulations on temperature and inundation, the master variables determining ecosystem processes and biodiversity in river floodplains (Junk *et al.,* 1989; Tockner *et al.,* 2000, Döring *et al.,* 2011). Although it is well known that alterations in the timing (season) and duration of inundation of floodplains may have major ramifications for ecosystem processes, only scant attention has been given to the combined effects of temperature and flow on ecosystem processes such as the release of nutrients and organic matter across a river-floodplain gradient (but see Fierer & Schimel 2002; Gergel *et al.,* 2002, Valett *et al.,* 2005; Langhans & Tockner 2006). In the temperate region, within which the Tagliamento lies, floods may occur at any season, with water temperatures as low as 4°C during a winter flood and exceeding 20°C during a summer flood (Tockner *et al.,* 2009). Therefore, we experimentally simulated inundation events of different seasons (4 to 25 °C) and duration (12 to 96 h). We selected the particle size fraction <2.0 mm because it was the dominant sediment fraction in all habitat types of the Tagliamento floodplain, with the exception of the channel shore (Döring *et al.,* 2011; Tab. 1). There is, in general, a close relationship between size fraction and organic matter and nutrient content, which tend to increase wth decreasing grain size (Chongfa *et al.,* 2001, Sutula *et al.,* 2004; Krishna Prasad & Ramanathan, 2008).

The objectives of the study were: 1) to determine the nutrient and organic matter content in sediments of seven different floodplain habitats, and in leaves of the dominant riparian tree species, the black poplar (*Populus nigra* L.); and 2) to quantify the effect of experimentally simulated inundation temperature and duration on the leaching of nutrients and organic matter from sediments of the dominant floodplain habitats arranged across a succession gradient, as well as from freshly fallen leaves of black poplar.

5.1.2 Materials and Methods

5.1.2.1 Study site

The Tagliamento River is a 7th order Alpine river in northeast Italy (Fig. 1). It flows, unimpeded by high dams, for 172 km from the southern fringe of the Alps to the Adriatic Sea. Influenced by both Alpine and Mediterranean climates, the Tagliamento has frequent flow and flood pulses throughout the year, with major peaks in spring and autumn (Tockner *et al.,* 2003). Flooding and drying lead to distinct expansion and contraction cycles, and even small changes in the water level may cause major changes in floodplain inundation (Van der Nat *et al.,* 2002; Döring *et al.,* 2007).

The Tagliamento has escaped intensive management, except for the lowermost 25 km that are channelized. This river is considered as a reference ecosystem of European importance, which allows the study of key ecosystem processes such as the cycling of carbon and nutrients under near-natural environmental conditions (Tockner *et al.,* 2003; Gurnell *et al.,* 2009).

Sampling was carried out in an island-braided section (1.7 km x 0.7 km) near the village of Flagogna (river km 85; 150 m asl; 46° 12´ N, 12° 58´ E; Fig. 2). At base flow (about 20 m^3 s^{-1}), this floodplain section is composed of exposed gravel habitats (51.8% of the total area), riparian forest (22.8%), the channel network (15.6%), vegetated islands (8.9%), numerous floodplain ponds (0.6%), and large wood accumulations (0.4%) (Döring *et al.,* 2011). The active plain is fringed along the right bank by riparian forests, while the left bank is bordered by the steep wooded slope of Monte Ragogna. The dominant tree species in the active plain are willows (*Salix* spp.) and black poplar (*Populus nigra* L.) (Karrenberg *et al.,* 2003). Detailed information on the Tagliamento River and the study area are provided by Tockner *et al.,* (2003) and Langhans *et al.,* (2008).

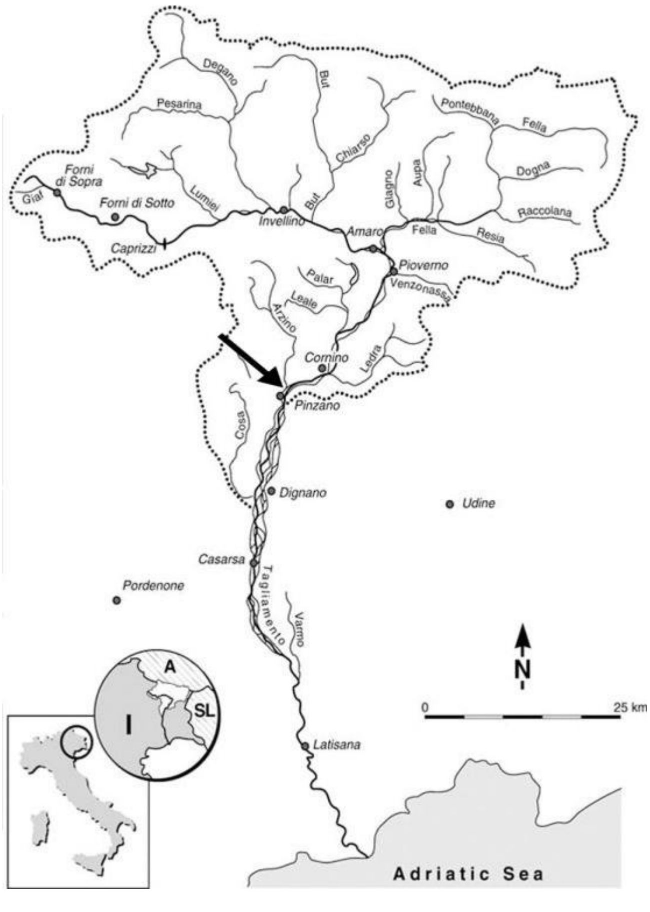

Figure 1. Map of Tagliamento catchment (NE Italy, Europe), and the location of the island-braided study reach (arrow) (modified after Ward *et al.,*1999).

Figure 2. Grayscale image of the island-braided study site of the Tagliamento River showing the complex mosaic of aquatic and terrestrial habitat types (May 2007; photo by A. Ostojić).

5.1.2.2 Sampling protocol

Sediment samples were collected in November 2006, during mean flow conditions, in the seven distinct habitat types of the river-floodplain mosaic: exposed gravel bars (EG), large wood accumulations (LW), pioneer islands (islands with tree shoots <3 m high) (PI), vegetated islands (I), and riparian forest (F) as representatives of the terrestrial group, and shoreline habitats along the main channel (CH), and along the floodplain ponds (P) as representatives of the aquatic group.

In each habitat type, three sediment samples were collected, each at a randomly selected location within the study area (for example three different gravel bars, three different pioneer islands). At each location, the sediment sample consisted of five pooled subsamples (sediment depth: 5 cm to-20 cm) to integrate for small-scale heterogeneity. Subsamples, approximately 1 kg each, were taken from a central pit and from four additional pits, each of which was 1.5 m from the central pit. Sediment samples were tagged and sealed in double plastic storage bags for transportation to the laboratory, where they were subsequently stored in a climatic chamber at 4°C (Dilly, 2001).

Leaves of black poplar, the dominant riparian tree species, were plucked from different trees or freshly fallen leaves were selected from around the base of the trees at several locations in the riparian forest (F) and on vegetated islands (I).

Sediments and leaves were weighed and dried at 22°C until reaching constant mass and were then reweighed. Subsequently, sediments were sieved through 16, 8, 4 and 2-mm sieves to quantify grain size distribution.

5.1.2.3 Leaching experiments: carbon, nitrogen and phosphorous analyses

To determine carbon and nutrient content prior to leaching, dried sediments from the seven habitat types, and the dried leaves, were analyzed for particulate organic carbon (POC), total nitrogen (TN) and total phosphorus (TP). Particulate organic carbon (POC) was determined by high-temperature combustion at 880°C with a Fuji infrared gas analyzer (Type: ZFU, Fuji Electric Systems Co., Ltd., Tokyo, Japan) (Uehlinger *et al.,* 1984). Total nitrogen and total phosphorous were determined using peroxodisulfate oxidation with an AutoAnalyzer 3 (Bran + Luebbe, Norderstedt, Germany) (Ebina *et al.,* 1983).

Leaching experiments were conducted to quantify the release of dissolved organic carbon (DOC), nitrogen (N) and phosphorus (P) species from the seven types of sediment and from the poplar leaves (Fig. 3).

Sediment samples consisted of 15 g dried sediments of the size fraction <2.0 mm. We selected this size fraction because this was the dominant sediment fraction in all habitat types, except the channel shore, which was characterized by evenly distributed particle size fractions, ranging from sand to very coarse gravel (Döring *et al.,* 2007). Leaf samples consisted of 2.5 g of dried leaves that were torn to pieces small enough to fit through the opening of the flasks.

To simulate leaching, we used artificial river water, similar in composition to the surface water of the Tagliamento at base flow (Döring *et al.,* 2007). The artificial water contained, per litre of ultrapure water, 26.14 mg total inorganic carbon (TIC), 37.54 mg Ca^{2+}, 12.56 mg Mg^{2+}, 0.768 mg NO_3^-, 2.14 mg K^+, 50.04 mg Na^+, 66.41 mg Cl^- and 49.64 mg SO_4^{2-} (Milli-Q (A10), Millipore, USA).

Sediment and dried leaves were put into Erlenmeyer flasks, pre-filled with 150 mL artificial river water, and covered with aluminium foil. Flasks were then placed on shaking tables in three climatic chambers (4°, 12° and 25°C) and incubated for 12, 36 and 96 hours, simulating different durations of inundation. We choose these temperatures and times because on the Tagliamento floodplain, floods occur at any season, (thus occurring in temperatures from 4°C to more than 20°C), and flood events vary in duration, (from few hours to several days) (Tockner *et al.,* 2009). Each of the seven sediment types was incubated at each of the three chosen temperatures and at the three durations of inundation. Each experiment was run in triplicate.

After the end of each trial, the shaking was stopped, and the flasks were left undisturbed for one hour to allow the suspended sediments to settle (Tzoraki *et al.,* 2007). Subsequently, the supernatant water was filtered through 0.7 µm glass filters (GF/F), and analyzed for seven parameters: dissolved organic carbon (DOC), ammonium (NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), total dissolved nitrogen (TDN), soluble reactive phosphorous (PO_4^{3-}) (SRP), and total dissolved phosphorous (TDP).

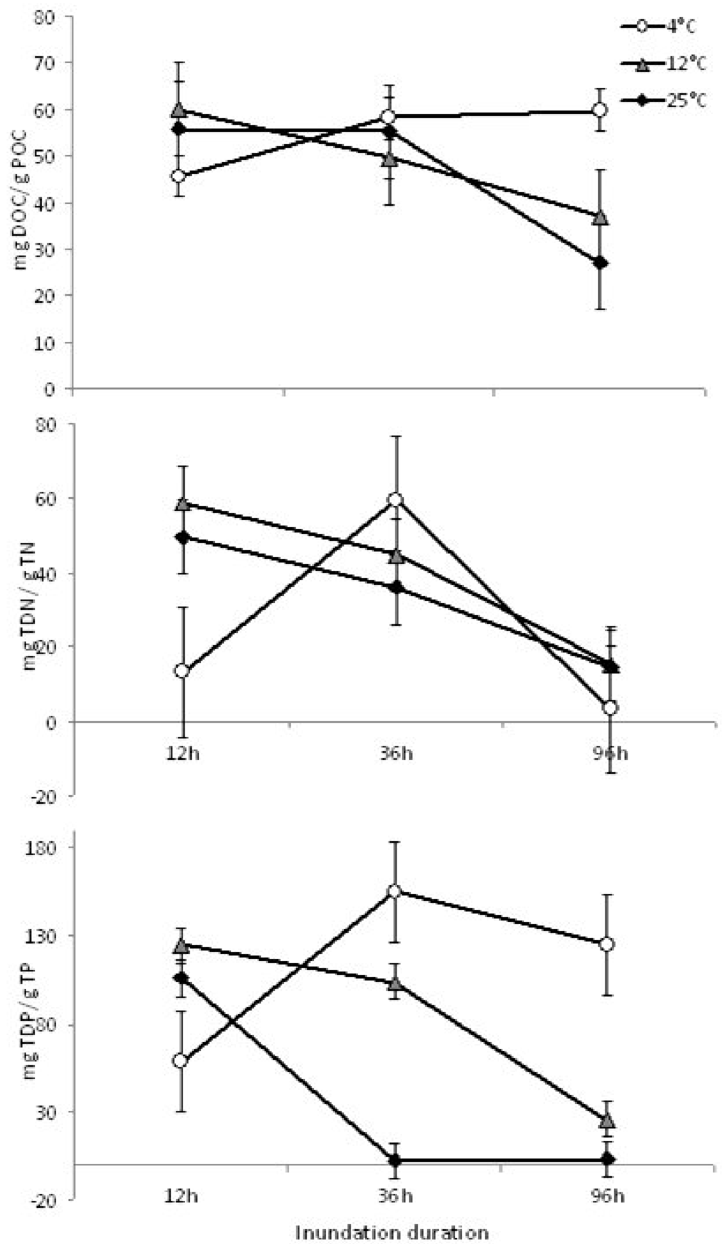

Figure 3. Relative leaching rates (average ± SE; mg g-1; n = 4 per treatment) of DOC, TDN and TDP from leaves at 4°C, 12°C, and 25°C after 12h, 36h and 96h of inundation.

Dissolved organic carbon (DOC) was measured as non-purgeable organic carbon in a filtered water sample with Shimadzu TOC-V analyzer (Shimadzu Corporation, Kyoto, Japan) (APHA, 1985). Ammonium (NH_4^+) was determined according to DEV (1983) using the Cary 50 UV/Vis Spectrophotometer (Varian Australia Pty. Ltd., Mulgrave, Australia). Nitrates and nitrites were determined with the automated hydrazine reduction method using AutoAnalyzer 3 (Bran+Luebbe, Norderstedt, Germany) (Downes, 1978). Total dissolved nitrogen (TDN) was determined using a total nitrogen measuring unit TNM-1 (Shimadzu Scientific Instruments, Columbia, USA) after all nitrogen forms had been oxidized to nitrate with $K_2S_2O_8$ at 121°C (Ebina *et al.,* 1983). Soluble reactive phosphorous (SRP) was determined according to the method of Vogler (1965) with Cary 50 UV/Vis Spectrophotometer (Varian Australia Pty. Ltd., Mulgrave, Australia). Total dissolved phosphorous (TDP) was determined as SRP after digestion with $K_2S_2O_8$ at 121°C, and was subsequently measured with Cary 50 UV/Vis Spectrophotometer (Varian Australia Pty. Ltd., Mulgrave, Australia).

Detection limits were as follows: DOC: 4 ppb; NH_4^+: 1 µg L^{-1}; NO_2^-: 2 µg L^{-1}; NO_3^- and DN: 0.1 mg L^{-1}. The measured concentrations of PO_4^{3-} and DP were often below the detection limit of < 5 µg L^{-1}.

5.1.2.4 Data analyses

We analyzed differences in the leaching rates of DOC, NH_4^+, NO_2^-, NO_3^-, TDN, PO_4^{3-} and TDP among habitat types, water temperature, and inundation duration, using repeated measures ANOVA, with habitat types (seven levels) and temperature (three levels) as the independent variables, and inundation duration (12, 36 and 96 hours) as the repeated-measures factor.

Subsequently, posteriori tests (Tukey HSD or Unequal N HSD - honestly significant difference) were applied to determine differences among the seven habitat types, and between pairs of the three categories (i.e., aquatic vs. terrestrial habitats, aquatic sediments vs. leaves, terrestrial sediments vs. leaves). Mann-Whitney U tests were used to examine differences in carbon, nitrogen and phosphorous content, and in C:N:P molar ratios in leaves and sediments.

