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An index to track the ecological effects of drought development and recovery on riverine invertebrate communities

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ABSTRACT

In rivers, the ecological effects of drought typically result in gradual adjustments of invertebrate community structure and functioning, punctuated by sudden changes as key habitats, such as wetted channel margins, become dewatered and dry. This paper outlines the development and application of a new index (Drought Effect of Habitat Loss on Invertebrates – DEHLI) to quantify the effects of drought on instream macroinvertebrate communities by assigning weights to taxa on the basis of their likely association with key stages of channel drying. Two case studies are presented, in which the DEHLI index illustrates the ecological development of drought conditions and subsequent recovery. These examples demonstrate persistent drought effects months or several years after river flows recovered. Results derived using DEHLI are compared with an established macroinvertebrate flow velocity-reactive index (Lotic-invertebrate Index for Flow Evaluation – LIFE score) and demonstrates its greater sensitivity to drought conditions. Data from a number of rivers in south east England were used to calibrate a statistical model, which was then used to examine the response of DEHLI and LIFE to a hypothetical multi-year drought. This demonstrated a difference in response between sampling seasons, with the spring model indicating a lagged response due to delayed recolonisation and the autumn model differentiating habitat loss and flow velocity-driven responses. The application of DEHLI and the principles which underlie it allow the effects of drought on instream habitats and invertebrates associated with short or long term weather patterns to be monitored, whilst also allowing the identification of specific locations where intervention via river restoration, or revision of existing abstraction licensing, may be required to increase resilience to the effect of anthropogenic activities exacerbated by climate change.

1. Introduction

Droughts have an important role in shaping lotic ecosystems (Extence 1981; Humphries and Baldwin 2003; Lake, 2011; Lu et al., 2016; Piniewski et al., in press). A potential increase in extreme events associated with our changing climate suggests the frequency of droughts is likely to increase in many areas of the globe (Dai, 2011; Prudhomme et al., 2014). Some recent studies indicate that the magnitude and frequency of short duration drought events (< 18 months) will increase in the future in tandem with rises in flood frequency (Ledger and Milner 2015; Watts and Anderson, 2013). While climate change is expected to intensify drought in many regions, its short and long-term ecological effects are poorly understood (Bogan et al., 2014).

Drought is a natural disturbance in rivers that influences community structure and functioning (Lu et al., 2016), altering species composition, abundance and richness (Atkinson et al., 2014) and favouring specialist species (Mainstone 1999). The impact of drought on ecological communities depends both on its duration and intensity, as well as antecedent conditions (Bogan et al., 2015; Chessman 2015; Stubbington et al., 2014). Lake (2003) distinguishes between regular seasonal and predictable droughts, as in Mediterranean regions, from supra-seasonal droughts which are usually unpredictable in nature and are associated

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with longer periods of drying across multiple seasons. Supra-seasonal droughts normally include one or more seasons typically associated with higher river flows. The distinction between different types of drought is important since the biota within rivers which experience regular seasonal channel drying typically display adaptions to such conditions (Boulton, 2003; Bogan et al., 2015), whereas unpredictable supra-seasonal droughts have the potential to result in greater ecological effects due to their protracted nature (e.g. Wood and Armitage, 2004). In addition, the antecedent conditions and timing of supra-seasonal droughts are important controls on the community effects (Dewson et al., 2007; Lake, 2011). The effects of a drought on river macroinvertebrate communities will vary according to the river type, in particular whether it is a groundwater or surface water-dominated river, the pattern of drying and degree of physical modification (see Lake, 2011 for review). More physically diverse river reaches, including those with marginal habitats or with variable water depth and flow-velocity, provide habitat heterogeneity to support a wider range of taxa. This physical heterogeneity is widely considered to result in populations and communities which are more resilient to extreme hydrological events by the provision of refugia which facilitate rapid recovery following disturbances (Townsend and Hildrew, 1994; Dunbar et al., 2010a; Dunbar et al., 2010b; Chester and Robson, 2011).

Drought disturbances typically exhibit a ramp pattern with the magnitude of effects growing with increasing duration of the event. Conditions during a drought may fluctuate, however, with brief rainfall events providing occasional inputs of water, but the magnitude of the drought steadily increases over time (ramps up) and often affects progressively greater spatial scales (Lake, 2000; Parry et al., 2017). The response of the aquatic stages of lotic communities to drought is punctuated by significant step changes, as thresholds between critical water levels are crossed (Boulton, 2003; Boulton and Lake, 2008). The step-like nature of these changes, as thresholds are exceeded, result from the abrupt loss or fragmentation of habitats (e.g. riffle areas), alteration in physico-chemical conditions and the loss of lateral, longitudinal and/or vertical connectivity (Boulton, 2003; Boulton and Lake, 2008). The ability of biota to withstand a disturbance (resistance) and their subsequent capacity to re-colonise (resilience) reflect the availability of refugia in the channel and wider catchment (Lake, 2000). Species and communities which possess strategies to survive low-flows, lentic conditions and drying, or are highly mobile, may be able to re-colonize and recover rapidly after the cessation of drought conditions. The time taken to re-colonise, however, is typically taxon-specific and reflects the timing, intensity, and duration of individual drought events (Boulton, 2003; Boulton and Lake, 2008).

