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Water abstraction in small lowland streams: Unforeseen hypoxia and anoxia effects

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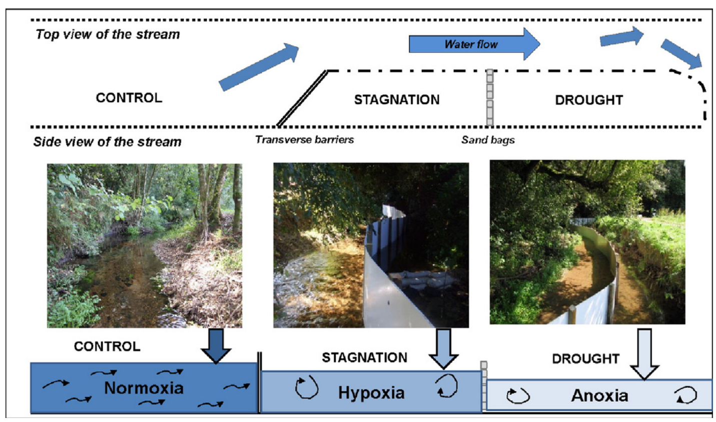
HIGHLIGHTS

- Flow reduction in small lowland streams can cause hypoxia and anoxia
- Observed strong reductions in dissolved oxygen evidenced the need to measure daily dissolved oxygen in experiments
- TITAN identified invertebrates sensitivity and resistance to oxygen deficits
- The eutrophic stream showed higher oxygen deficit than the mesotrophic stream
- Extensive water abstraction during summer low flows has the potential to impact stream biodiversity and function.

GRAPHICAL ABSTRACT



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ABSTRACT

Flow reduction generated by water abstraction can alter abiotic and biotic properties of stream ecosystems. We hypothesized that reducing stream flow will reduce oxygen levels affecting sensitive invertebrates. We experimentally suppressed flow with longitudinal barriers in two lowland streams of mesotrophic and eutrophic status In each stream we fixed an upstream free flowing control and two downstream disturbed stretches without flow: an initial stagnation stretch and a final drought stretch separated from the stagnation by sand bags to force a greater lowering of the water level. Invertebrates were sampled in control and disturbed stretches before and after the experimental setup for 10 weeks, and temperature and oxygen were recorded with data loggers. Flow reduction caused a significant decrease in oxygen, resulting in hypoxia (<4 mg O_2/L) in the stagnation stretches and anoxia (0 mg O_2/L) in the drought stretches mainly at night, without influencing water temperature. Invertebrate responded with differential sensitivity to flow and oxygen reduction, some indicator taxa declined at 7.3 mg O_2/L, others at 6.3 mg O_2/L, while at 5.3 mg O_2/L many taxa were severely reduced. Flow reduction generated oxygen depletion, reducing rheophilous and oxygen dependent taxa, while favouring tolerant limnophilous taxa with atmospheric respiration. Passive filterers and scrapers were significantly reduced. Our results indicate that flow reduction can cause hypoxia and anoxia in lowland streams and is an unforeseen effect not addressed in the assessment of flow reduction impacts to streams. Further research is required to evaluate if spatially extensive flow reductions and hypoxia result in long-term impairment of stream biodiversity and function.

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1. Introduction

Water abstraction, in the form of water diversions, withdrawals and damming (for flow regulation and water storage), is a major driver influencing abiotic and biotic properties of aquatic ecosystems (Malmqvist and Rundle, 2002). Major climate change effects in aquatic ecosystems are expected to be more dramatic in those vulnerable regions of the planet where natural shortages in waterresources co-occur with human demands (i.e. agriculture, populations, tourism) (Vörösmarty et al., 2000; Falloon and Betts, 2010; Gössling et al., 2012). Decreases in water resources are predicted to reach up to 60% in Southern Europe (EEA, 2012), suggesting that these temperate regions will become more "Mediterranean" in climate (see Beniston et al., 2007), with the potential to compromise natural water volumes in streams and rivers (Bates et al., 2008). Decreased flows can have multiple effects in running water ecosystems, including changes in water quality and on invertebrate community structure, behaviour, and biotic interactions. These effects depend on the severity (duration and magnitude) of the flow decrease (see review in Dewson et al., 2007).