Data were log-transformed if necessary, to meet the assumptions of normal distribution. In cases when post-transformed sets of data did not achieve normal distribution, we applied non-parametric tests. Statistical analyses were conducted using Statistica (Version 7.1, StatSoft Inc., Tulsa, USA) and SigmaPlot (Version 10.0, Systat Software Inc., USA).

5.1.3 Results

5.1.3.1 Sediment and leaf litter characteristics

The sediments of the riparian forest, vegetated islands, pioneer islands and large wood deposits were mostly composed of the size fraction <2.0 mm (>80%; Tab. 1). In contrast, the sediments of the shore habitats (CH and P) and bare gravel deposits (EG) contained a broad spectrum of grain sizes (Tab. 1). The relative water content (gravimetric mass) in sediments ranged from <4% (the shore habitats and exposed gravel) to 23.3% (riparian forest), while it was 65.4% in leaves) (Tab. 1).

The content of POC and TP in the grain size fraction <2.0 mm was not significantly different among the seven habitat types (Kruskal-Wallis test: H (6, n= 62 for TN and TP; n= 42 for POC) $p>0.05$). The TN content was significantly higher in sediments from riparian forest and vegetated islands compared to the shoreline near the main channel, exposed gravel bars and large wood accumulations (Kruskal-Wallis test: H (6, n=62) =36.68, $p<0.05$).

The POC, TN and TP content of the sediments were significantly lower than that in the leaves (Mann-Whitney U test, U=0 for POC and TN, U=1 for TP, n_1=21, n_2=4, p<0.001 for all three elements). The sediments (size fraction <2.0 mm) contained on average 9.3% to 12% POC, 0.007% to 0.047% TN, and 0.013% to 0.020% TP (Tab. 1). In contrast, poplar leaves contained on average 73.0% POC, 0.86% TN, and 0.06% TP.

The molar C:N:P ratios were not significantly different among the seven habitat types, but the molar ratios in the sediments differed significantly from that in the leaves (U=8 for C:P and U=0 for N:P and C:N, n_1= 21, n_2= 4, p<0.01). The C:P and N:P ratios were both significantly higher in the leaves than in the sediments, while the C:N ratio was significantly lower in leaves than in the sediments (Tab. 1).

5.1.3.2 Total and relative leaching rates

The total leaching rates for carbon, nitrogen and phosphorous species (total amounts leached per gram of dry material) were all significantly higher from leaves than from floodplain sediments (grain size: <2.0 mm; ANOVA: n=225, d.f.=7, p<0.001). A post-hoc test (Unequal N HSD) additionally revealed that total leaching rates of nitrogen species (TDN, NH_4^+, NO_2^-) from the sediments of the riparian forest and the vegetated islands were significantly higher than that in sediments from the other five habitat types. The differences between habitats were independent of temperature and duration of inundation.

Table 1. Characterization of the sediments from aquatic and terrestrial habitats, and of poplar leaves (mean ± SD; n = 3). Grain size distribution (% of the sum of all size fractions), water content (% of dry sediment), carbon and nutrient content (mg/g dry mass sediment) in size fraction <2.0 mm.

Habitat	Aquatic habitats		Terrestrial habitats					
	CH Channel shoreline	P Floodplain ponds	EG Exposed gravel bars	LW Large wood	PI Pioneer islands	I Vegetated islands	F Riparian forest	L Poplar leaves
Grain size (mm)								
>16	19.6±0.034	10.2±0.122	15.9±0.140	2.2±0.03	0	0	0	n.a.
8–16	24.7±0.047	20.3±0.168	21.4±0.186	5.3±0.06	0	0	0	n.a.
4–8	20.3±0.044	12.1±0.103	12.4±0.101	6.7±0.04	0	0.2±0.002	0.1±0.000	n.a.
2–4	11.9±0.016	6.1±0.056	6.7±0.050	5.7±0.03	0.1±0.000	0.1±0.001	0.4±0.003	n.a.
<2	23.5±0.060	51.3±0.412	43.6±0.464	80.1±0.12	99.9±0.000	99.7±0.002	99.6±0.003	n.a.
Water content	3.5±0.005	7.2±0.055	3.7±0.014	9.8±0.015	9.4±0.005	0.163±0.024	0.233±0.020	0.654±0.034
Carbon and nutrient content (mg/g)								
POC	112.3±17.6	101.9±18.9	110.0±15.6	93.3±13.9	103.8±12.3	104.4±13.6	119.5±13.9	730.0±148.3
TN	0.327±0.134	0.159±0.055	0.163±0.113	0.126±0.067	0.074±0.026	0.421±0.134	0.466±0.209	8.591±0.943
TP	0.177±0.067	0.197±0.115	0.164±0.071	0.126±0.033	0.131±0.010	0.132±0.028	0.189±0.022	0.572±0.225
Molar ratio								
C/N	454±202	776±128	1062±655	1042±527	1755±509	322±157	329±105	99±12
C/P	1828±748	1702±962	2064±1264	2060±910	2043±169	2149±710	1639±208	3848±2128
N/P	4±1	2±2	2±1	2±1	1±0.4	7±1	5±2	38±19

POC particulate organic carbon, *TN* total nitrogen, *TP* total phosphorus. *MR* Molar ratio, *n.a.* not applicable

The relative leaching rates (mg per g of the relevant element) of available carbon, nitrogen and phosphorous were also significantly higher from leaves than from floodplain sediments (MANOVA; Wilks´ λ $F_{42,225}$=44.78, p<0.001). Although relative leaching rates of NO_2^- and NO_3^- were higher from leaves than from the seven habitat types, differences were statistically not significant.

The maximum total and relative leaching rates (single observations) for all seven parameters were usually recorded from leaves: at 4°C after 36h for DOC, at 4°C after 36 h for TDN, and at 4°C after 96h for TDP. The exception was the relative leaching rate of TDN that peaked in exposed gravel habitats (at 4°C after 96h) (Tab. 2).

Table 2. Repeated measures ANOVA tests for differences in leaching rates of seven parameters between aquatic and terrestrial habitats, and minimum and maximum total and relative leaching rates (single observation value) along with protocols where they were measured. Mean total and relative leaching rates (average ± SD, n = 3 per habitat) pooled from seven habitats at 12°C after 36 h of inundation.

Parameter	Units	Leaching rate	*F*	*P*	Minimum	Protocol	Maximum	Protocol	Mean 12 °C/36 h
DOC	mg/g sediment	Total	45.09	*	0.003	atEG 25°/36 h	0.080	at F 4°/36 h	0.020±0.015
	mg/g POC	Relative	47.87	*	0.029	atEG 25°/36 h	0.666	at F 4°/36 h	0.182±0.066
NH_4^+	µg/g sediment	Total	58.21	*	0.110	atEG 25°/96 h	13.312	at F 25°/96 h	1.161±0.956
	mg/g TN	Relative	20.81	*	0.569	atCH 25°/96 h	28.572	at F 25°/96 h	4.740±1.889
NO_2^-	µg/g sediment	Total	27.14	*	0.010	at P 4°/36 h	0.732	at F 25°/96 h	0.131±0.055
	mg/g TN	Relative	6.70	**	0.063	at P 4°/36 h	6.864	at EG 25°/96 h	0.696±0.226
NO_3^-	µg/g sediment	Total	0.24	n.s.	3.707	at P 25°/96 h	10.981	at EG 25°/96 h	7.489±0.356
	mg/g TN	Relative	2.09	n.s.	10.306	at F 25°/96 h	105.79	at PI 25°/96 h	43.448±1.323
TDN	µg/g sediment	Total	22.17	*	0.008	at P 12°/36 h	0.083	at EG 4°/96 h	0.015±0.003
	mg/g TN	Relative	16.45	*	20.648	at I 25°/12 h	509.20	at EG 4°/96 h	83.102±7.435
PO_4^{3-}	µg/g sediment	Total	0.00	n.a.	0.025	at any habitat	0.025	at any habitat	0.025±0.000
	mg/g TP	Relative	23.58	*	0.127	at P (any)	0.198	at LW (any)	0.162±0.030
TDP	µg/g sediment	Total	0.00	n.a.	0.025	at any habitat	0.098	at I 4°/36 h	0.025±0.000
	mg/g TP	Relative	79.98	*	0.127	at P (any)	0.747	at I 4°/36 h	0.162±0.030

Terrestrial habitats: *EG* exposed gravel bars, *LW* large wood accumulations, *PI* pioneer islands, *I* vegetated islands, *F* riparian forest, *n.s.* not significant, *n.a.* not applicable. Aquatic habitats: *CH* shoreline near the main channel *P* floodplain ponds

The d.f.=1 in each case

**P*<0.001, ***P*<0.01

If leaves were excluded, the maximum total and relative leaching rates for DOC were recorded from the riparian forest sediments, for TDP from the vegetated islands, and for the nitrogen species either from forest or exposed gravel sediments (Tab. 2). The lowest total and relative DOC leaching rates (leaves excluded) were from exposed gravel habitats, while the lowest total leaching rates for nitrogen species were from pond habitats. The lowest relative leaching rates of phosphorous species were mainly from the pond sediments (Tab. 2; also Fig. 4). Both maximum and minimum leaching rates (total and relative rates) were recorded after 36 or 96h. While the maximum values were measured at either 4° C or 25°, the minimum values were usually recorded at the highest temperature (25°C).

The total and relative leaching rates for all seven nutrient species significantly differed among the seven different sediment habitat types (ANOVA Wilks´λ: n=193, d.f.=6, p<0.001). In general, the highest relative and total leaching rates were from the sediments of the riparian forest and vegetated islands (belonging to the terrestrial habitat types). Total and relative leaching rates of DOC, TDN, NH_4^+ and NO_2^- were significantly higher in terrestrial than in aquatic habitats (d.f.=6, p<0.001; Tab. 2). Although the highest leaching rates were in the forest sediment, total and relative leaching rates of NO_3^- were not significantly different between aquatic and terrestrial habitats.

The concentrations of TDP and PO_4^{3-} were often below the detection limit, and thus we were unable to make comparisons among habitats for total leaching rates. However, their relative leaching rates were significantly higher in terrestrial habitats than in aquatic habitats (Fig. 4).

5.1.3.3 Effects of temperature and inundation duration

In aquatic and terrestrial habitat types, the relative leaching rates of DOC significantly decreased with inundation duration, independent of temperature. At the same time relative leaching rates of TDP significantly decreased, and the NO_2^- rates significantly increased, with increasing temperature and duration of inundation. In terrestrial habitats the NH_4^+ leaching rates increased with inundation duration independent of temperature, while leaching of NO_3^- peaked at low temperature (Tab. 3).

The Pearson r revealed a positive correlation between temperature and the relative leaching rates for nitrogen species (r=0.26 for NH_4^+, r=0.46 for NO_2^-, p<0.001), and a negative correlation between temperature and TDP (r=-0.23, p=0.002). The relative leaching rates of nitrogen species and duration of inundation were only weakly correlated (r=0.23 for NH_4^+, r=0.39 for NO_2^-, r=0.23 for NO_3^-, r=0.46 for NO_2^-, p<0.001; r=0.12 for TDN p=0.101).

The relative leaching rates from leaves were significantly influenced by inundation duration alone, and inundation duration in concert with temperature (Tab. 4). Even though temperature was only at the borderline of significance (p=0.062), it influenced the relative leaching rates from leaves. A post-hoc test (Tukey HSD) revealed that relative leaching rates for DOC, NH_4^+, TDP and PO_4^{3-} were inversely proportional with temperature. Pearson r correlations between temperature and tested parameters were all negative, but statistical significance (p<0.05) was found only for TDP (r=-0.44) and PO_4^{3-} (r=-0.47). At the higher temperatures of 12°C and 25°C, the relative leaching rates of DOC, TDN and TDP peaked after only 12 hours of inundation. In contrast, at the lowest temperature of 4°C, the relative leaching rate peaked after either 36 h (TDN and TDP) or 96 h of inundation (DOC) (Fig. 3).

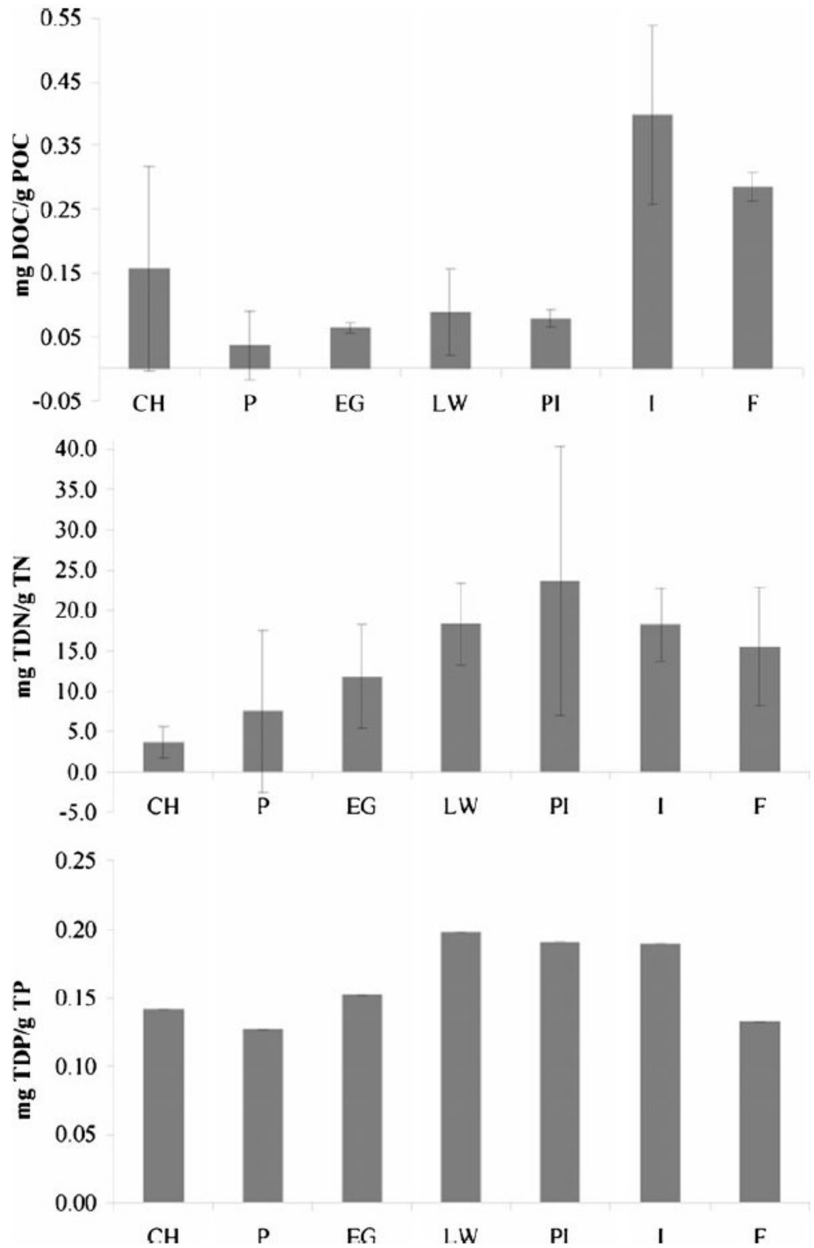

Figure 4. Relative leaching rates (average ± SD, n = 3 per habitat) of DOC, TDN and TDP from seven habitat types at 12°C after 36 h of inundation.