There is a need to understand the ecological effects of high magnitude supra-seasonal drought events in order to anticipate the effects of climate change and help to balance the need for anthropogenic water supply, whilst maintaining the ecological integrity of river habitats (Wilby et al., 2010). There is also a growing recognition for the need for more robust and defensible data to address multiple issues related to water resources and environmental legislation, such as management of protected species and habitats and maintenance of ecological standards for healthy ecosystems enshrined in the European Community Habitats Directive and Water Framework Directive (WFD) (Acreman and Ferguson, 2010). To make use of these data we need tools and techniques to ascertain the influence of different environmental pressures. The need to assess the ecological effects of variations in river flow led to the development of the macroinvertebrate index: Lotic-invertebrate Index for Flow Evaluation (LIFE; Extence et al., 1999). LIFE uses recognized flow associations to weight invertebrate groups according to their preference for flow velocity. Existing biological indices, such as LIFE in the UK, and others developed in Canada (Armanini et al., 2012), Australia (Rose et al., 2008) and New Zealand (Caruso, 2002), have been correlated with historic hydrological conditions and hydraulic parameters (Extence et al., 1999; Monk et al., 2008; Dunbar et al., 2010a, 2010b) with some degree of success. The relationship between the LIFE index and flow volume (discharge) breaks down, however, under extreme low flow conditions (Monk et al., 2006) possibly reflecting the ramp disturbance and threshold-crossing nature of drought pressures.

To address this deficiency, this study aimed to develop a new macroinvertebrate community-based metric, the Drought Effect of Habitat Loss on Invertebrates (DEHLI) index. This paper aims to outline the process of DEHLI calculation and to test its utility by using data from two case studies (involving monthly and annual sampling, respectively) and by undertaking a modelling exercise to test the drought response of both the DEHLI and LIFE indices to a hypothetical multi-year drought, calibrated to actual data from 114 samples. The index is based upon the concept outlined in Boulton and Lake (2008) linking the steps of the ramp disturbance with the sequential loss of aquatic invertebrates to changing abiotic and biotic conditions. It has initially been designed to be derived using data from the Environment Agencies of the United Kingdom, but could be readily adapted for use in any country or global region.

2. Methods

2.1. Index structure

The primary theoretical element of the ramp disturbance model of drought (*sensu* Lake, 2000) is the sequence of changes in hydrological connectivity and wetted habitat (Boulton, 2003; Boulton and Lake, 2008) as the drought progresses (see Fig. 1). The gradual intensifying of drought conditions will initially lead to a reduction in river flow (volume, depth and in some instances, velocity) severing lateral connectivity to marginal riparian habitat (2) and subsequently longitudinal connectivity (3), as topographic high points on the river bed are exposed. Ultimately, only isolated pools of water may remain (4) and as the drought progresses these will continue to shrink until surface water is lost and only moist sediments and subsurface water remains (5). Each stage of the ramp disturbance will potentially be characterised by a loss of indicator taxa relating to a reduction in available habitat and associated changes to abiotic parameters (*e.g.,* water chemistry and flow velocity).

The Drought Effect of Habitat Loss on Invertebrates (DEHLI) index places the aquatic stages of invertebrate taxa into groups based on these sequential stages of habitat availability, according to the invertebrates' relative tolerance to the loss of suitable habitat at each stage.

As outlined in Boulton and Lake (2008), stage 1 is characterised by the presence of taxa which require very fast flowing water or cool, well-oxygenated flowing water for effective metabolism, in order to carry out feeding and processing of nutrients. Such conditions become less common when river discharge declines during the early stages of drought, with associated reductions in flow velocity beside reduction of turbulence. The relevant taxa lost at this stage are all families and genera of aquatic insects in the orders Ephemeroptera, Plecoptera and Trichoptera.

Taxa lost at stage 2 use stream-side vegetation for emergence, food, shelter and case-building material and/or are intimately associated with floodplains. The disconnection of marginal habitats effectively removes the necessary elements required for survival. Such taxa include, for example, Odonata or Lepidoptera.

As the river moves to stage 3, taxa which not only require lotic water to respire effectively, but also some which need a current for provision of food (e.g. Hydropsychidae and Simuliidae), may be progressively lost as the river enters a fully lentic phase, resulting in a sharp decline in lotic taxon richness. This loss is typically balanced by colonisation by lentic taxa, such as certain Hemiptera, Coleoptera and Diptera which are physiologically and anatomically adapted to lentic-water environments.

In stage 4, remaining pools of surface water contract with a resulting deterioration in water quality (specifically, reducing dissolved oxygen and