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Research article

Overcoming the dichotomy of implementing societal flood risk management while conserving instream fish habitat – A long-term study from a highly modified urban river

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ABSTRACT

Flood Risk Management (FRM) is often essential to reduce the risk of flooding to properties and infrastructure in urban landscapes, but typically degrades the habitats required by many aquatic animals for foraging, refuge and reproduction. This conflict between flood risk management and biodiversity is driven by conflicting directives, such as the EU Floods and Water Framework Directives, and has led to a requirement for synergistic solutions for FRM that integrate river restoration actions. Unfortunately, ecological monitoring and appraisal of combined FRM and river restoration works is inadequate. This paper uses a case study from the River Don in Northern England to evaluate the effects of the FRM and subsequent river restoration works on instream habitat and the associated fish assemblage over an 8-year period.

Flood risk management created a homogeneous channel but did not negatively affect fish species composition or densities, specifically brown trout. Densities of adult brown trout were comparable pre and post-FRM, while densities of juvenile bullhead and brown trout increased dramatically post FRM. River restoration works created a heterogeneous channel but did not significantly improve species composition or brown trout density. Species composition post-river restoration works returned to that similar to pre-FRM over a short-term period, but with improved numbers of juvenile bullhead. Although habitat complexity increased after river restoration works, long-term changes in species composition and densities were marginal, probably because the river reset habitat complexity within the time framework of the study.

1. Introduction

Floods are an integral component of natural hydrological regimes (Junk et al., 1989; Tockner et al., 2000; Acreman et al., 2014), but can cause substantial damage to property and infrastructure, and more frequent extreme precipitation events, as predicted by the IPCC (2014), will increase the risk of flooding. Furthermore, the risk and severity of flooding will particularly increase in many parts of industrialised countries, where urban areas are more prevalent and flooding is exacerbated by the cumulative impacts of multiple anthropogenic pressures, such as channel engineering, artificial structures and impervious riparian surfaces, which increase run-off volume and river discharge (Butler and Pidgeon, 2011). Flooding in urban areas has had devastating effects on people, property, infrastructure and the economy worldwide in recent decades (Everard and Moggridge, 2012), and is likely to increase in frequency and magnitude in the future (IPCC, 2014).

Flood Risk Management (FRM) interventions reduce the risk of flooding to properties and infrastructure in urban and rural landscapes. FRM typically involves modification of river channels to enhance the conveyance of flood water, for example through with the removal of meanders, river substrate, riparian vegetation and instream features, such as islands (Roni and Beechie, 2013). Conventional FRM also involves construction of extensive flood defence structures, such as in Rotterdam in the Netherlands, New Orleans in the United States and the Huai River in China, where main river channels have been isolated from their floodplains (Sayers et al., 2013). This isolation profoundly affects fluvial processes and ecosystem functioning, and also eliminates or degrades the habitats required by many aquatic animals for foraging, refuge and reproduction (Bernhardt and Palmer, 2007; Weber and

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Wolter, 2016; Zajicek et al., 2018).

There is inevitably a need to compromise between FRM and biodiversity, especially if both are enshrined in legislation, such as the EU Floods Directive (FD (2007/60/EC)), Water Framework Directive (WFD (2000/60/EC))) and Habitats Directive (HD (92/43/EEC)) (Jackson et al., 2016). This has led to a requirement for synergistic solutions for FRM that integrate river restoration works (RRW) into their planning and implementation, to optimise benefits for both agendas (Rouillard et al., 2015; Friberg et al., 2016; Jackson et al., 2016). Although this integrated FRM and RRW approach is widely supported in principle, it is still in its infancy with only a few studies evaluating the ecological impact of FRM (Collas et al., 2018), meaning evidence of its application, efficacy and/or success in practice is limited. The majority of existing literature evaluates flood management measures and impacts on society, but ecological monitoring and appraisal of FRM and RRW to determine the effectiveness of such projects is typically weak, due in part to limited timescales and resourcing of such studies (Adams et al., 2014; Angelopoulos et al., 2017). As flood risk increases globally due to climate change, and societal and environmental policy changes are expected in the near future (Wiering et al., 2017), there is a need to advance knowledge about FRM impacts on urban river ecosystems. To do this, ecological assessment needs to be integrated into FRM planning to evaluate how it changes habitat and aquatic biota, but this is rarely done, presenting a critical knowledge gap that is the key focus of this paper (Roni and Beechie, 2013).

In June 2007, 4000 homes and 1800 businesses were flooded during a 1-in-150-year event in the City of Sheffield, United Kingdom (Pitt Review, 2008), which resulted in FRM actions in 2009 to reduce the risk of further flooding, and then RRW in 2010 and 2011 to rehabilitate instream fish habitat. Fish are key ecological indicators of the ecological quality of rivers, and the impacts of FRM and RRW, because the various fish guilds integrate a wide range of habitat conditions over their life cycles that are linked to the environmental requirements of particular species and ontogenetic life stages (Weber and Wolter, 2016). This paper assesses the long term changes in physical characteristics and mean daily flow (m^3s^{-1}), subsequent available habitat and the fish community in response to FRM and subsequent RRW, and is one of the first to use ecological assessment to inform future flood risk governance on the integration of river restoration.