The release of DOC and TDN from leaves was always significantly lower after 96h compared to 12 and 36h (see also Fig. 3). ANOVA revealed statistically significant differences in relative leachates of DOC (Wilks'λ: $F_{2,36}$ = 6.04, p<0.05) and TDN (Wilks'λ: $F_{2,36}$ = 39.20, p<0.001). Statistically significant correlations (Pearson r) between leaching rates in leaves and inundation duration were found for DOC (r=-0.36), TDN (r=-0.48) and TDP (r=-0.39). Among the three tested compounds in leaves (C, N and P), phosphorous leached significantly more than the other two.

Table 3. Repeated measures ANOVA tests for the effects of temperature and duration of inundation on relative leaching rates in aquatic and terrestrial habitats. *** p<0.001; **p<0.01; * p<0.05; n.s.= not significant.

		Aquatic habitats			Terrestrial habitats		
		d.f.	F	P	d.f.	F	P
DOC (mg/g POC)	Temperature	2	0.30	0.747n.s.	2	1.24	0.317n.s.
	Duration	2	13.52	0.000***	2	19.85	0.000***
	Temperature × Duration	4	1.89	0.137n.s.	4	10.96	0.000***
NH_4^+ (mg/g TN)	Temperature	2	0.86	0.441n.s.	2	33.26	0.000***
	Duration	2	0.09	0.915n.s.	2	409.10	0.000***
	Temperature × Duration	4	3.14	0.029*	4	21.99	0.000***
NO_2^- (mg/g TN)	Temperature	2	4.99	0.022*	2	40.10	0.000***
	Duration	2	14.89	0.000***	2	207.03	0.000***
	Temperature × Duration	4	2.46	0.067n.s.	4	45.47	0.000***
NO_3^- (mg/g TN)	Temperature	2	0.02	0.975n.s.	2	5.27	0.023*
	Duration	2	4.61	0.019*	2	7.26	0.003**
	Temperature × Duration	4	2.01	0.120n.s.	4	6.62	0.000***
TDN (mg/g TN)	Temperature	2	0.29	0.755n.s.	2	1.61	0.235n.s.
	Duration	2	0.69	0.511n.s.	2	3.28	0.050*
	Temperature × Duration	4	0.85	0.508n.s.	4	0.79	0.539n.s.
PO_4^{3-} (mg/g TP)	Temperature	2	0.00	1.000n.s.	2	1.06	0.369n.s.
	Duration	2	0.00	1.000n.s.	2	2.13	0.137n.s.
	Temperature × Duration	4	0.00	1.000n.s.	4	2.13	0.102n.s.
TDP (mg/g TP)	Temperature	2	6.38	0.009**	2	6.09	0.011***
	Duration	2	4.87	0.014	2	17.92	0.000***
	Temperature × Duration	4	4.87	0.004**	4	17.92	0.000***

Table 4. Results of the multivariate test of significance (Wilks test) for the effects of temperature and duration of inundation on relative leaching rates in leaves; * p<0.05.

	Value	F	Effect d.f.	Error d.f.	P
Temperature	0.44	1.89	12	44.00	0.062*
Duration	0.37	2.39	12	44.00	**0.017***
Temperature × Duration	0.23	1.72	24	77.96	**0.038***

5.1.4 Discussion

Solutes, released from sediments and leaf litter through leaching, are essential components of the organic matter and nutrient cycles in river floodplains (Baldwin, 1999; Inglett *et al.,* 2008). In the present study, we compared the leaching rates across seven aquatic and terrestrial habitat types within a complex ecosystem mosaic. The results revealed very high potential release rates from vegetated islands and the riparian forest. Leaf litter accumulates at the sediment surface and forms a key resource of nutrients and organic matter for surface and subsurface waters.

Of the underlying sediments, we only used the size fraction <2.0 mm, because it was the dominant fraction in most floodplain habitats (Tab. 1), it contained disproportionately more nutrients and organic matter than coarse size fractions (e.g. Döring *et al.,* 2011), and it allowed a standardized comparison across habitats. Furthermore, it was difficult to collect gravel sediment cores, transfer them to the laboratory, and carry out leaching experiments in replicates using Erlenmeyer flasks. However, we were aware that the area-specific leaching rates would be (slightly) higher in open tract habitats (exposed gravel, ponds and shore habitats) by including the size fractions >2.0 mm.

Drying and rewetting determine ecosystem processes such as leaf litter decomposition (Langhans *et al.,* 2006; Bruder *et al.,* 2011), sediment respiration (Döring *et al.,* 2011), nutrient uptake (Von Schiller *et al.,* 2011), and leaching (this study). While the effect of drying and rewetting on organic matter and nutrient dynamics is a well-studied subject in terrestrial soils (Birchm 1964; Fierer & Schimel 2002; Jarvis *et al.,* 2007; Gordon *et al.,* 2008) less is known about its effect in aquatic systems, especially in complex river floodplains. Furthermore, the interaction of inundation duration and temperature on ecosystem processes had been almost completely ignored despite the fact that temperature and flow form the master variables in floodplains (cf. Junk *et al.,* 1989; Tockner *et al.*,2000). Brinson (1977), for example, quantified the decomposition and nutrient exchange of litter in an alluvial swamp forest (SE USA). He found that temperature and moisture appeared to be the most important controlling variables. In the present study, we found relatively small effects of temperature, albeit a general decrease in leaching with increasing temperature. For the Krathis River (Greece), a similar declining trend of N (%) release with increasing temperature had been observed (Tzoraki *et al.,* 2007), but with high variability rendering this trend statistically insignificant.

Floods may cause rapid leaching of nutrients from dried leaves present on the floodplain soil, as exemplified in the initial pulse of DOC, DN and DP,12 h after the leaves were submerged in water (12 and 25°C, Fig. 3). This release of nutrients is expected to cause a rapid increase in microbial activity and nutrient cycling processes, resulting in a generally highly fertile and productive system. At 4°C, the initial pulse of nutrient release was delayed, postponing the peak for 24 h.

The Tagliamento exhibits a very flashy inundation regime, i.e., flood duration ranges from a few hours to a few days. Hence, processes such as leaching, adsorption and mineralization, are predominant processes of the nutrient cycle. Furthermore, the duration and frequency of inundation depends on the topographic position of the individual floodplain habitats. While shore areas, ponds, and bare gravel habitats are exposed to frequent water level fluctuations, vegetated islands and the riparian forest are inundated only during bankfull events (i.e., 1-2 times per year; Bertoldi *et al.,* 2009). The sediments of aquatic and terrestrial habitats are therefore already depleted in carbon and nutrients, as they release them with each flooding event (Kobayashi *et al.,* 2009). At the same time, flooding redistributes sediments across the entire floodplain, leading to similar nutrient and carbon contents in the < 2.0 mm size fraction, independent of habitat type (cf Tab. 1).

Bankfull events, however, are expected to lead to a pulsed release of nutrients and organic matter (so-called "first flush events", Obermann *et al.,* 2009). In addition, islands and the riparian forest are exposed to frequent rainfall events that do not lead to a lateral transfer of matter. Hence, we must differentiate between leaching events caused by inundation and those caused by rainfall events. Rainfall events may lead to a nutrient enrichment of the unsaturated soils, and subsequently of the groundwater system. In this respect, vegetated islands, and to a lesser extent the riparian forest, may serve as "islands of fertility", similar to what had been described for upland dryland areas by Schade & Hobbie (2005). Consequently, vegetated islands serve as important instream riparian zones that provide nutrients and organic matter, in dissolved and particulate form, to the adjacent less productive aquatic and terrestrial habitats. At the same time, vegetated islands are among the first habitats that disappear as a consequence of flow regulation and river canalization (Gurnell *et al.,* 2005).

Changes in the components of the flow regime such as timing, duration, frequency, and severity may have major ramification for the functional performance of a floodplain system. Reduced hydrological connectivity, and inundation regime, following flow regulation and river regulation, leads to an increase in the local retention and recycling of organic matter and nutrients, altering the quality and in particular the quantity of material entering the aquatic system (e.g. Langhans *et al.,* 2013).

Organic matter and nutrients released from freshly fallen leaves may differ in quality, and bioavailability, from material released from aged leaves or from sediments. Dahm (1981) and Findlay *et al.,* (1991) showed that 70% of the leachates from red alder leaves and alligator weed, respectively, were removed from the microbiota within the first 48 to 77 hours, compared to 30% of the DOM leached from terrestrially aged leaves (see also Baldwin, 1999). An open question is if leachates derived from fresh leaves stimulate the transformation of more refractory organic compounds such as lignins and polyphenolic tannins in the sediments (i.e., the so called priming affect). Therefore, the quality and quantity of DOM and nutrients exported from the floodplain to the river will depend not only on the source of DOM and nutrients, but also on how long the material had been aged, and, therefore, on the timing and frequency of inundation pulses (e.g. Baldwin 1999). In the Tagliamento River, floods may occur at any time of the year, although they are most frequent in spring (snow melt) and in autumn (heavy rainfall events). A spring flood may release material from aged leaves, while a winter flood will release organic matter of high bioavailability.

Along the Tagliamento River, the nutrient and organic matter concentrations of leachates were always higher than the average concentrations in river water (Kaiser *et al.,* 2004). This is consistent with the findings of Tzoraki *et al.,* (2007), who showed that the leaching of N and P species from the sediment of the Krathis River (Greece) was much higher than the dissolved concentration of these species in the river water. The higher concentration of leachates indicates the propensity of the sediments in providing nutrients and organic matter for surface and subsurface aquatic systems. In our experiments, sediments were taken from a depth of 5 cm to 20 cm, demonstrating that sediments can build up major nutrient and organic matter reservoirs during the dry periods that are released during flooding or heavy rainfall events.

Leaching was always higher in leaves. From leaf samples, the relative release of DN was somewhat lower than that of DOC and DP; in contrast to the underlying sediments, where the release of DN was relatively higher than that of DOC and DP. The reason for the relatively lower values of leached DN from leaves could be that fresh leaves contained more nitrogen species bound in the living tissue. The higher leaching of DN from inorganic sediments could be due to the accumulation of leaf litter covering floodplain floor, which slowly releases N species to the sediments (Tibbets & Molles 2005).

In the sediments of the Tagliamento, we found a relatively high C:N ratio, and this was partly due to the C content of the floodplain samples (9% to 12% C), which was high compared to riparian wetland soils (1.6% to 3.7% C; Altor, 2007). In leaves, the high N:P ratio, and low C:N ratio, can be explained by the high nitrogen content in leaf litter compared to the sediments (0.86% compared to 0.007% to 0.047% N), and by the low phosphorus content of both leaves and sediments. The nitrogen content in the Tagliamento floodplain sediments was very low compared riparian wetland soils (0.16% N; Altor, 2007). The increase in leached N species (TDN as well as NH_4^+ and NO_2^-) with increasing inundation duration from floodplain sediments may be caused by the high microbial activity following re-wetting of sediments (Baldwin & Mitchell, 2000). However, we need to consider that we measured the net release rather than the gross release of nutrients and organic matter because microbial uptake rates were not quantified.

An accurate calculation of area-specific leaching rates per habitat type requires quantitative information of organic matter per area (<2.0 mm and total OM), as well as spatially-explicit information on inundation duration and frequency. Unfortunately, this information was not available. However, we do have data about habitat-specific carbon storage and transformation rates (i.e., sediment respiration, leaf litter decomposition, standing stock of CPOM; Döring *et al.*, 2011; Langhans *et al.*, 2013; Tab. 5). This information allows us to put the present results into a broader context of floodplain functioning. Due to the specific characteristics, each of the various aquatic and terrestrial habitats performs different processes (Tockner *et al.*, 2010).

Table 5. Ecosystem properties and processes of various aquatic and terrestrial habitat types of the Tagliamento River. Mean values are given for grain size distribution, organic matter content, sediment respiration, leaf-litter decomposition (coarse mesh size), and leaching. Detailed information about methods and results are given in Langhans *et al.* (2008), Döring *et al.* (2011), Tockner *et al.* (2010) and this study.

	Aquatic habitats		Terrestrial habitats			
	CH	P	EG	LW	I	F
Area (ha)	18.2	0.6	60.3	0.4	10.4	26.5
Area (%)	15.6	0.5	51.8	0.3	8.9	22.8
Grain size (<2.0 mm; %)	23.5	51.3	43.6	80.1	99.7	99.6
Organic matter (g AFDM/kg)	6.3	6.6	6.5	19.2	23.3	40.9
CPOM (g AFDM/m^2)	50	5	<1	NA	1000	1000
Respiration (g C/m^2 year)	292	160	168	624	1206	982
Respiration (%)	9.7	0.2	18.7	0.5	23.1	47.8
Leaf decomposition (k/d)	−0.019	−0.005	−0.005	−0.002	−0.002	−0.002
Leaching (mg DOC/g sediment, 12 °C/36 h)	0.179	0.062	0.087	0.116	0.422	0.307

The results of our experiments confirmed the significant role that riparian areas play as pivotal energy sources for adjacent aquatic and downstream reaches. Floodplains exist as a catena of aquatic and terrestrial habitats that differ in their environmental properties and functional performance (Tab. 5). The functional performance of a habitat patch not only depends on its specific properties (e.g. sediment organic matter, inundation probability) but also on the performance of and the connectivity to adjacent patches. For example, the release of nutrients from high productive areas, such as vegetated islands, may determine the productivity of adjacent less productive bare gravel habitats as well as surface and groundwater waters (Tockner *et al.,* 2010). Therefore, understanding the nature of the linkages among contrasting patches is critical in understanding how river floodplains function as ecosystems (e.g., Poole *et al.,* 2008).

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River Research and Applications

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5.2 The effect of different nutrient sources and first flood event on system functioning in a Mediterranean temporary stream (SE Portugal)

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Abstract

Hydrological disturbances and nutrient sources are key factors in temporary streams functioning. In Mediterranean streams, the characteristic water level fluctuations during the expansion and contraction periods, is mainly linked to rainfall and can affect both physical and biological conditions. However, despite the natural disturbances, Mediterranean rivers are also under the influence of anthropogenic disturbances such as pollution and habitat fragmentation, which can lead to nutrient enrichment, interfering not only on primary producers growing, but in the entire river functioning. Thereby, evaluating the relative contribution of different nutrient input sources may provide an initial step to manage mechanisms that may cause surface water enrichment, through catchment runoff.

The present study summarizes the effect of different nutrient sources on stream functioning, in a temporary Mediterranean catchment from SE Portugal. It focused on the effect of first flood event and in input sources from the catchment, measured as nutrients loads (TN, TP and TSS) and biomass from primary producers (periphyton chlorophyll-*a* and macrophytes) and leaf litter. Results pointed to hydric stress as the major factor responsible for the early summer leaf fall,

which started in the beginning of the dry period and reached a peak in October, with the onset of the first rains. At the end of the dry period, macrophytes and leaf litter contribute particularly in terms of readily digestible biomass and particulate organic carbon (approximately 50% content) to the system. The scouring effect of high discharges together with the high amount of TSS transported within the first flood events promoted the erosion and removal of periphytic communities, which registered imperceptible values with the impact of the first floods. Results also demonstrated that nutrient loads are the main input source of nutrients to aquatic system during first flood events. As nutrient loads are closely linked to land use within the catchment, this proves to be particularly important in temporary catchments as the excess of nutrients can induce eutrophication, especially in areas subjected to diffuse and point pollution sources, such as settlements, agriculture and livestock farming. Overall, understanding the importance of nutrient inputs in aquatic ecosystems will improve our knowledge on system functioning and promote the correct management of temporary stream catchments.

