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Response of freshwater macroinvertebrates to rainfall-induced high flows: A hydroecological approach

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ABSTRACT

Hydraulic-habitat and biological data were integrated within a twofold-purpose study: (i) to investigate the response of freshwater macroinvertebrates to a rainfall-induced high flow event of moderate magnitude and (ii) to derive hydroecological relationships between habitat variability and macroinvertebrate microdistribution. 142 microhabitats (unique combinations of flow velocity, water depth and substrate type) allocated in four sites of no or very minor anthropogenic influence were sampled and analyzed, before and after the event. Freshwater macroinvertebrates were additionally collected and specific community metrics were derived. To identify possible pre- and post- impact benthic community differences, independent sample *t*-tests were applied, while Boosted Regression Tree models were developed to quantify the response of macroinvertebrates to flow alteration. Macroinvertebrate abundance, taxonomic richness, EPT richness and diversity decreased significantly by 90%, 60%, 50% and 25% respectively between the pre- and post- impact microhabitats. The relative abundance of macroinvertebrate predators and passive filter feeders increased after the event, mainly in specific substrate types (boulders and large stones), which served as flow refugia, maintaining less degraded (compared to finer substrates), still heavily impacted, benthic communities. According to the hydroecological analysis, the high flow event exerted the strongest impact on all macroinvertebrate metrics. Optimal (suitable) ranges of the hydraulic-habitat variables for benthic macroinvertebrates were identified (optimal flow velocity from 0.3 m/s to 0.7 m/s, optimal water depth at 0.2 m), while boulders and large stones were the most suitable substrate types. The aforementioned data provide valuable information for the provisioning of biologically-derived environmental flows and an essential input of hydrodynamic habitat models to facilitate the selection of the optimal environmental flow scenario towards ensuring the integrity of aquatic ecosystems downstream of anthropogenic activities provoking hydrological alteration.

1. Introduction

Flow is a fundamental determinant of physical habitat in fluvial ecosystems, which in turn is a major determinant of the distribution, abundance and diversity of aquatic communities (Allan, 1995; Bunn and Arthington, 2002). Hydrological processes affect instream organisms both directly by applying hydrodynamic forces of varying magnitude, depending on the hydraulic properties of the water (Giller and Malmqvist, 1998) and indirectly by determining substrate composition, water chemistry and habitat availability (Hart and Finelli, 1999). The detailed examination of such processes has been acknowledged as a challenging prerequisite for the conservation and management of aquatic ecosystems (Acreman and Ferguson, 2010) and research has long been trying to link and quantify the response of aquatic communities to naturally occurring or anthropogenically-induced hydrological-hydraulic variation (Poff and Zimmerman, 2010; Caiola et al., 2014; Papadaki et al., 2016). Freshwater macroinvertebrates are often used as a target community in such studies (Gibbins et al., 2001; Theodoropoulos and Iliopoulou-Georgudaki, 2010; Karaouzas et al., 2011; Armanini et al., 2014). Within this effort, most studies have focused on the influence of extreme hydrological events on the aquatic communities, such as floods (Herbst and Cooper, 2010; Mesa, 2010; Mundahl and Hunt, 2011) and droughts (Lake, 2011; Skoulikidis et al., 2011; Chessman, 2015), occurring either naturally within the seasonal or

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interannual variation in the hydrological cycle, or artificially due to water regulation by dams and water abstractions.

A flood is defined in the EU Floods Directive as 'the temporary covering by water of land not normally covered by water' (European Commission, 2007). The effects of floods on aquatic communities have been well documented (Leigh et al., 2015), being related to the alteration of physical habitat provoked by the increased flow velocity/discharge, which in turn alters the composition of instream assemblages. During and after floods, large amounts of organic and inorganic matter are transferred downstream (Lake, 2000), affecting water chemistry and as a consequence, community composition. In-stream productivity, retention of particulate organic matter and decomposition are also affected (Hladyz et al., 2012), channel morphology is altered, macrophytes are translocated and other aquatic organisms are dislodged and transferred downstream (Brittain and Eikeland, 1988; Lake, 2000). This results in reduced macroinvertebrate density and diversity (Gjerlov et al., 2003; Melo et al., 2003; Suarez et al., 2016), while taxonomic richness may be reduced or remain constant (Rempel et al., 1999; Effenberger et al., 2008). Macroinvertebrates however have behavioral, morphological and physiological adaptations, evolved over large time scales to resist physical disturbances. Such adaptations to prevent dislodgment include small-sized bodies and specialized structures such as mucilage (Biggs and Hickey, 1994), hooks (Crosskey, 1990) and suckers (Frutiger, 1988), while many animals actively drift to microhabitats which offer protection from floods, usually called refugia (Negishi and Richardson, 2006; Fuller et al., 2010).