2. Methods

2.1. Site description

The study site is located in the City of Sheffield, United Kingdom, at the confluence of the rivers Rivelin and Loxley (Ordnance Survey National Grid reference: 53.399698–1.511562), which are regulated by Rivelin Dams (53.377511–1.589666) and Damflask (53.413377–1.582340) reservoirs, respectively. The site is in a highly urbanised location surrounded by impervious surfaces; there are road bridges at the upstream and downstream limits, and the river is constrained by embankments. Prior to FRM (2009) the channel was defined by riparian deciduous trees and shrubs which overhung the water surface by approximately 80%, stabilised the bank and seemingly prevented meandering given their size and age, and (Fig. 1a). Following a 1-in-150-year event in 2007, FRM works in October 2009 involved removing all riparian vegetation, some gravel shoals and larger instream substrates to help reduce the risk of blockages at the downstream road bridge (Fig. 1). This also prevented recolonization of vegetation that would in time pose a flood risk, and optimise hydraulics around the structures to reduce the likelihood of future flooding in the surrounding urbanised area (Fig. 1). Overall this created a uniform over-widened and shallow channel, and reduced variability in substratum, water depth and overall flow characteristics (Fig. 1b). The channel was then re-profiled in November 2010 (after 2010 habitat and fish surveys but prior to those in 2011) as part of RRW by introducing large boulders back-filled with cobbles and gravel, as well as in-channel boulder clusters and by creating a variable longitudinal depth profile along the thalweg. These works were intended to diversify water depths and velocities to provide cover for fish (Fig. 1c). In-channel substrate was highly dynamic, and mobilised by high flows in the first two years post-RRW, evidenced by a new mid-channel gravel bar forming in 2011, which had redistributed by 2012 and reformed on the right bank by 2013 (Fig. 1c–e). Riparian habitats were allowed to regenerate (from 2012) through a combination of reseeding, replanting and natural recovery (Fig. 1f).

Mean daily flow was < 1 m^3s^{-1} for the majority of the year, with high seasonal peaks in December to February for 2009–2010 (highest daily flow of 6.4 m^3s^{-1}), 2012–2013 (highest daily flow of 11.6 m^3s^{-1}), 2014 (8 m^3s^{-1}) 2016 (9.8 m^3s^{-1}) (Appendix 1). In 2015, the high flows came in March and April (highest daily flow of 3.8 m^3s^{-1}) while in 2012, high flow events occurred late in the year in April (highest daily flow of 14.7 m^3s^{-1}), June (highest daily flow of 5 m^3s^{-1}), and July (highest daily flow of 15 m^3s^{-1}) (Appendix 1).

2.2. Sampling methods

Instream habitat and fish surveys were undertaken annually between July to August in each year from 2009 to 2016 at average summer flows, with 2009 surveys representing pre-FRM, 2010 surveys post-FRM and pre-RRW, and 2011–2016 surveys post-RRW.

2.2.1. Habitat surveys

Instream habitat surveys were conducted using the HABSCORE methodology, an empirical habitat-fish model developed for measuring and evaluating stream salmonid habitat features that is widely used in the UK for impact assessment (Barnard and Wyatt, 1995; Wyatt et al., 1995; Milner et al., 1998). The same two experienced researchers carried out the HABSCORE field recording each year. HABSCORE is based on a series of empirical models relating the population size of five salmonid species/age combinations (juvenile 0 + Atlantic salmon *Salmo salar* L.; adult ≥1 + salmon; juvenile 0 + brown trout *Salmo trutta* L.; sub-adult ≥1 + brown trout (< 20 cm); and ≥1 + brown trout (> 20 cm) to observed habitat variables (Milner et al., 1998); salmon was excluded from the study as the species is currently absent from the upper reaches of the River Don catchment due to a number of impassable barriers downstream.

Instream habitat characteristics were measured for each 10-m section of the fish survey study site following the HABSCORE methodology. Water depth (to the nearest 0.01 m) and wetted river width (to the nearest 0.1 m) at ¼, ½ and ¾ of the channel width were measured at the upstream and downstream limit of each 10-m section. Substratum [bedrock, boulders (> 25.6 cm longest axis length), cobbles (6.4–25.6 cm), gravel (0.2–6.4 cm), fine sand (< 0.2 cm)] and flow [cascade, turbulent (deep or shallow), glide (deep or shallow) and slack (deep or shallow), where the threshold between deep and shallow water was defined as being deeper than 50 cm for sections with a width less than 5 m, but as deeper than 10% of the width for sections with a width greater than 5 m] categories were recorded as absent (0%), scarce (> 0–4%), common (5–19%), frequent (20–49%) or dominant (> 50%) according to their contribution by surface area.

2.2.2. Fish surveys

Quantitative, three-catch depletion electric fishing surveys were carried out, involving three personnel (one anode operator and two netters) fishing in an upstream direction, with a fourth on the bank ensuring safe operation of the equipment. A 2-kVA generator powering an electric fishing control box producing a 220-V, 50 Hz Pulsed Direct Current output was employed. Stop nets were deployed at the upstream and downstream limits of the site, to prevent fish leaving or entering the site during the surveys. As many fish as possible were caught by netsmen either side and downstream, of the anode operator; during