Keywords: ecosystem functioning, first flood event, leaf litter, macrophytes, Mediterranean temporary streams, nutrient loads, periphyton chlorophyll-*a*

5.2.1 Introduction

In Mediterranean streams, the hydrological disturbances associated with the expansion and contraction periods affect both biotic communities and ecosystem functioning (Boulton, 2003). Their characteristic water level fluctuations, mainly linked to rainfall, interfere in the natural processes driven by water flow (Gasith & Resh, 1999; Lake, 2000). Some of these hydrological disturbances are events particularly extreme but of low frequency, and can have tragic effects in both physical and biological conditions (e.g. Thorndycraft *et al*., 2005). The nature of rewetting, either by flash floods or by slow inundation, has huge effects on the input of materials from the exposed soils within the catchment. The occurrence of heavy rainstorms rather than a prolonged steady precipitation, lead to severe soil erosion and large amounts of sediment and nutrients exportation out of the catchment (Lake, 2011). Yet, Mediterranean river systems are fairly well adapted to recover from these disturbances, both in terms of biological structure and functioning (Margalef, 1983; Sabater *et al*., 1995). They host a well-adapted biota to the expansion and contraction periods that characterize these systems (Sabater *et al*., 1995; Gasith & Resh, 1999; Lake, 2003). However, despite the natural disturbances, Mediterranean rivers are also under the influence of anthropogenic disturbances (Gasith & Resh, 1999) such as nutrient enrichment, habitat alteration and network simplification (Sabater *et al*., 2006).

Disturbances that lead to nutrient enrichment are peculiarly important since nutrients are able to affect not only the primary producers, but the whole river functioning, especially when they are applied in a continued way (Slavik *et al*., 2004). Both the structure and function in these systems are organized around the type and quality of the inorganic and organic matter available to organisms, always modulated by the particular hydrological and climatic conditions. Thus, evaluating the relative contribution of point source and non-point source nutrient loads may provide an initial step to managing the mechanisms which cause surface water enrichment, by the influence of catchment runoff and overland flow.

The present study summarizes the effect of different nutrient sources on stream functioning in a temporary Mediterranean catchment from SE Portugal. It will focus on the effect of first flood event and in sources of nutrient input from: i) the catchment, measured as the amount of total loads of nitrogen (TN), phosphorus (TP) and suspended solids (TSS) in the water column, ii) the primary producers, measured as periphyton chlorophyll-*a* and macrophytes autochthonous biomass contribution and iii) the leaf litter, measured as allochthonous biomass contribution from the riparian vegetation.

5.2.2 Study area

This study was conducted in Pardiela, a temporary stream located in southern Portugal (38° 38' N, 07° 42'W; catchment area 514 Km^2; river km 10; Fig. 1). The Pardiela Stream catchment ranges from 505 m at headwaters to 169 m at its confluence with the Degebe River (Gallart *et al.*, 2008). The mean air temperature ranges from 9ºC in winter (December–February) to 23ºC in summer (June–September) (Lillebø *et al.*, 2007). The average annual precipitation is around 600 mm (Lillebø *et al.*, 2007), irregularly distributed throughout the year and between different years. This rainfall pattern results in lower discharges in spring/summer, when precipitation is scarce or absent, and higher discharges in autumn/winter, due to intense rainfalls.

Field measurements were made at a 250 meters study site in a middle reach of the river (Fig. 1), selected for its location and ease access. Since the earliest records Pardiela's catchment is mostly agricultural (Gaspar, 1972), with considerable areas used as pasture of black Iberian pig and cows (Tangarrinhas, 1994). As a result, nutrient pollution is mainly from small rural industries, arable land and agriculture and urban areas (Fig. 1; INAG, 2012).

The hydrograph for the studied reach illustrated the typical pattern of annual discharge in temporary streams; an expansion period during October to April and a contraction period from late May to September (Fig. 2). During the studied period, the first flood event always caused the stream to flow, pointing out to its huge importance in temporary ecosystems. The variation in flow within and between years can be particularly great, which is very important feature in Mediterranean temporary rivers and makes them exceptional dynamic environments (Poff *et al.*, 1997).

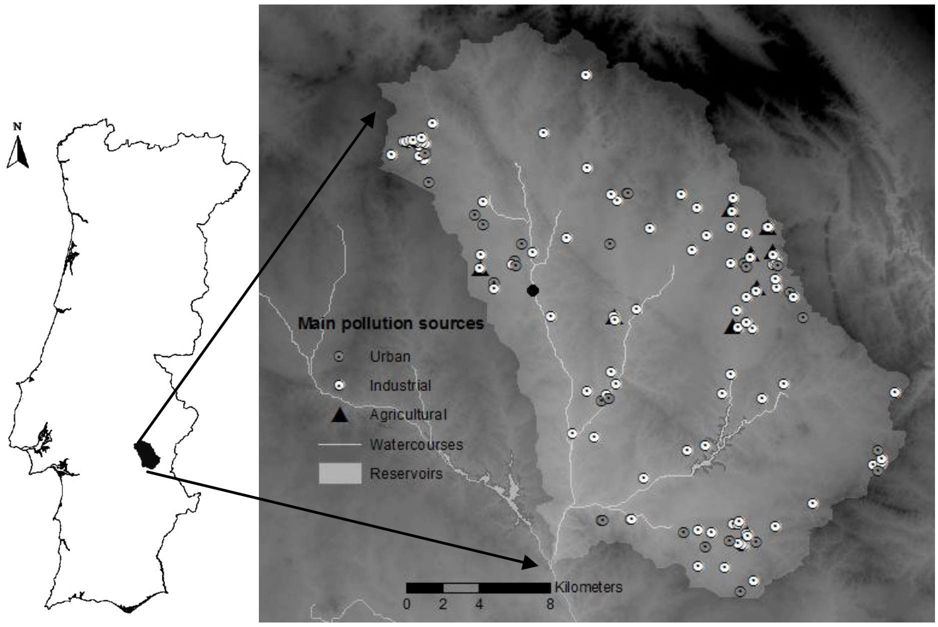

Figure 1. Map showing the geographic localization of Pardiela catchment (38° 38' N, 07° 42'W) and sampling reach (marked with black dot; river km 10). Identification of the main pollution sources by category: small rural industrial, agricultural and urban sources (INAG, 2012).

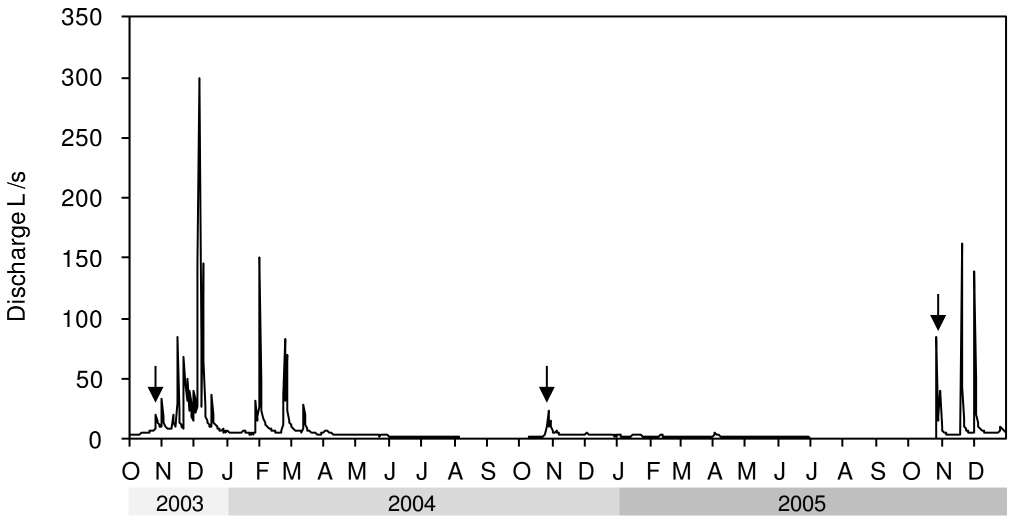

Figure 2. Hydrograph for the two hydrological years (2003/2004 and 2004/2005; SNIRH, 2007). Arrows show the first flood events.

The riparian vegetation is mostly composed by deciduous species, such as ash (*Fraxinus angustifolia* Vahlenberg), willows (*Salix atrocinerea* Brotero and *Salix salviifolia* Brotero) and poplars (*Populus alba* Linneus and *Populus nigra* Linneus) (Lillebø *et al.*, 2007). The African tamarisk (*Tamarix africana* Poiret) is especially common in temporary riverbeds and can support long dry periods and high discharges (Biléu, 2008). During spring, macrophytes dominate the riverbed. In Pardiela, the most common macrophytes are the narrowleaf cattail (*Typha* *angustifolia* Linneus), roundhead bulrush (*Scirpoides holoschoenus* (L.) Soják) and sedge (*Cyperus longus* subsp. *badius* (Desf.) Bonnier & Layens) (Biléu 2008, Fonseca 2004; Fig. 3b).

Figure 3. Photos from Pardiela stream: magnitude of first flood events in Pardiela catchment (a); macrophytes maximum standing crop at the end of spring (b); dry riverbed at the end of summer; detail of vertical traps and leaf litter deposits (c); and the presence of biofilm in cobbles and sediment (d).

5.2.3 Methods

5.2.3.1 Nutrient loads assessment

Water samples were collected on a monthly basis, during the hydrological years of 2003/2004 and 2004/2005, and taken to laboratory for physical-chemical analysis. The concentrations (C) of total suspended solids (TSS; mg/L), total nitrogen (TN; mg/L) and total phosphorus (TP; mg/L) were determinate. Parameters were analyzed according to the following methods: TSS by Total Suspended Soils Dried at 103-105°C Method, TN by Nitrate Cadmium Reduction Method, Nitrite Colorimetric Method and Organic Nitrogen by Macro-Kjeldahl Method, and TP by Phosphorus Ascorbic Acid Method (APHA, 1999).

The cross-section profile was measured in the study reach, where it was inserted an YSI multiparametric probe that recorded water depth each 30 minutes. Discharge (Q) was then calculated through the section-velocity method (Gore, 1996), based on water velocity measurements (Lencastre & Franco, 1984) and ISO 748:2007.

The principle of constant concentration was used to estimate the mean monthly loads (Chapman, 1996). It was assumed that the concentration (C_i) determined for a given time (t_i) is constant during a time interval (δt_i) around the time of sampling, and that the hydrological characteristics are maintained during the same time interval. The load (Φ) was obtained by integrating the concentration (C) and discharge rates (Q) for a daily time interval (t_1 and t_2) within a month (D_t) according to the following equation:

$$\Phi = \int_{t_1}^{t_2} C(t)Q(t)\delta t$$

5.2.3.2 Primary producers survey

The periphytic autotrophic biomass, measured as chlorophyll-*a* (Chl-*a*) content (in mg/m^2), was collected from individual pebbles collected within the study area (Fig. 3d). At the laboratory, a defined area was scraped with a nylon toothbrush from each pebble, resulting in a suspension of ≈10 ml. This suspension was then used to extract Chl-*a* in 90% acetone in darkness and low temperature, and measured with spectrometer (Thermo Scientific Evolution 300 UV-Vis). Values were obtained by Lorenzen (1967) equations.

Macrophytes were sampled according to their coverage area in the study reach. Given their biomass representativity, macrophytes were separated in three groups: 1) *Typha angustifolia*, 2) *Scirpoides holoschoenus* and *Cyperus longus* and 3) other small hydrophytes. Macrophytes were sampled in 5 transects, perpendicular to streambed, covering a 25 cm × 25 cm area. Only the aerial part of macrophytes was collected. Macrophytes biomass was determined by oven drying the samples at 40ºC to constant weight (Esteves, 1988).

Because of the important role of biofilm as digestible organic matter, the periphytic autotrophic biomass was sampled monthly during the hydrological years 2003/2004 and 2004/2005. Macrophytes were collected only at the end of the dry period and after the first flood event, from 2003 to 2005, in order to assess their contribution in terms of nutrient input to the system due to their high biomass.

5.2.3.3 Leaf litter assessment

Vertical litterfall was sampled in 4 transects perpendicular to river channel, within the 250 meters reach. Each transect included two vertical traps of a 1 mm mesh, covering an area of 50cmx50cm. Traps were placed every 50 meters, suspended ≈3 m above the river dry bed, attached to the surrounding trees (Elosegi & Pozo, 2005; Fig. 3c). Leaf litter samples were collected monthly from 2003 to 2005. Only leaves were considered to leaf litter biomass quantification. At laboratory leaf litter biomass was determined by oven drying the samples at 40 ºC until constant weight (Esteves, 1988).

5.2.3.4 Nutrient contents in macrophytes and leaf litter

Nutrients contents in terms of total nitrogen (N_{total}), total phosphorus (P_{total}) and total carbon (C_{total}) were assessed by comparing the elements that contribute most to the aquatic system, in terms of biomass. Thus, periphytic autotrophic biomass was not considered; only macrophytes and leaf litter samples were analysed. Samples were smashed, homogenized and extracted before nutrient analysis. Total carbon and total nitrogen were obtained through an elemental analyzer and total phosphorus was obtained by the Ascorbic Acid Method (APHA, 1999).

5.2.3.5 Data analysis

The patterns of evolution of different descriptors were graphically reviewed and their response to first flood events was evaluated by comparison with the dry riverbed conditions. In relation to macrophytes, their resistance to the first flood event was evaluated by Independent T-Test (PASW® Statistics 18).

5.2.4 Results and discussion

5.2.4.1 Evaluation of in-stream nutrients loads of TN, TP and TSS

Nutrient loads express the amount of an element which passes in a given section of the river, during a determined time range. The element under analysis reflects the effect of river basin conditions, and so loads can provide an estimation of the pollution at a catchment scale. Figure 4 shows the estimated loads for the hydrological years 2003-2005 of TN, TP and TSS (Kg/month). As expected, loads increased during river floods. On an annual basis, the pattern is similar for all three elements, with higher loads during the autumn and winter months, coinciding with flood events. The loads of TSS are mainly due to banks and soil erosion in the catchment during runoff and by the resuspension of particles deposited in the dry riverbed. TN and TP loads increase mainly due to fertilizer additions and waste effluents from agricultural, domestic and industrial origin. As a result, TSS, TN and TP loads have a peak during the flood events, due to surface runoff of the entire drainage area (Fig. 4)

Apart from the urban point sources of pollution, in Pardiela catchment some point sources were identified, such as cattle farms, which do not have any type of system effluent treatment. However, loads inputs are not usually relatively easy to control as they come from both point and diffuse pollution sources. Urban point source pollution might only require an intervention at the level of drainage systems to improve the removal of nutrients but diffuse pollution relies on farmers awareness, which is not so easy to control. The problem of soil contamination with fertilizers requires good agricultural practices, and effluent livestock control is also essential to prevent extra inputs of nutrients and the microbiological contamination to rivers.

