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Analysis of structural and functional indicators for assessing the health state of mountain streams

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ABSTRACT

Mountain streams play a key role in the conservation of aquatic biodiversity and key ecosystem services; however human activities are threatening these ecosystems as mountain areas become more and more developed and intensively used. Many of these streams are not considered in current national monitoring programs due to their small catchment area. However, assessing their status and monitoring their trends is well needed to ensure their proper management and conservation. In this study, we evaluated the use of a range of indicators related to different ecosystem structural and functional components in 2 streams affected by sewage outflows and compared with an unpolluted stream in the Picos de Europa National Park (Spain). We surveyed benthic periphyton, macroinvertebrate communities and fish assemblages and also estimated periphyton growth rates, wood decomposition rates and river metabolism. Additionally, we compared the performance of the selected indicators in different hydraulic conditions. Results revealed an effect of the organic pollution on most of the functional and structural indicators for the most polluted stream. Only the number of Ephemeroptera, Plecoptera and Trichoptera taxa, the Iberian Biomonitoring Working Party index, the invertebrate multimetric index used by the regional water agency, the fish abundance and biomass were sensitive enough to detect low levels of pollution and followed the expected response to the pollution degree. Moreover, most of the indicators behaved similarly under different hydraulic conditions, without major differences between pools and runs. However, the combination of both pool and run replicates at the reach scale resulted in a higher detection capacity of the effects of organic pollution.

1. Introduction

Mountain streams are small in size but represent a large extension of the whole river network (e.g. streams of order 1 and 2 can achieve up to 60% of the length of many river networks; Strahler, 1957; Leopold et al., 1964). They constitute a unique set of habitat conditions within the river networks, characterized by fast flows, well oxygenated waters and low water temperatures. These conditions support a diverse set of organisms (Finn et al., 2011), some of which are unique to these streams, and serve as refuge for aquatic species that move into headwaters seasonally or at particular life history stages (e.g., for spawning or nursery areas). Furthermore, mountain streams receive high inputs of organic matter from the surrounding terrestrial environment (Rosemond et al., 2015), conferring them an important role in nutrient regulation and export to downstream river reaches (Peterson et al., 2001).

Mountain ecosystems are continuously threatened by human activities such as water extraction, channelization, logging, mining (Meyer et al., 2007) or river pollution from untreated wastewater derived from domestic, agricultural and farm activities (Lecerf et al., 2006). Impact trends on mountain ecosystems are increasing and are expected to increase in the proximate future due to the intensification of human uses on mountain areas worldwide (Wohl, 2006). Nowadays, there is specific legislation as the Water Framework Directive in Europe (WFD; 2000/60/EEC) or the "Clean Water Act" in the US (CWA; US Government 1977) that ensures the good status of aquatic ecosystems. Nevertheless, many mountain rivers are excluded from national or regional monitoring programs due to their small watershed area (many of them below 10 km^2). Moreover, official methods are commonly based on a reference condition approach, in which a single river reach estimate from a composite sample is contrasted with a reference benchmark without taking into account within site variability (see application of WFD in the EU, e.g., Bohmer et al., 2004; Ofenbock et al., 2004; Couto-Mendoza et al., 2014). This contrasts need robust spatial designs (e.g., control-impact) that generate solid statistical tests to infer whether river

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health impairment occurs or not (for a revision see Downes et al., 2002).

River health monitoring has traditionally focused on structural ecosystem components such as water quality or bioindicators based on aquatic communities (fish, benthic macroinvertebrates and periphyton communities). Mountain streams, however, are dominated by oligotrophic conditions and cold and well-oxygenated waters what favors the dominance of sensitive taxa such as the number of Ephemeroptera, Plecoptera and Trichoptera (EPT) taxa (EPT_{taxa}) or salmonids (Bonada et al., 2006; Whitmore et al., 2011). Thus, the dominance of sensitive taxa together with the fact that the reference conditions and the performance of a given set of indicators have not been properly defined and assessed, makes quite difficult assessing the health status of many of these mountain streams. This hampers the development of adaptive management programs that ensure the conservation of species, habitats and river functioning (Bunn et al., 2010) in many of these mountain ecosystems. In this sense, Palmer and Febria (2012) stated that the key to defining the health state of an ecosystem is to consider the mutual contribution of the structure and functionality (see also Woodward et al., 2012). A set of functional indicators such as nutrient retention, river metabolism, dynamics of periphyton biomass and wood breakdown rates have arisen in the last years (e.g. Von Schiller et al., 2008a; Young and Collier, 2009; Silya-Junior et al., 2014), although its use is still incipient within freshwater ecosystem monitoring.

