Science of the Total Environment 650 (2019) 2648–2656

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Macroinvertebrate community responses to river impoundment at multiple spatial scales

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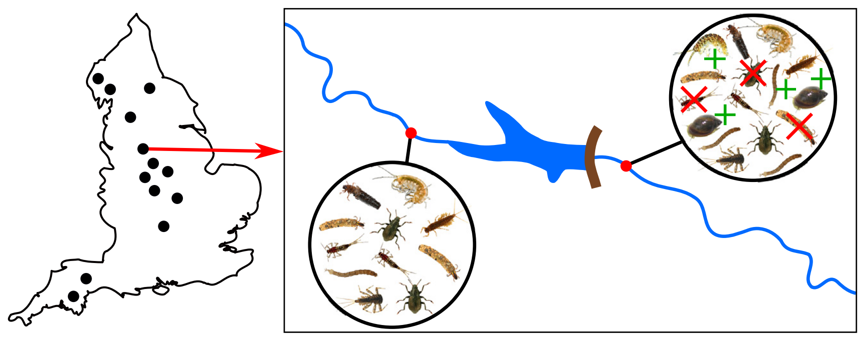
HIGHLIGHTS

- Macroinvertebrate communities downstream of reservoirs differed from control sites.
- Community differences were detected at both the national and regional scales.
- Taxonomic richness was higher at impounded sites than control sites.
- Proportion of sensitive macroinvertebrate groups was lower downstream of reservoirs.
- Community differences were detected by macroinvertebrate biomonitoring indices.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 12 July 2018
Received in revised form 19 September 2018
Accepted 20 September 2018
Available online 27 September 2018

Editor: Damia Barcelo

Keywords:
River regulation
Water supply reservoirs
Heavily modified waterbodies
Macroinvertebrates
National-scale analysis
Biomonitoring

ABSTRACT

River impoundment by the construction of dams potentially modifies a wide range of abiotic and biotic factors in lotic ecosystems and is considered one of the most significant anthropogenic impacts on rivers globally. The past two decades have witnessed a growing body of research centred on quantifying the effects of river impoundment, with a focus on mitigating and managing the effects of individual large dams. This study presents a novel multi-scale comparison of paired downstream and control sites associated with multiple water supply reservoirs ($n = 80$) using a spatially extensive multi-year dataset. Macroinvertebrate community structure and indices were analysed in direct association with spatial (e.g. region) and temporal variables (e.g. season) to identify consistent patterns in ecological responses to impoundment. Macroinvertebrate communities at monitoring sites downstream of water supply reservoirs differed significantly from those at control sites at larger spatial scales, both in terms of community structure and taxa richness. The effect was most significant at the regional scale, while biogeographical factors appeared to be important drivers of community differences at the national scale. Water supply reservoirs dampened natural seasonal patterns in community structure at sites downstream of impoundments. Generally, taxonomic richness was higher and %EPT richness lower at downstream sites. Biomonitoring indices used for river management purposes were able to detect community differences, demonstrating their sensitivity to river regulation activities. The results presented improve our understanding of the spatially extensive and long-term effects of water supply reservoirs on instream communities and provide a basis for the future implementation of mitigation measures on impounded rivers and heavily modified waterbodies.

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http://dx.doi.org/10.1016/j.scitotenv.2018.09.264

1. Introduction

Streams and rivers are among the world's most threatened ecosystems (Malmqvist and Rundle, 2002; Vörösmarty et al., 2010; WWF, 2016), mainly as a result of increased anthropogenic management and modification on a global scale (Nilsson et al., 2005). The worldwide alteration of the terrestrial water cycle has been described as a global issue alongside climate change (Vörösmarty and Sahagian, 2000). River impoundment by the construction of dams and the creation of reservoirs is considered one of the most significant forms of river regulation (Petts, 1984; Zarfl et al., 2015). Today, there are an estimated 58,500 large dams (higher than 15 m) worldwide (ICOLD, 2017).

The physical and chemical impact of river impoundment has been extensively documented (e.g. Webb and Walling, 1993; Gilvear, 2004; Yang et al., 2014; Maavara et al., 2015). Modification of the discharge regime affects all critical components of the natural flow regime (Poff et al., 1997; Magilligan and Nislow, 2005), is regarded as a major cause of stream degradation (Gordon et al., 2004; Tonkin et al., 2018) and is one of the most important factors influencing instream communities (Rosenberg et al., 2000). River impoundment has a profound effect on the instream ecology of lotic environments by affecting flow-ecology relationships (Bunn and Arthington, 2002). Benthic macroinvertebrate communities in particular have been intensively studied in relation to the effect of impoundment, with research examining community structure (Lessard and Hayes, 2003; Ladrera et al., 2015; Santos et al., 2017) and species diversity and richness (García de Jalón et al., 1994; Growns and Growns, 2001; Bredenhand and Samways, 2009). Both flow and thermal regime have been linked to changes to downstream macroinvertebrate communities (Petts, 1984; Martínez et al., 2013; White et al., 2017a). Since direct comparison of pre- and post-dam macroinvertebrate communities is often not possible, due to an absence of pre-impoundment baseline monitoring data (but see Armitage, 1978; Maynard and Lane, 2012), most studies have compared sites downstream of impoundments with control sites (i.e. sites assumed to represent unregulated conditions at the downstream sites - e.g. Growns and Growns, 2001; Holt et al., 2015).