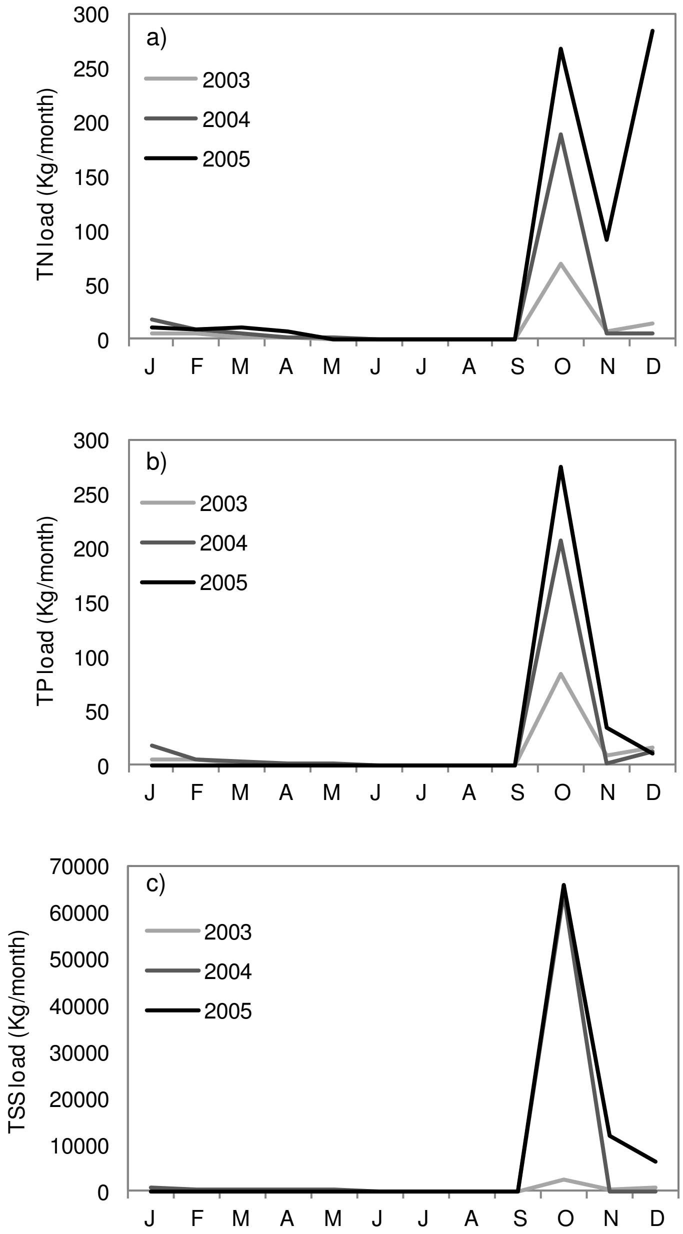

Figure 4. Monthly variation of (a) total nitrogen (TN), (b) total phosphorus (TP) and (c) total suspended solids (TSS) loads, during the two hydrological years 2003-2005.

5.2.4.2 The role of primary producers

The significance of primary producers is likely to increase with increasing aridity (Gasith & Resh, 1999) and mean temperature (Lamberti & Steinman, 1997; Mulholland *et al.*, 2001). Given this, in Mediterranean rivers primary producers have a great significance and is highly related to seasonal variations in discharge, light and temperature, and nutrients (Armengol *et al.*, 1991; Sabater *et al.*, 2006; Velasco *et al.*, 2003).

In terms of riparian forest, Pardiela stream has predominantly open sections (due to deforestation), where light can easily reach the stream bottom, favouring primary producers. Periphytic autotrophic biomass given by chlorophyll-*a*, registered tendentially high values during summer, like July 2004 with 21.65 mg/m^2 (Fig. 5), when discharge is lower and water temperature is higher. Occasionally there were some winter months (e.g. December 2005) that also recorded high values (e.g. 22.03 mg/m^2 in December 2005; Fig. 5). In contrast, periphyton registered imperceptible values (below the detection limit) with the impact of the first floods (in autumn and winter), due to their scouring effect. Several authors also observed a decrease in periphyton biomass with the sudden increase of discharge (e.g. Grimm & Fisher, 1989; Morais 1995; Nielsen *et al.*, 1984). Horner & Welch (1981) also indicate that the amount of TSS transported within the floods contributes to the erosion and removal of periphytic communities.

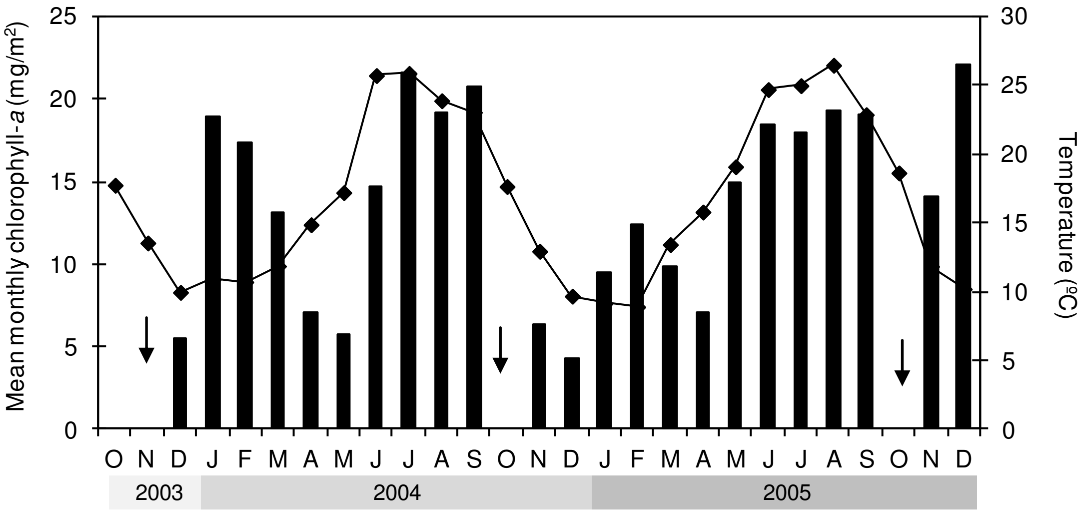

Figure 5. Mean monthly variation of periphytic autotrophic biomass (chlorophyll-a, mg/m2) in Pardiela stream. Mean monthly temperature variation values from SNIRH (2007). Arrows show the first flood event.

Thereby, the periphyton autotrophic biomass decrease with flood events in Pardiela might be due to the high loads of TSS registered during the first flood event (Fig. 4b.). Under favorable conditions it could be expected that a higher nutrient availability was able to cause a remarkable biomass increase in the autotrophic component of the stream (e.g. Pringle, 1987; Sabater *et al.*, 2005). However, the abrasive effect of first flood event caused a drastic decrease in periphyton communities during that time period. Nevertheless, even though these communities have low resistance to high discharges, they are high resilient and their response to flood events could be particularly fast (Fig. 5). Some authors referred an algae recovery period of 21 days (Power &

Stewart, 1987), 21-30 days (Fisher *et al.*, 1982) and 20-78 days (Grimm & Fisher, 1989). In Pardiela, once the flow was re-established, periphytic communities appear to take about one month to re-establish after the first flood event (Fig. 5). But despite the annual decreasing associated mainly with the first flood event, periphytic communities also have a great seasonal variability, which can be checked by the wide variation along the year. Periphytic communities, as an important component of biofilm, constitute an important food source for grazers and detritivorous organisms, such as macroinvertebrates and fishes. Indeed, periphyton represents the main basis of functioning in shallow streams, where temporal and spatial heterogeneity together with seasonal differences, are the two major impact factors controlling benthic biofilm and its role on nutrient cycling (Sabater *et al.*, 2006).

Macrophytes as another important primary producer, assist in the overall stream functioning, and provide food and habitat for some fishes and animals. However, an overabundance of macrophytes can result from high nutrient levels, which may contribute to system eutrophication. The loss of connectivity during the dry period triggers several reactions, namely high encroachment of vegetation into stream channels (Gasith & Resh, 1999). At the end of the dry period, almost all macrophytes are completely dried, which will turn their removal by floods easier. In Pardiela, *Typha angustifolia* L. dominates the riverbed (Fig. 2b), frequently in dense colonies (maximum of 787.5 gDW/m^2; Fig. 6). Yet, the first flood event also causes a decrease in macrophytes biomass (Fig. 6). The highest decreases in macrophytes' biomass matched the highest peaks of discharge of first flood event, in 2004 and 2005 (Fig. 2). Floods, throughout the abrasive effect of high water velocity and TSS, have often been reported as agents of changes and removal of aquatic macrophytes (e.g Bilby, 1977; Pedro *et al.*, 2006) and as a direct cause of spacing heterogeneity in the vegetation. Nevertheless, despite the tendency, the Independent T-test showed that macrophytes biomass before and after the first flood event were not significantly different (t (4) = 0.447, p = 0.678), which may point to a someway resistance to floods. This results demonstrated that though their decreased in biomass with first floods, macrophytes community in Pardiela are somehow resistant to first flood events.

From an ecosystem point of view, the high extent of dry macrophytes at the end of summer, confirms their important role as a possible key energy source of nutrients, e.g. via breaking and exportation of CPOM (CPOM, woody materials and leaves >1mm) during floods, shredders processing or decomposition.

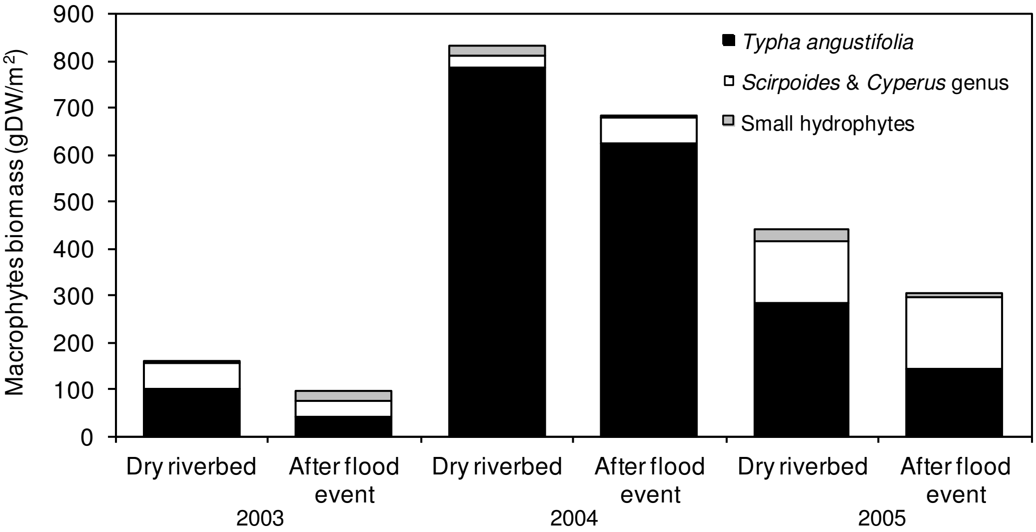

Figure 6. Mean biomass (gDW/m^2) of the most dominant macrophytes in riverbed (*Typha angustifolia*, *Scirpoides holoschoenus* and *Cyperus longus* subsp. *badius* and small hydrophytes) at dry riverbed (end of the dry period) and after the first flood event.

5.2.4.3 Riparian leaf litter input

The vegetation in Mediterranean climate is naturally adapted to water stress during the dry period (e.g. Maamri *et al.*, 1994). Typically, the input of allochthonous leaf litter to streams occurs in autumn, and is the most important basis of food webs in streams (Fisher & Likens,1973; Cummins *et al.*, 1973). Therefore, temporal variation of litter fall is mainly due to the seasonality of inputs from the riparian forest, which is also related to the hydrologic regime (e.g. Acuña *et al.*, 2004). The dry period allow large litterfall accumulations in riverbed which will be transported downstream during flood events.

The riparian vegetation in Pardiela stream, typically constituted by deciduous trees, creates punctual leaf litter input due to its irregular distribution. Leaf litter showed a seasonal variation, with maximum values in autumn, with 78.6 gDW/m^2 and 224.5 gDW/m^2 in October 2004 and 2005, respectively (Fig. 7). However, both years had an intense leaf fall during the dry period, under high temperatures and low water levels. In 2004 and 2005 the leaf litter annual input in Pardiela stream, was 0.269 kgDW·m^{-2}·yr^{-1} and 0.784 kg·m^{-2}·yr^{-1}, respectively, mostly from poplar and ash trees. These inputs were similar to those registered in other temporary Mediterranean streams namely via litterfall direct fall from alders of 0.491 kgDW·m^{-2}·yr^{-1} in Sabater *et al.* (2001). Leaf litter constantly starts with the beginning of the dry period, in summer, reaching a maximum in October, with the onset of the first rains (Fig. 7). It is noteworthy that beside the seasonal pattern of leaf fall, the two years registered a great variability on the amount per month. The hydric stress affects the riparian vegetation and might be responsible for the early summer litterfall (Sabater *et al.*, 2001). Several other studies have already pointed out to the relation between the increasing temperatures and consequent litterfall. Pardo & Álvarez (2006) in Majorcan streams, shown a substantial input at the time of increasing temperatures and progressively reduced water levels. Berg & Laskowski (2006) referred that, in a continental to a regional scale, factors such as climate (e.g. precipitation) influence leaf fall. In arid zones, where water is the main limiting factor, several species react to hydrological stress reducing their surface though leaf fall (Strojan *et al.*, 1979). As in Pardiela stream the riparian leaf fall input occurs during the summer period, when almost riverbed is dried, most of the CPOM storage remains without being decomposed until the stream starts to flow. Consequently, the first flooding has a huge impact in dry riverbed, breaking and exporting the accumulated CPOM downstream.

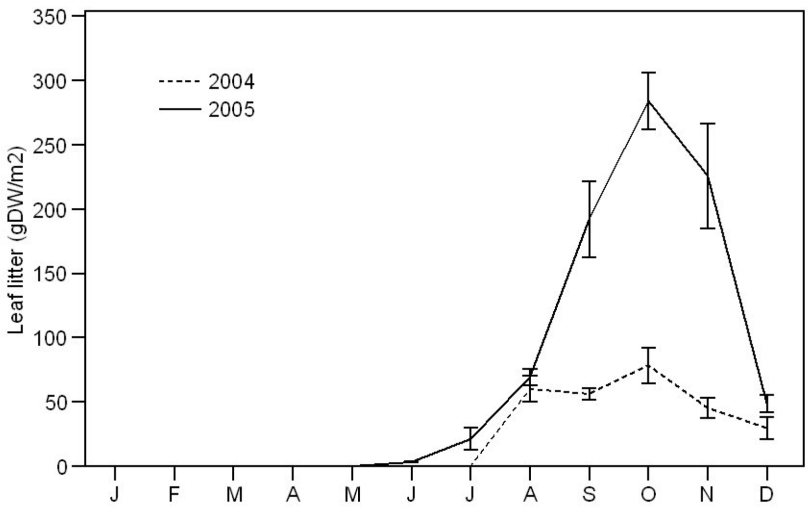

Figure 7. Monthly variation of leaf litter in Pardiela stream (gDW/m^2; mean+SE).

5.2.4.4 Nutrients availability of autochthonous and allochthonous inputs

During the dry period, the CPOM in Pardiela riverbed was almost exclusively from dry macrophytes and leaf litter. As in the studied reach almost the entire riverbed dries, the accumulated organic matter, exported with the first flood may leave the system incompletely processed (energy "leakage" *sensu* Vannote *et al.*, 1980). Only the remaining pools may contribute to the regeneration of nutrients from organic and inorganic matter during the flow cessation period (Lillebø *et al.*, 2007); the remaining CPOM is decomposed and exported only after the time of the first flood event.