Within ecosystem functional indicators, periphyton growth and wood decomposition using artificial substrates have been proposed as a cost-effective way to assess ecosystem functioning rates (Young et al., 2008). These indicators integrate different channels of energy transformation (e.g. primary production and microbial and consumers activity; Niyogi et al., 2003; Young et al., 2008; Artigas et al., 2012), providing relevant information about stream processes and energy transference. Periphyton dynamics are affected by flow velocity, light intensity, nutrient concentration and substrate type (Horner et al., 1990; Kelly and Harwell, 1990; Jarvie et al., 2002), whereas wood decomposition is influenced by temperature (Dang et al., 2009), nutrient concentration (Suberkropp and Chauvet, 1995; Young and Huryn, 1999), hydrological regime, river geomorphology and bed substrate (Young et al., 2008). In addition, both algae and microbial communities are affected by the reach hydraulic characteristics (Battin et al., 2003; Besemer et al., 2009; Artigas et al., 2012). Hence, the location of artificial substrates within the riverbed given the numerous hydraulic conditions that characterize high order streams and how these estimates are combined at the reach scale will influence the functional rates. This is something that has rarely been taken into account (but see Besemer et al., 2009).

Moreover, the principal processes of metabolism, ecosystem respiration and gross primary production, respond to different human pressures (e.g. increases on nutrient concentration or turbidity; Mulholland et al., 2006). Consequently, its use as a functional indicator has increased over the last decade. River metabolism is usually estimated either using the open-channel method (Uehlinger, 2000; Houser et al., 2005; Yates et al., 2013) or substrate incubation chambers (Fellows et al., 2006; Aristegi et al., 2010). Within the open channel method, whole stream metabolism is measured based on diel changes in oxygen concentration in the water, while the estimation of stream metabolism using enclosed chambers is based on the difference of oxygen concentration in the water after a given amount of time on dark and transparent chambers. The open-channel method is preferred, as provides more information on the activity of all stream ecosystem compartments within the river channel. On the contrary, the use of incubation chambers only accounts for periphyton production and respiration rates. However, the open-channel method relies on the estimation of the exchange of oxygen between air and water (reaireation coefficient), which is especially high in small and turbulent mountain streams, and could neglect the estimation of ecosystem respiration and gross primary production. Therefore, the use of incubation chambers becomes highly recommended in these situations.

In this study, we will focus on understanding the effects of organic pollution in mountain streams comparing the results from a diverse set of functional and structural indicators in 2 polluted streams with a control stream with similar characteristics. Specifically, the present study aims to (1) compare the performance of functional (periphyton growth and wood breakdown rates and river metabolism) and structural indicators (periphyton biomass, invertebrate metrics and fish density and biomass) as well as (2) their behavior by aggregating replicates in different hydraulic conditions (i.e. mesohabitats) and at a reach scale in order to assess the effects of sewage outflows in mountain streams.

2. Material and methods

2.1. Study sites

This study was conducted within the Picos de Europa National Park (Northern Spain), comprising an area of 64,660 ha (Fig. 1). The National Park is part of the Cordillera Cantábrica mountain range. The geology is constituted predominantly of carboniferous limestones combined with outcrops of quartzites, sandstones and conglomerates. Climatic conditions are highly variable (e.g. large temperature fluctuations), mainly driven by two factors: the proximity to the sea (less than 50 km in straight line to the coast) and the altitude and orographic effects (highest mountain tops up to 2600 m a.s.l. with some valley bottoms as low as 600 m). The snow represents nearly 20% of the precipitation, while the annual precipitation exceeds 2000 mm. Storms are common all throughout the year. Valley vegetation is dominated by an Atlantic mixed deciduous forests that mainly consist of broad-leaved trees (ash, maple, chestnut, oak, hazel, linden, walnut, etc.). As altitude increases, beech forests with few associated species (yew, rowan, holly, white oak, etc.) are replaced by shrubbery of broom, gorse, heather and other plants adapted to a more alpine environment.

This National Park represents a major challenge for conservation managers as there are up to 4600 humans inhabiting within the park limits carrying out a wide variety of activities (e.g., forestry, cattle rising, small agro-industries and tourism). Moreover, this area also harbours some endangered Iberian vertebrates such as the Atlantic salmon (*Salmo salar*), the Iberian desman (*Galemys pyrenaiucs*) and important populations of up to 5 species of amphibians (*Rana temporaria*, *Mesotriton alpestris cyreni, Chioglossa lusitánica, Rana ibérica, Salamandra salamandra*). Endangered invertebrate fauna as the southern damselfly (*Coenagrion mercuriale*) or stream crayfish (*Astropotamobius pallipes*) is also found in these streams and rivers.

2.2. Study design: control vs impact locations

A control–impact design was chosen in this study to assess the effect of sewage outflows within the Picos de Europa National Park. Two river reaches were selected as impacted sites because of the presence of organic effluents. One impacted site was located in the Bulnes stream, 2.5 km downstream from the Bulnes village's untreated effluent. This effluent is composed of domestic waters, increasing substantially in the summer due to tourism. The other impacted site was located in the Duje stream, 2 km downstream from the Tielve village. This outflow is composed of untreated sewages from the village and several cattle sheds that lead to the accumulation of cow manure in the stream bed. The Casaño stream was selected as a control site based on physical and environmental