One of the most important impacts caused by water abstraction is flow reduction. Flow is the most intrinsic property of running waters to which many organisms are adapted, as it influences organismal dispersal, resource acquisition and species interactions (Hart and Finelli, 1999). In spite of the dependence of oxygen levels on flow conditions and instream hydromorphological features (Cox, 2003), little has been advanced over what concerns the consequences of flow reduction has for Dissolved oxygen (DO) levels and the stream ecosystem. Dissolved oxygen concentrations in aquatic systems are the result of the balance between oxygen diffusion from the atmosphere, oxygen production by aquatic autotrophs, and oxygen consumption from aquatic organisms. If the rate of oxygen consumption exceeds its production, oxygen is depleted until the water becomes anoxic. Even though oxygen depletion in aquatic ecosystems is generally associated with the build-up of organic wastes and eutrophication (Díaz and Rosenberg, 2011; Franklin, 2014), very low oxygen concentrations can occur under natural conditions in flowing freshwaters. For example, low oxygen concentrations naturally occur during blackwater events in lowland rivers with forested floodplains, in ephemeral streams receiving high litter amounts (Hladyz et al., 2011), in groundwater-fed streams (Hynes, 1970), in naturally drying temporary streams (Boulton, 2003, Acuña et al., 2005; von Schiller et al., 2011), and more generally when temperatures and organic contents are high (Kerr et al., 2013). Moreover, low oxygen levels can also occur in low gradient streams where reaeration rates are very critical in average oxygen deficits (Wilcock et al., 1998; Justus et al., 2012). In addition to natural situations, expected increases in temperature due to climate change can also accelerate organic matter decomposition (see review in Tank et al., 2010), and in turn, decrease dissolved oxygen levels. If combined with high organic/nutrient inputs, a reduction in circulating flows can exacerbate the occurrence, frequency, and duration of hypoxia-anoxia events in streams (Franklin, 2014). General consequences of oxygen deficits influence survival, emergence and drift of aquatic invertebrates, resulting in reduced biodiversity of aquatic invertebrate communities (Connolly et al., 2004). A generalized influence of hypoxia in river networks can emerge as a major threat to stream and river ecosystems.

Invertebrates have colonized a diversity of freshwater habitats by adopting specific respiratory systems to facilitate gas exchange (Richards and Davies, 1984), and are adapted to natural variations in dissolved oxygen concentrations (Hynes, 1970). When exposed to hypoxia, few taxa can maintain their rate of metabolism similar to when they are under "normal" oxygen conditions, i.e. air or air saturated water (Barnes et al., 2001). The natural diversity of respiratory traits among benthic invertebrates should allow the persistence of the organisms able to better withstand hypoxia. Ultimately, the individual sensitivities of invertebrate taxa in correspondence with their respiratory-control mechanisms will establish invertebrate resistance to low-oxygen levels (Verberk and Bilton, 2013).

In this study we use a data set obtained from an in-stream experiment with a Before–After, Control–Impact paired (BACIP) design carried out in two lowland forested streams of mesotrophic-eutrophic condition (Dodds et al., 1998). In the experiment, we simulated complete flow reduction by damming longitudinal stretches of the streams and compared spatio-temporal differences in water chemistry variables and benthic invertebrate community to control free-flowing stretches (García and Pardo, 2016). In García and Pardo (2016) we detected loss of invertebrate biodiversity and abundances that were attributed to the induced changes in discharge, oxygen and nutrients. During the execution of the experiment, we realised that oxygen data loggers recorded night oxygen deficits higher than those observed during the day. In this study, we further explore how reduction in flow and water velocity affects diurnal oxygen levels and temperature, and concurrent effects on benthic invertebrates. In this study, we tested the hypothesis that experimental flow reduction will modify oxygen levels and temperature, influencing both invertebrate species distribution (increase or decrease) and their sensitivity and resistance to the novel environmental gradients manipulated during the experiment. We predicted that explicitly linked species traits (respiration, current preferences and feeding style) will be most affected by flow reduction, leading to a decrease in gill-breathing taxa highly dependent oxygen levels, and of rheophilous and flow dependent filter feeders. This study emphasizes the importance of the unexpected effects of short-term flow reduction in generating hypoxia and anoxia in lowland stream ecosystems, and the specific impacts on the invertebrate community.

2. Methods

2.1. Study sites

We studied two 2nd order lowland streams in the floodplains of the lower Miño River basin, the largest river basin in western Spain flowing into the Atlantic Ocean. Study streams, the Caselas and Pego, were separated by a distance of 15 km at their confluence with the Miño. Both streams represent environmental conditions and urban and rural land uses typical in the region: both streams cross rural fields and dispersed villages, but the Pego is also influenced by discontinuous runoff from a pig farm. The Caselas and Pego are perennial streams with discharge values in summer ranging from 0.24 ± 0.08 m^3/s to 0.32 ± 0.08 m^3/s (mean $\pm$ SE), respectively. The in-stream experiment followed a Before–After, Control–Impact paired (BACIP) design. In each stream, a 100-m length experimental stretch was selected for study. Experimental reduced flow stretches were created by fixing a longitudinal enclosure made of panels (Foamed-PVC, 3 m long x 1 m wide) to the streambed with wooden sticks, which was closed upstream by a transverse barrier (i.e., wooden gate), resulting in the absence of superficial flow. The two experimentally disturbed stretches were located downstream of the experimental enclosure (~50 m): a first initial stagnation stretch (S), and a final drought stretch (D) (Fig. 1). The drought stretch was separated from the stagnation stretch by a transverse barrier of sand bags that allowed for the lowering of the water level by pumping mechanically water out from it, initially and after brief rainfall periods. Undisturbed control stretches (C) were located ~50 m upstream from experimental barriers (Fig. 1). Therefore, control stretches had natural water flow, but the disturbed stretches had no superficial flow and zero velocities during the experiment. For additional details of the BACIP experimental stream design see García and Pardo (2016). The study ran for 3 months: first sampling was on the 4 and 6 July and last sampling on the 2 and 4 October 2012, in the Caselas and Pego streams, respectively. The barriers were closed on the 28 July 2012 (see Fig. 2 for sampling times). At each stream, water chemistry, hydromorphological variables, and benthic macroinvertebrate communities were sampled in all stretches. Before the stagnation-drought period, samples were