The highest particulate organic carbon contents registered during summer, both in macrophytes and leaf litter, supports the observations from several authors (e.g. Vannote *et al.*, 1980) where both, autochthonous and allochthonous plant litter constitutes a key source of carbon and energy to the system. The total nitrogen (N_{total}) and phosphorus (P_{total}) contents of leaf litter and macrophytes was low (<2%), while total carbon (C_{total}) contents were high (approximately 50%), both in leaf litter and macrophytes (Tab. 1). Results pointed out to the value of temporary rivers as important sources of readily digestible CPOM biomass, confirming that both, autochthonous (macrophytes) and allochthonous (riparian vegetation) inputs are an important contribution of particulate organic carbon to the stream. Thereby, this type of inputs should also be considered in management strategies, as it will provide an additional input of organic carbon that may contribute to eutrophication phenomena at downstream reaches and reservoirs.

Table 1. Table 1. Nutrient content of total carbon, nitrogen and phosphorus at the end of the dry period (mean ± SD).

Nutrients	2003		2004	
	Leaf litter	Macrophytes	Leaf litter	Macrophytes
C_{total} (%)	50.1±1.7	48.6±1.1	49.7±0.7	48.6±1.8
N_{total} (%)	1.2±0.3	1.0±0.4	0.9±0.1	1.5±0.7
P_{total} (%)	0.1±0.0	0.1±0.0	0.1±0.0	0.1±0.1

5.2.5 Conclusions

Flow intermittency strongly affected nutrient availability in Pardiela stream. The link between habitat and biological communities was mainly constrained by the seasonal changes in water flow. Figure 8 summarizes the main nutrient sources and their linkages in Pardiela. The results clearly showed that the dynamics of temporary streams are of high importance to the overall mass transport. Nutrient loads have been identified as the main potential allochthonous inputs of nutrients to the aquatic system. They are closely linked to land use and extremely important as they can induce eutrophication, especially in areas subjected to diffuse and point pollution sources, in catchments with large settlements, agriculture and livestock. Macrophytes and leaf litter also contribute, particularly in terms of biomass and particulate organic carbon (Fig. 8; Tab. 1). Typically, the input of aleaf litter occurs in autumn, but the hydric stress affects the riparian vegetation and might be responsible for the early summer litterfall. As the riparian leaf fall input occurs during the summer period, when almost riverbed is dried, most of the CPOM storage remains without being decomposed until the stream starts to flow. Consequently, the first flooding has a huge impact in dry riverbed, breaking and exporting the accumulated CPOM downstream. Anthropogenic pressures like the removal of riparian vegetation and livestock grazing promotes soil erosion and, during the rainy season, increases the carry of soil and nutrients from the surrounding areas to the stream, contributing to nutrient enrichment. Additionally, the high availability of CPOM might lead to a reduction in dissolved oxygen in the water column, becoming harmful to aquatic organisms and promoting eutrophication phenomena. Periphyton, as a constituent of biofilm matrix, constitutes an important food for the trophic chains, playing a key role in nutrient cycling uptake and remineralisation (House, 2003; Von Schiller *et al.*, 2007) and energy and organic matter supplier to higher trophic levels

(Lamberti, 1996). Indeed, periphyton represents the main basis of functioning in shallow streams, being extremely dependent on light, temperature, discharge and nutrients availability.

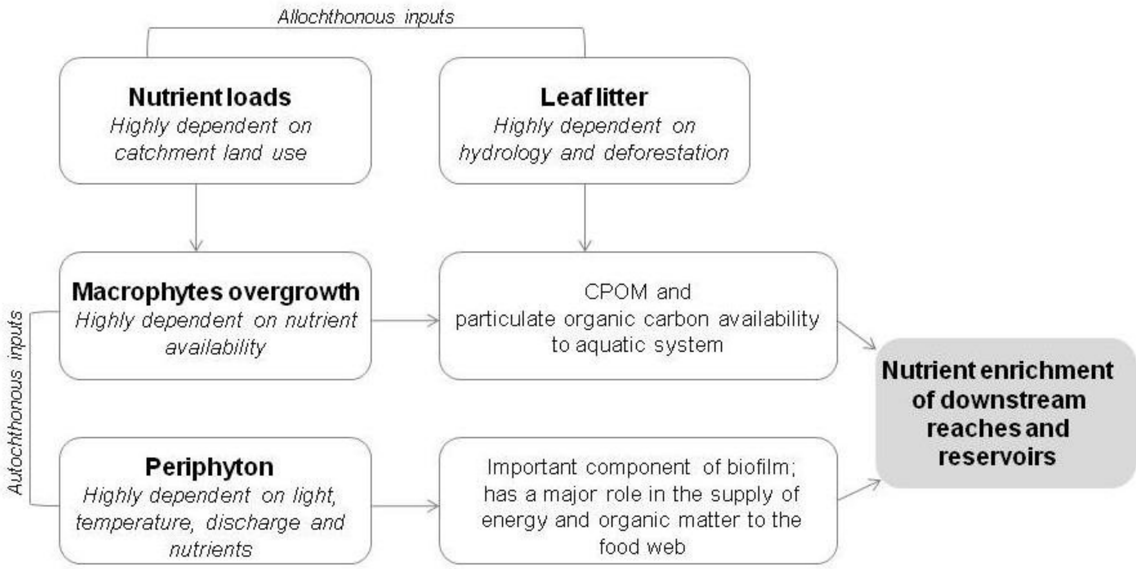

Figure 8. Conceptual summary of different nutrient and organic carbon sources in Pardiela stream and their major outcomes to the aquatic system.

Both the dry and wet periods are important components of the hydrologic cycle. During the rewetting period, floods set off a number of processes such as restoring channel connectivity, scouring of accumulated sediments and debris, washing of in-stream riparian vegetation and homogenizing water quality conditions along the stream channel (Gasith & Resh, 1999). Nevertheless, further research is required to determine the impact of autochthonous and allochthonous inputs to river functioning, in order to estimate the amount of CPOM and nutrients transported within river channels to downstream reaches and reservoirs. Allochthonous organic matter as a fuel to stream food webs, it is a very well studied subjected on ecological subsidies (Tank *et al.*, 2010). Obermann *et al.* (2009) also highlighted that the variation of flow cause concentrated waves of nutrients and pollutants, which will add a substantial risk for downstream water bodies as the substances will have a harmfull potential there. Thereby, in terms of river management, several measures have to be applied focusing for example on the problems caused by different pollution sources. It is necessary to apply conservation and rehabilitations strategies that improve the morphological features and diminish nutrients transport during flooding events, in order to prevent eutrophication. In particular, downstream the Pardiela catchment is located an important water system (Alqueva-Pedrogão system), affluent of the largest reservoir in southern Portugal (Alqueva reservoir), and so, it is important to have adequate management policies to reduce and control the loads of sediments and nutrients into rivers, in order to prevent reservoirs eutrophication. The impact of anthropogenic pressures in nature has led to an overexploitation of natural resources and to dramatic changes in land use including the use of fertilizers which contribute to the deterioration of water quality and environment. The population density together with industrialization and the use of fertilizers constitute the main causes for eutrophication of river systems, estuaries and seas (Jonge *et al.*, 2002).

The knowledge of the interactions between hydrology and ecosystem functioning is the basis of a future sustainable management of temporary Mediterranean systems, particularly vulnerable to climate changes. The predictable increase in air temperature is likely to be translated directly into warmer water temperatures throughout Europe, which linked to the expected worsen of drought conditions, can have an huge and direct impact in ecosystems functioning (Edwards *et al.*, 2012). This is particularly important because the stress imposed by drought can intensify the effects of anthropogenic activities, in a region already vulnerable to water shortages. According to Rosado *et al.* (2012), different management strategies such as the use of education, incentives and regulation, can be applied to catchments with temporary rivers, but they need to be shared by interested stakeholders and land owners, so that the proposed actions can be sustainable and applicable to local people. Connections among factors operating at different spatial scales (i.e., from catchments to streams), might distinctly influence stream ecosystem function, and so should be taken into consideration when designing stream management and restoration plans. Ecological success of stream management and restoration is expected to restore function as well as structure to streams, therefore the use of appropriate measures of functional processes is required (von Schiller *et al.*, 2008). Nutrient retention and metabolism parameters are good candidates to fill this gap. Overall, understanding of the importance of nutrient inputs and metabolism parameters will improve our knowledge on system functioning and promote the correct management of temporary stream catchments.

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Chapter 6

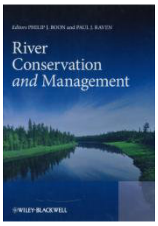
Temporary rivers management

Chapter 6

Summary

In Mediterranean regions, the annual distribution of rainfall determines the seasonal flow characteristics of rivers. Their high inter-annual variability and seasonal annual patterns of dry and wet periods makes them unique in terms of biodiversity but also extremely vulnerable due to climate change. The Mediterranean region, in which Portugal is included, is one of the world's richest places in terms of biodiversity but within a near future, climate change may decrease the water availability and introduce new threats to human health, ecosystems and also national economy. Most Mediterranean streams are temporary, characterized by seasonal events of flood and drought. The temporary rivers, in the broadest sense, are systems that during part of the year appear limited by the interruption of flow or extreme situations caused by the loss of water. As the demand for water increases, its availability becomes a major problem, especially during the dry Mediterranean summers.

The southern Portugal is under the Mediterranean influence, and is thus characterized by high air temperatures and reduced precipitation. The temporal precipitation variability within the year frequently leads to severe problems of water scarcity during the dry period, in southern regions, in which most rivers are temporary. One of the major problems associated with the dry period is the natural decrease of water quality, which increases rivers vulnerability both in terms of water quality and ecosystem biodiversity. An important implication of climate change is that it could hinder substantially efforts for a truly sustainable approach of water management in these regions. The specific hydrology of southern Portuguese temporary rivers makes them particularly sensitive to anthropogenic pressures in their watersheds, especially in terms of the availability of good quality water. Therefore, any actions taken in river basins can have adverse effects on water status and its ecology, with potential implications at an environmental, economic and social scale. To improve the current knowledge on temporary river catchments, this chapter includes the results of the effects of climate change in stream hydrology, carried out in a temporary stream catchment from southern Portugal.



River Conservation and Management

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6.1 Key factors in the management and conservation of temporary Mediterranean streams: a case study of the Pardiela river, southern Portugal

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Abstract

Temporary waters are widespread in the Mediterranean and in many semi-arid regions worldwide. Most streams in the Mediterranean regions are temporary watercourses that expand during autumn and winter (wet period) and contract during spring and summer (dry period). The most important issues concerning temporary streams include the interactions between hydrology and stream dynamics and our capacity to understand and predict their dynamics.

The main objectives of this study were: 1) to study the key patterns of temperature and precipitation in a temporary river basin, 2) to use the SWAT modeling to simulate the total runoff and discharge in the entire river basin, and 3) to develop management and conservation strategies, practical enough to involve the public participation of stakeholders and other interest groups.

Man-Kendall statistical test showed that there is an existing trend of increasing temperature and a beginning tendency of decreasing precipitation in Pardiela basin. The SWAT modelling confirmed the natural ephemerality of headwater reaches, with less discharge, less total runoff and consequent higher percentage of days without current flow. On the other hand, downstream

reaches start to flow with the first flood event and naturally maintain the base flow until late spring, when they contract into large pools.

Key words: management and conservation, Mediterranean region, SWAT model, temporary streams, water management

6.1.1 Introduction

Rivers are complex systems and are strongly influenced by the landscapes through which they flow (Hynes, 1975; Vannote *et al.*, 1980). Actions taken well away from the river can sometimes have adverse effects on channel morphology, river flow, water quality and biological communities, with consequent environmental, economic and social implications and costs. These landscape-scale factors are particularly relevant in Mediterranean regions of the world because they amplify the effects of the annual seasonal wet and dry periods and the unpredictable variability of precipitation between years (Boulton, 2003). The impacts on aquatic ecosystems can be particularly severe during the dry season (Fisher *et al.*, 1998; Stanley *et al.*, 1997).

Most Mediterranean streams are temporary, characterized by seasonal events of flood and drought and inhabited by aquatic communities that are adapted to this pattern and uncertainty. As the demand for water increases, especially for agricultural use, its availability is becoming a major problem, especially during the dry Mediterranean summers. This has led to extensive physical modification of rivers to provide more reliable access to water both for human consumption and agricultural irrigation (Kondolf & Batalla, 2005). Extreme water shortages and crop failures during the droughts of the early 1990s exposed the vulnerability of Mediterranean areas to climatic extremes (Weiß *et al.*, 2007). An important conclusion from these events was that future climate change could hinder substantially efforts for a truly sustainable approach to water management in the region. The potential consequences of more frequent and longer droughts include an increase in desertification, a decrease in water availability for food production and new threats to human health, ecosystems and the economies of affected countries. At a strategic scale, the construction of dams and reservoirs is a way of increasing the volume and reliability of water supplies for agricultural and urban use. However, dams disrupt significantly the natural hydrological and fluvial morphological processes that control habitat structure, the intensity and frequency of floods, floodplain connectivity and water quality conditions (Bunn & Arthington, 2002). The cumulative effect of small-scale local modifications to the river channel and water flow can have equally adverse effects on the special type of freshwater ecosystem represented by temporary streams. For example, the physical disturbance and modification of temporary streams is widespread in Mediterranean regions where local people rely on streams and rivers for their water supply and to graze their livestock in the dry periods (Gasith & Resh, 1999).

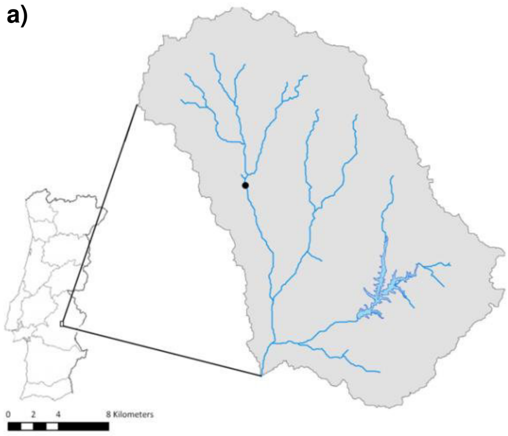
Action to tackle one problem often leads to adverse effects on other sectors of society, so a wide range of interests needs to be taken into account when managing land and water within a river catchment (Lee & Dinar, 1996). Consequently, involving a range of stakeholders in the planning and decision-making process is important and this is a key principle enshrined in the European Water Framework Directive (WFD, Council of the European Communities, 2000; Leal, 2006). However, the technical guidance for the WFD does not refer explicitly to the temporary, seasonally-intermittent streams; aiming to achieve 'good ecological status' is more readily associated with permanent watercourses. Therefore, securing the full environmental benefits expected from the WFD legal requirement for Member States to achieve good ecological status in water bodies ('good ecological potential' for heavily modified water bodies) is a major challenge for Mediterranean countries. For example, monitoring methods and assessment protocols need to take account of the seasonal and between-year variations in assessment programmes for temporary watercourses, not only to safeguard water supplies for human use but also to conserve ecological interest and integrity. This means it is important to develop effective decision-support tools for catchments with temporary streams, particularly as climate change is most likely to increase pressure on already scarce water resources (Weiß *et al.*, 2007).