Despite the aforementioned assiduous research, studies on ecologically significant habitat features associated with river morphology and flow regime still remain scarce (Belmar et al., 2013). This fact, in combination with the lack of studies examining the response of freshwater communities to disturbances of smaller magnitude of hydrological alteration (between 0–50% of the naturally occurring flow) inhibits the development of quantitative relationships between ecological responses and altered flow regimes (Poff and Zimmerman, 2010). Such relationships however are of critical importance to derive robust environmental flow recommendations downstream of anthropogenic activities provoking hydrological alteration, while they comprise essential input for advanced hydrodynamic habitat modelling approaches, which offer water managers and stakeholders the ability to select the optimal, among various environmental flow scenarios (Waddle and Holmquist, 2011; Theodoropoulos et al., 2015a), with the purpose of maintaining the integrity and functionality of freshwater ecosystems.

The current study had two main purposes:

(i) to investigate the response of freshwater macroinvertebrates to a rainfall-induced high flow event of moderate magnitude (given the flood definition provided in the Floods Directive 2007/60/EC) in specific Greek mountainous streams and rivers. Focusing on the microhabitat scale (defined as the unique combination of flow velocity, water depth and substrate type), we tested the null hypothesis (H_0) that there are no differences in the macroinvertebrate communities between the pre- and post-impact samples in terms of abundance, diversity, taxonomic and EPT (Ephemeroptera, Plecoptera, Trichoptera) richness. Rejection of the H_0 would suggest that the structure of benthic assemblages is altered after a high flow event of moderate magnitude;

(ii) to examine hydroecological relationships between hydraulic properties—habitat variability and the macroinvertebrate metrics, aiming to derive optimal (suitable) ranges for flow velocity, water depth and substrate type.

Within this context, we examined (a) the extent to which macroinvertebrate abundance, diversity, taxonomic richness and EPT richness were influenced by the rainfall-induced high flow event, (b) which functional feeding groups were more resistant, (c) which microhabitats, if any, served as refugia during and after the disturbance and (d) how the changing hydraulic habitat affected the microdistribution of freshwater communities.

2. Materials and methods

2.1. Study area

The study was conducted at the upper, mountainous reaches of four rivers in central Greece (Fig. 1). The selected reaches are characterized by natural landscape with no or very minor anthropogenic activities; mountainous relief with altitudes ranging from 407 to 972 m, large areas with evergreen forests mainly composed of firs belonging to the species *Abies cephalonica* and *Abies borisii regis*, which are often mixed with deciduous forests of *Quercus ceris, Cornus* sp. and *Fagus* sp. The riparian vegetation is composed of thick riparian forests including plane trees (*Platanus orientalis*), willows (*Salix alba*), poplars (*Populus nigra*), alders (*Alnus glutinosa*) and ash trees (*Fraxinus angustifolia*).

The study area has a temperate mediterranean climate, characterized by hot, dry summers and cold, wet winters, with temperatures ranging between 0 °C (or lower) and 35 °C (or higher during extreme events). The flow regime is highly seasonal, influenced by the amount of precipitation, most of which falls between October and April (maximum in January), with the driest months being July, August and September (minimum rainfall during August). Due to the high variety of climatic subtypes resulting from the influence of the topography on the incoming air masses from the central Mediterranean Sea, we selected meteorological stations, near each sampling area to describe the particular microclimatic conditions (Theodoriana, Pertouli and Koniakos at altitudes of 924, 1170 and 840 m respectively) by deriving mean monthly precipitation values for the period 2010–2015 (Fig. 2). The maximum and minimum average precipitation for Theodoriana and Koniakos stations was in January (395.7 and 158.2 mm respectively) and August (48.5 and 24 mm respectively). For the 'Pertouli' station, the maximum values were observed in October (212.9 mm) and the minimum in July (23.12 mm).

Sampling was applied prior to (August 2015) and after (October 2015) a heavy rainfall event, which took place between the 21st and 24th of October 2015. The precipitation observed during the event was 117 mm at the Theodoriana station (40% of the month's average rainfall), 57.6 mm at the Pertouli station (30% of average) and 89.8 mm at the Koniakos station (110% of average).

2.2. Site selection and sampling periods

Four reference sites were selected (Fig. 1; Table 1) according to the REFCOND guidelines (WFD CIS Guidance Document No. 10, 2016) in order to assess only the effects of flow-related changes, avoiding possible bias of the results from pressures resulting from water quality degradation. At each site, a maximum of 20 rectangular microhabitats of 0.0625 m^2, delineated as combinations of flow velocity, water depth and substrate type was sampled, taking into account safety considerations, resulting in a dataset of 142 microhabitats over two periods, prior to (August 2015) and after (October 2015) the high flow event investigated. Detailed characteristics of each microhabitat are shown in Table A1. Three additional unpolluted sites not impacted by the high flow event were sampled during the same periods (data not shown) to account for possible seasonal influence on the results of the study (and as indicated and