To mitigate the perceived deleterious effects of impoundments, the implementation of environmental flows or e-flows (Acreman et al., 2009; Poff et al., 2010; Horne et al., 2017) has been proposed, referring to the quantity, timing and quality of river flow that is required to sustain lotic ecosystems and the services they provide (Dyson et al., 2003; Acreman et al., 2014; Overton et al., 2014). A range of studies have investigated reservoir outflow modification to enhance downstream ecosystems (for a review, see Gillespie et al., 2015b). Research centred on the effects of river impoundment has typically taken place on the site-specific scale involving single or several reservoirs (e.g. Greenwood et al., 1999; Holt et al., 2015), with a focus on the effects of large hydropower dams with rapidly changing discharge regimes (Alfredsen et al., 2012; Yang et al., 2014; Phillips et al., 2015). Moreover, most studies cover short time periods (Jackson et al., 2007; Gillespie et al., 2015a), generally restricted by the availability of appropriate ecological datasets.

The use of long-term observation datasets has recently been deployed in related ecological studies, for instance to demonstrate the effect of climate change on benthic macroinvertebrate communities on a large spatial scale (Jourdan et al., 2018). However, transferable flow-ecology relationships beyond the site scale remain elusive (Poff and Zimmerman, 2010). Moreover, the impact of reduced flow variability downstream of water supply reservoirs is not yet fully understood. Most dams of water supply reservoirs release water to the downstream river via a managed discharge regime that bears little resemblance to the natural hydrograph (historically termed ‘compensation flows’ in the UK - Gustard, 1989; Acreman and Dunbar, 2004), often reducing peak flows and increasing low flows (Higgs and Petts, 1988; McManamay et al., 2012; Stewardson et al., 2017).

This paper presents a large-scale comparison between the macroinvertebrate communities of monitoring sites downstream of multiple water supply reservoirs operating fixed flow releases and control sites. The overarching research aim was to identify consistent downstream patterns in ecological responses to water supply reservoirs beyond the site-specific scale. To address this, a multi-year (covering 2012–2016) national-scale biomonitoring dataset associated with 37 reservoir clusters (80 reservoirs) in England was used. The study aimed to assess the following hypotheses: 1) Consistent differences exist between macroinvertebrate communities at sampling sites downstream of water supply reservoirs and at control sites at the regional and national scales; 2) Patterns in ecological responses can be detected by existing macroinvertebrate biomonitoring tools employed to assess environmental variability.

2. Methods

2.1. Study area

The current study used data from the monitoring network SHEBAM (Setting the Hydro-Ecological Basis for Adaptive Management), which was established in 2012 by the Environment Agency of England (the statutory environmental regulatory agency in England, UK) to improve understanding of the ecological response to river flow alteration downstream of water supply reservoirs. This is to support assessments for the EU Water Framework Directive, particularly the ecological basis for adaptive management trials. The key feature of the network is the pairing of monitoring sites downstream of water supply reservoirs subject to compensation flow release schemes (called ‘downstream sites’ hereafter) and control sites, predominantly located in upland areas of England. As only limited pre-impoundment biomonitoring took place, control sites were selected to reflect the conditions that would occur at the downstream sites without the presence of the impoundment. These control sites were located either on the river reach upstream of the reservoir or on an unregulated tributary. The total network comprised 37 clusters (Fig. 1) of either individual or serial impoundments, involving a total of 105 monitoring sites associated with 80 reservoirs (1–6 reservoirs per cluster). From each cluster, 1 downstream and 1 control site closest to the impoundment were selected, resulting in a total of 74 sample sites (37 downstream-control site pairs). From the 37 control sites examined, 28 sites were upstream of the impoundment and 9 sites were located on tributaries.

2.2. Sampling

All monitoring sites were sampled biannually (spring and autumn) 2012–2016, yielding a maximum of ten samples per site, with the exception of sites that were introduced or replaced in 2015 after a network revision ($n = 20$; mainly control sites). For these sites, samples were only available for 2015 and 2016 (maximum of 4 samples). Spring samples were collected March–May and autumn samples were collected September–November. Benthic macroinvertebrates were collected by means of a standardised 3-minute kick- sampling method with an additional 1-minute hand search (Murray-Bligh, 1999). All samples were preserved using denatured alcohol (70% ethanol) in the field (ISO, 2012) and were returned to the laboratory for processing and identification. Macroinvertebrate taxa were identified to a consistent mixed taxonomic level (species level where possible, but some taxa at genus level or family level - see Davy-Bowker et al., 2010), with abundances being recorded. For a number of samples, faunal identifications were independently verified following Environment Agency quality assurance protocols.

The total number of samples available for analysis was 615 (315 downstream site samples, 300 control site samples), initially comprising >500 taxonomic entries (called ‘taxa’ hereafter). Pre-analysis was undertaken to ensure a consistent taxonomy across all samples by merging overlapping family, genus and species entries occurring in