Several catchment-based land and water quality models have been developed in the past 20 years (Lenzi & Di Luzio, 1997; Lowrance *et al.*, 2000; Cerucci & Conrad, 2003; Gassman *et al.*, 2007). These have explored the impact of land-use change on water conditions, notably the Soil and Water Assessment Tool (SWAT) which was developed by the US Agricultural Research Service as an interdisciplinary catchment modelling tool, with over 30 years of application focusing on stream-flow calibration and associated hydrological analyses, pollutant loading and climate change impacts on hydrology (Gassman *et al.*, 2007). However, the assumptions used in these models are based on permanent watercourses, so their application in catchments where streams and rivers are dry for part of the year is limited (Trancoso *et al.*, 2009). A study on the effects of climate change on stream hydrology was carried out in a demonstration river catchment in southern Portugal to improve current knowledge about river catchments with temporary watercourses. The main objectives of this research were: (i) to study long-term patterns and trends of air temperature and precipitation; (ii) to use the SWAT model to simulate total runoff and discharge across the entire catchment; and (iii) to develop practical management guidance for implementing conservation strategies.

6.1.2 Study area

The study area was the River Pardiela catchment in southern Portugal. The Pardiela is a fourth-order Mediterranean stream with a total catchment area of 514 km^2 (Fig. 1a). The altitude range is from 505 m in the headwaters to 169 m, at its confluence with the River Degebe (Gallart *et al.*, 2008). Mean air temperature ranges from 9°C in winter to 23°C in summer, with a mean annual precipitation of 600 mm (Lillebø *et al.*, 2007). The Pardiela has a typical Mediterranean hydrological regime, with low discharge in the dry summer period and high discharge in the wet autumn and winter. During the summer, the river-bed dries out completely in the headwaters and contracts to a series of pools in the middle reaches. The downstream reaches contain water all year round owing to the presence of two dams located in adjoining tributaries and a weir where the Pardiela joins the Degebe River. Catchment land-use is dominated by holm oak (*Quercus ilex* ssp. *rotundifolia*), olive groves, vineyards and pasture land. Riparian vegetation is fragmented and mainly consists of ash (*Fraxinus angustifolia*), willows (*Salix atrocinerea* and *S. salviifolia*), poplars (*Populus nigra*) and introduced African tamarisk (*Tamarix africana*). Field measurements were made at a 1 × 1 km study site in the middle reach of the river, selected for its location and ease of access (Fig. 1a). The river in the study site had a bedslope of 0.32%, a mean channel width of approximately 20 m and a maximum depth of 1.4 m. The main river-bed substratum comprised sand, gravel and pebbles. Maximum altitude in the study site was 243 m. Changes in land use and stream morphology at the study site were assessed using aerial photographs taken in 1958 and 2005 (Fig. 1b).

a)



b)

Figure 1. Map of Portugal, showing the location of the River Pardiela catchment (38° 38' N, 07° 42'W), the 1 km× 1 km study site (black dot) and Vigia reservoir (a). Aerial photographs of the study site taken in 1958 (left) and 2005 (right) (b).

6.1.3 Methods

6.1.3.1 Establishing climatic patterns and trends

Climatic information for the catchment was based on temperature and precipitation data generated by a long-term weather station at Évora (*Instituto de Meteorologia*, http://www.meteo.pt/) and national weather stations in Azaruja and Santa Susana (*Sistema Nacional de Informação de Recursos Hídricos*, http://snirh.pt/). The national stations provided more than 60 years of temperature and precipitation data. These were compared with the 30 average for the period 1961–1990, in line with the minimum recommended time period required to observe climatic trends. Climatic trends were tested using the non-parametric Mann-Kendall statistic test; time series patterns were analysed using the so-called progressive and retrograde series of the sequential Mann–Kendall test in order to establish the likely beginning of significant trends (Sneyers, 1990).

6.1.3.2 Applying the Soil and Water Assessment Tool

The 2009 version of SWAT (SWAT2009; ArcGIS Version 9.3; http://swatmodel.tamu.edu/software/) was used to simulate a time series of river discharge hydrographs for 46 different locations of the Pardiela catchment, selected randomly to represent the headwaters, middle and lower reaches of the river. Data used for the SWAT model were taken from a number of sources, including: (i) 1:100 000 scale soil map (Gonçalves *et al.*, 2005); (ii) Corine Land Cover 2000 at 1:100 000 scale (http://www.igeo.pt/); and (iii) the Alentejo Digital Terrain Model, provided by the *Administração da Região Hidrográfica do Alentejo, I.P.* Field measurements included data from a weather station specially installed in the study reach which provided continuous information on air temperature, precipitation, wind speed and direction, solar radiation and relative humidity. An automatic multi-parameter probe, inserted in the riverbed, measured the water level every 30 minutes. Discharge measurements were recorded in the study reach during and after the flood events and for each month during the two hydrological years from October 2007 to October 2009. The SWAT model was calibrated using the field measurement data from October 2007 to October 2009 in order to establish the discharge pattern throughout each of the two hydrological years. The information was used to predict the number of days without flow and infer the pattern of ephemeral flow along different reaches and tributaries throughout the catchment.

6.1.4 Results

6.1.4.1 Climatic trends

The pattern of annual variability in mean air temperature at Évora during the period 1941–2006 showed a gradual increase when compared with the average air temperature for 1961–1990 (Fig. 2a). The Mann-Kendall statistical test confirmed a trend of increasing mean air temperature. Both progressive (blue line in Fig. 2b) and retrograde (red line) series began to increase after 1977, but the upward trend only became statistically significant (t=1.96, α=0.05) in 2003, following the intersection point between the two in 2002.

The annual variability of mean precipitation during the period 1932–2007 indicates a gradual decrease when compared with the average precipitation for 1961–1990 (Fig. 3a). The progressive and retrograde series (in blue and red respectively; Fig. 3b) suggest that the precipitation started to decrease in 1973, but the intersection point of the two suggests that 1978 represented the beginning of a statistically meaningful downward trend. However, the decreasing trend did not cover the entire period; for example, in 2005 the progressive series exceeded the statistically significant level (t=1.96), indicating a temporary reversal reflecting an unusually wet year.

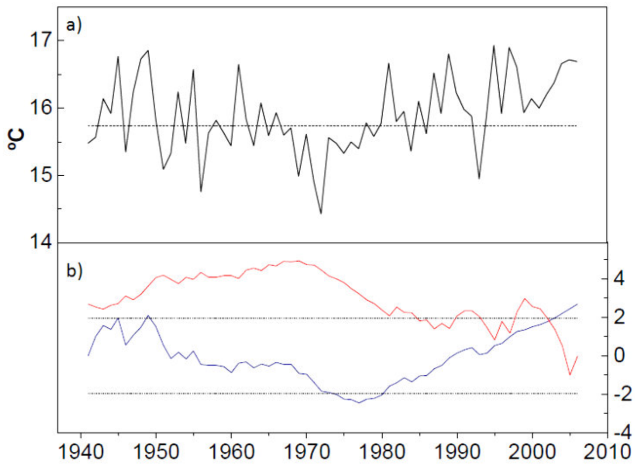


Figure 2. Annual variability of mean air temperature in the River Pardiela catchment during 1941–2006. The dashed line represents the average air temperature during the period 1961–1990 (data from the Évora weather station) (a). Progressive (blue) and retrograde (red) series of Mann-Kendall statistic test (b). The dashed lines represent the significance boundaries (t = 1.96; α = 0.05).

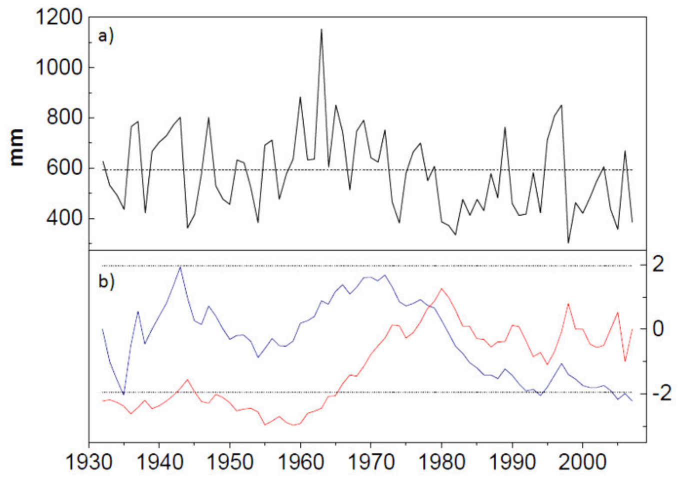


Figure 3. Annual variability of mean precipitation in the River Pardiela catchment during 1932–2007. The dashed line represents the average air temperature during the period 1961–1990 (data from the Azaruja and Santa Susana meteorological stations) (a). Progressive (blue) and retrograde (red) series of Mann-Kendall statistic test (b). The dashed lines represent the significance boundaries ($t = 1.96$; $\alpha = 0.05$).

6.1.4.2 Hydrological modelling

Comparison of field measurements for discharge taken in the study site with modelled outputs using automatic probe, weather station and *in situ* measurements indicated that the SWAT simulations were able to capture the annual pattern of flow with an adjustment factor of $r^2 = 0.9693$ (SWAT simulations = 1.9146 × *in situ* measurements). Given the good calibration between the model and field measurements, the SWAT model was used to estimate total annual runoff from the entire river catchment. The modelled hydrographs demonstrated the typical pattern of annual discharge in temporary streams; an expansion period during October to April and a contraction period from late May to September (Fig. 4). The headwater reaches had a natural tendency to flow only during and shortly after heavy rainfall. In the middle reaches flow started as a result of the first autumn flood and a base flow was maintained until late spring, when a lack of rainfall and increasing temperatures gradually led to an interruption in flow causing contraction of the river into a series of large pools. The pattern for the downstream reaches was similar to the middle reaches but with higher discharge levels. In all cases maximum discharge occurred during flood events.

The SWAT model was able to estimate total runoff for the two hydrological years and allocate the proportion of this to different parts of the catchment (Fig. 5). As expected, this shows that the main-stem channel accounts for the greatest proportion while headwaters contribute the smallest amount. Transforming the modelled data into information estimating the percentage of days without flow over the 2-year period shows the effects of the seasonal pattern more clearly

(Fig. 6). Headwaters had no flow for 89% of days compared with 56–84% in middle reaches and 56% at downstream end.

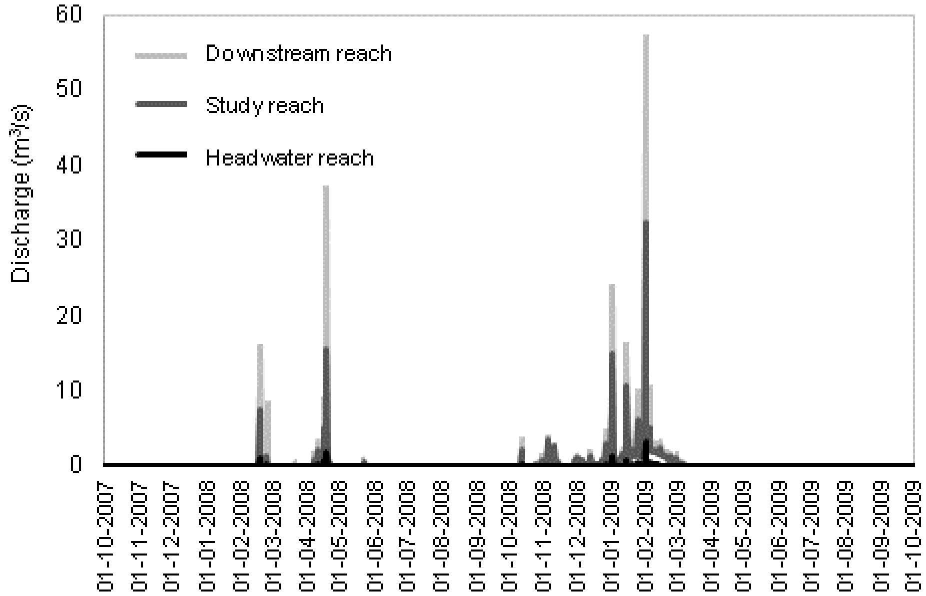


Figure 4. Hydrograph outputs for the two hydrological years (October 2007–October 2009) generated from the SWAT modelling. The lines represent different reaches of the River Pardiela: black line – headwater reach; dark grey line – study site (middle reach); light grey line – downstream reach.

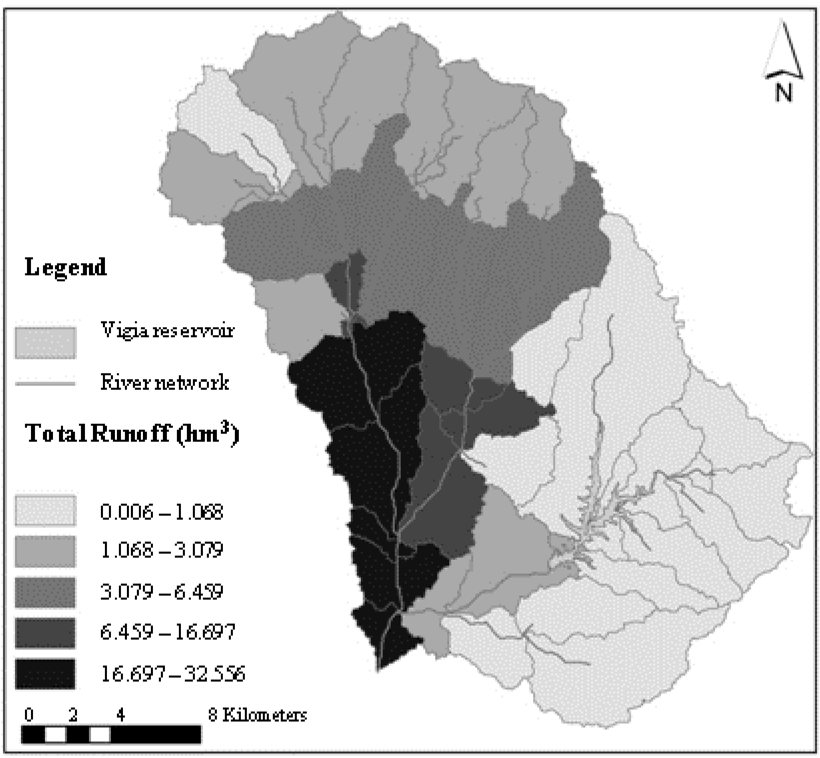


Figure 5. Total run-off for the two hydrological years (October 2007–October 2009) generated from SWAT modelling. The main stem accounts for the greater part of total runoff (black and dark grey areas). Tributaries only add part of the total runoff, and headwater reaches have the smallest contribution to the amount of total runoff (light grey areas).

6.1.4.3 Land use and stream morphology

Comparison of aerial photographs (Fig. 1b) of the Pardiela study site indicates that predominant land-use in the 1 km^2 study site remained broadly the same between 1958 and 2007. Holm oak forest declined from 46% to 36% and olive groves from 23% to 22%, whilst pasture land increased from 30% to 34%. The most notable changes were an increase in urban land-use from 1% to 4% and the establishment of vineyards, which occupied 4% of land in 2005. Average channel width declined from 38.8 m to 17.6 m, while morphological features such as gravel bars that were obvious in the 1958 aerial photograph were no longer visible in the narrower channel by 2005, when the stream course could only be distinguished by the outline of fringing riparian vegetation (Fig. 1b).

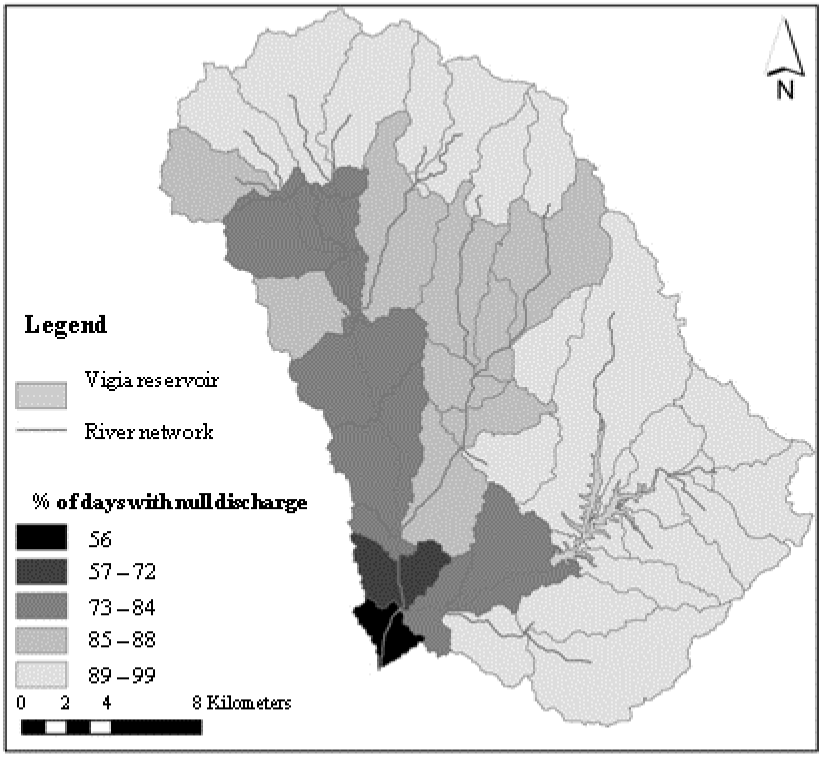


Figure 6. Percentage of days with no discharge (October 2007–October 2009) generated from SWAT modelling. Headwater areas have more than 89% of days without flow (light grey areas). The main-stem river has the smallest percentage of days without flow (from 56 to 84%), especially in the lowermost reaches (56%).

6.1.5 Discussion

The Pardiela catchment demonstrates the broad characteristics and problems of temporary rivers in the Mediterranean region. Evidence for increasing mean annual air temperature and decreasing mean annual precipitation detected in the Pardiela catchment reflects similar findings from other parts of the Mediterranean and could lead to major problems being experienced elsewhere. For example, Bladé & Castro-Díez (2010) found evidence for an overall decrease in precipitation over the entire Mediterranean region, but particularly in northwest Africa, the south of the Iberian Peninsula, Italy, the Balkans and Turkey; this has resulted in reduced availability of water for surface and underground aquifer systems. Several authors have predicted that by the 2070s there could be a decrease in annual runoff of up to 36% in the south (Alcamo *et al.*, 2007), resulting in an increasing drought risk in western and southern Europe (Lehner *et al.*, 2006). Headwater tributaries in the Mediterranean region usually have stream flow only following consecutive days of rainfall that is sufficient to saturate the soil. At other times the channel is naturally dry. However, the natural flow regime in the middle and lower reaches is affected significantly by water abstraction, particularly for agriculture.

This is a particular problem during the dry period, when the unregulated water abstraction together and livestock roaming the riverbed disturb channel habitats and in some cases create health risks associated with poor water quality. These factors and water abstraction in particular may have caused the channel in the Pardiela study site to narrow between 1958 and 2005 (Fig. 1b). Given that the most likely impacts of climate change in Mediterranean regions will affect the availability of water it is extremely important to develop policies and management practices that will not only safeguard human health, but also maintain and conserve the ecological status of temporary rivers. However, the between-year variation in precipitation, combined with trends of increasing temperature, decreasing rainfall and greater human demand for water means that sustainable ecosystem management is particularly difficult in Mediterranean regions (Baron *et al.*, 2002). Suitable hydrological models are needed to predict with greater confidence than now the amount of water available and the ecological consequences associated with different scenarios of climate change so that conservation strategies and water management practices are complementary and effective.

Mediterranean rivers are valuable ecosystems that have been recognized as one of the foremost 25 ‘global biodiversity hotspots’ (Myers *et al.*, 2000). Action needs to be taken at the landscape level to safeguard this ecological interest. In Portugal, landowners have the responsibility for maintaining rivers by clearing the stream-bed and channel margins, but in an uncontrolled fashion this has resulted in unsustainable use of water and river landscapes. A catchment management approach, applying the principles of the WFD (Council of the European Communities, 2000), is therefore required to protect the special character and ecological value of temporary Mediterranean streams and their corridors. To demonstrate the practical aspects and benefits of sustainable management a small number of ‘demonstration catchments’ could be used to apply practical conservation strategies which could then be tested and monitored at relatively low cost. These conservation strategies should reflect sustainable development principles, balancing human needs and ecosystem health and fostering the benefits provided by traditional land management such as holm oak forest and olive groves. Special attention should be focused on the problems caused by water abstraction and livestock damage to the river channel and margins. Using the experiences of physical and biological problems from other similar catchments (Gómez *et al.*, 1995, 2005), generic management principles, including the use of education, incentives and regulation, can be applied to catchments with temporary rivers

(Tab. 1). Conservation and rehabilitation strategies should identify critical reaches, including headwaters and middle reaches that represent the most vulnerable locations in terms of water availability and demand. Management strategies need to be shared and influenced by interested stakeholders and land owners, so that proposed actions can be designed to suit local circumstances. In this way they are more likely to be understood, supported and implemented by those who are affected by the need to change their behaviour (Åberg & Tapsell, 2012). The proposals should reflect overall policy objectives such as achieving WFD objectives, but should clearly explain the benefits of sustainable water management to local people, which is one of the most important requirements for successful river conservation.

Table 1. Generic proposals for the management and conservation in temporary Mediterranean stream corridors.

Politicy and technical proposals
Management Plans should include temporary streams basins (landscape and riparian areas) and monitoring, assessment and management strategies should reflect their particular needs.
Hydrological models need to be adapted to reflect the special nature of river catchments with temporary streams to improve the monitoring of present conditions and predict future scenarios in terms of water availability and quality.
Human activities along temporary river corridors (e.g. grazing, vegetation cutting and sediment extraction) should be restricted and a network of locations for priority action should be developed.
Stakeholders and landowners should be encouraged to conserve riparian vegetation and channel margins.
Demonstration catchments should be selected according to their biological and/or ecological importance or quality status, to show the benefits of applying new management and conservation techniques.
Social and educational proposals
Stakeholders and locals should be involved in advice and education regarding the importance of temporary river corridors, the protection of their biodiversity and the maintenance of water quality. They should also be offered technical assessment and guidance to solve management problems.
Regulation and incentive proposals
Where relevant, use regulations, economic incentives and taxes to encourage sustainable catchment managements.

6.1.6 Conclusions

Hydrological and ecological knowledge about temporary streams needs to be improved if these special ecosystems are to be conserved. Their vulnerability to a combination of climate change and increasing demand for water is particularly acute. There is an urgent need for catchment-scale management strategies to be developed and implemented to reduce this vulnerability and promote sustainable land-use. Sharing information and developing management strategies with local people, focused initially on a few key catchments to demonstrate the principles in practice will help to improve the chances of success.

6.1.7 Acknowledgements

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Chapter 7

Final overview

Chapter 7

The present research highlights the overall importance of temporary rivers and their functioning and biodiversity. Notwithstanding their particular features, natural temporary river systems are under threat because their ecological and societal values have been overlooked and poorly recognised. Temporary streams have been considered as biologically inactive, and therefore, they have been used for water abstraction, cattle grazing, hunting and recreation, among other uses, all of them impacting their ecological integrity. While more and more rivers are turning temporary due to climate change and land use alteration, there are temporary river basins that have been inundated due to the construction of reservoirs (e.g. Alqueva reservoir in the south of Portugal; Wadi Allaqi in Egypt, Briggs et al., 1993).

A main reason why temporary rivers are at risk is because they are not recognized by many river management policies. Consequently, they are not considered in river health monitoring and assessment programs. Even the European Union Water Framework Directive (Council of thre European Communities, 2000) has ignored the importance of temporary ecosystems; therefore, some European countries are experiencing difficulties regarding the classification of their rivers and stream types. In Portugal, for instance, the temporary river basins have been classified without including all the biological elements recommended in the Water Framework Directive to avoid their misclassification in terms of water quality (e.g. Guadiana River Basin Managment Plans; INAG, 2012), since the current methodologies do not consider the ephemerality of this type of rivers.

7.1 Main outputs from this research

Each chapter covered pertinent topics concerning temporary rivers. The main outputs of the individual chapters are summarized below (Table 1):

Table 1. General overview of the main research outcomes.

	General theme		Main outcomes
Chapter 2	Main problems concerning the water scarcity in the mediterranean regions	-	Climate change will affect negatively the mediterranean regions by increasing the frequency of floods and droughts, increasing temperatures, reducing precipitation and intensifying the already existing water scarcity problems.
		-	The decrease in water availability will inevitably interfere in biological cycles, decreasing biodiversity.
		-	The decrease of water availability will be particularly important in temporary catchments, extremely dependent of water uses and management strategies.
		-	The main strategies to attenuate the effects of water scarcity include new technologies to increase its natural availability at the same time that promote a reduction of the water demand.
		-	Currently there are different types of strategies to deal with the lack of water such as the construction of reservoirs, deviation water channels and the extraction of water from aquifers. In poorer areas are being developed simple and less expensive strategies such as rainwater cisterns and underground dams.
Chapter 3	The importance of temporary streams biodiversity	-	Results from a total of 512 Diptera specimens emerging from temporary pools revealed:
			a) a new species for science (*Homoneura alata* sp. n.);
			b) the description and illustration of the female of *Rachispoda iberica* (Rohácek, 1991) for the first time;
			c) a new species to Europe (*Leopoldius anatolii* Zimina, 1963);
			d) five new species to the Iberian Peninsula (*Dixa nebulosa* Meigen, 1830, *Homoneura limnea* (Becker, 1895), *Minettia tetrachaeta* (Loew, 1873), *Metopia tshernovae* Rohdendorf, 1955 and *Miltogramma rutilans* Meigen, 1824);
			e) new families, genera and species to Portugal and mainland Portugal.
Chapter 4	Effects of first flood event in dry riverbed	-	During the first flood events, floating organic matter (OM) that gets deposited along shorelines is important for the survival of terrestrial arthropod assemblages, early inhabiting dry riverbed.
		-	After flood recession, the arthropod composition in drift deposits changes, allowing the colonization of new downstream habitats and providing a food supply for arthropods searching for food.
		-	Rafting on floating organic matter during floods is an important dispersal mode for terrestrial arthropods along temporary rivers.

	General theme	Main outcomes
Chapter 5	The seasonal inundation dynamics on ecosystem functioning	- Nutrient loads are main potential allochthonous inputs of nutrients to the aquatic system. They are closely linked to land use and extremely important as they can induce eutrophication, especially in areas subjected to diffuse and point pollution source, in catchments with large settlements, cropped areas and livestock. - The drying and rewetting determine ecosystem processes such as leaching, which had a general decrease with the increasing of water temperature. - Floods may cause the rapid leaching of nutrients from dried leaf litter. - The nutrient and organic matter concentrations of leachates were always higher in sediments than the average concentrations in the river water. - Vegetated islands and riparian forest, where leaf litter accumulates at the sediment surface, revealed a very high potential release rates and forms a key source of nutrients and OM for both surface and subsurface waters. - Results confirmed the significant role that riparian areas play as potential key energy sources for the various floodplain habitats as well as for downstream areas.
Chapter 6	Temporary rivers management	- An evidence of increasing mean annual air temperature and decreasing mean annual precipitation was detected in Pardiela river basin. This is a problem particularly important during the dry period, when water abstraction is higher. - Suitable hydrological models are needed to predict with greater confidence the amount of water available and the ecological consequences associated with different scenarios of climate change so that conservation strategies and water management practices are complementary and effective - The conservation strategies should reflect sustainable development principles, balancing human needs and ecosystem health and fostering the benefits provided by traditional land management such as holm oak forest and olive groves. Special attention should be focused on the problems caused by water abstraction and livestock damage to the river channel and margins. - There is an urgent need to develop and implement management strategies to reduce the vulnerability of temporary catchments. Sharing information and developing management strategies with local people, focusing initially on a few key catchments is essential to demonstrate that good practices will help to improve the probability of success.

7.2 Outlook and future research directions

Our understanding of the ecological and economic importance of temporary rivers is still in its early years; only most recently, researchers have started to study temporary ecosystems with more accuracy, in part because more and more perennial rivers are being turned into temporary ones as a result of water abstraction, land use and climate change (e.g. Steward *et al.*, 2012).

Although the present research added key information on various aspects of temporary rivers functioning there remain fundamental gaps in understanding their functioning, especially in relation to climate change impacts in water availability and biodiversity preservation. For instance, further researches may start focusing in the identification of temporary rivers, streams and entire basins, as well as in their classification concerning the nature of their ephemerality (i.e., natural or anthropogenic causes). This is particularly important because it will provide a) an important database for further research, b) a basis for adapting monitoring programs and ecological status assessments and c) an advanced and more appropriate water management scheme for this catchment type. Furthermore, it would allow the identification of native and nonnative species and therefore it could be applied for the implementation of different intervention strategies to trigger autochthonous flora and fauna variability, namely for the protection of floodplains and lateral marginal habitats. It may be helpful to establish adequate measures to protect the dry riverbed from anthropogenic interferences, i.e., preventing sediment extraction, water abstraction (mainly groundwater), cattle assess or its use as recreational areas. This knowledge will permit the correct management of reservoirs concerning nutrients dynamics, flow variation in upstream and downstream reaches and habitat dynamics and biodiversity. In addition, the aquatic, amphibic, and terrestrial biodiversity of temporary streams is not well studied yet, despite the fact that Mediterranean ecosystems are among the most threatened ecosystems globally. Overall, about one fifth (19%) of all species is listed as threatened, and about 1% of all species is already extinct in this region (Cuttelod *et al.*, 2008). Taking into account that most species are endemic, there is a further risk in rapid extinction of species. Many species may disappear before they even have been described. As we could observe, an intense sampling of a single temporary stream revealed an extensive list of species, new for Portugal, the Iberian Peninsula and Europa. For example, for the first time the female of *Rachispoda iberica* was described (Carles-Tolrá & Rosado, 2009), as well as a new species to science (Carles-Tolrá, 2009). Other works such as Wishart (2000) also pointed out the diverse and unique diversity of dry riverbeds, where more than 320 terrestrial taxa were collected in a semi-arid South Africa dry riverbed. Therefore, the contribution of temporary rivers to worldwide biodiversity is most likely much higher than the currently thought and this need to be studied. Nevertheless, the effects of climate change on biota may lead not only to a decrease in biodiversity but may increase at the same time the proportion of nonnative species (non-European and translocated species), some of them are of concern for public health such as mosquitoes species that can spread human infectious diseases.

We recognize that the findings of this research have raised several new research questions and identified key knowledge gaps concerning temporary rivers ecology and management. Nevertheless, we need to start recognizing temporary rivers as an important component of aquatic ecosystems and whole river catchments. This knowledge needs to be incorporated into water resource management planning to guarantee that the importance of temporary ecosystems is recognized, protected, and restored, whenever necessary.

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