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Identifying indicators and quantifying large-scale effects of dams on fishes

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ABSTRACT

Although localized effects of individual dams on stream fish assemblages have been relatively well-studied, less is known about the effects of multiple dams within a stream network on fishes and the patterns that emerge when the combined effects of individual and multiple dams are viewed across entire river basins, ecoregions, and states. This study evaluated multiple stream network fragmentation metrics representing localized (e.g., distance-to-dams) and cumulative (e.g., total upstream reservoir storage) dam influences on streams in Michigan, Wisconsin, and Minnesota, developing an approach for identifying suitable fish indicators of dam effects. We used change point and correlation analyses to determine associations of stream fish catch per unit effort and various stream network fragmentation metrics with data from more than 2000 fish survey sites stratified by stream size, thermal regime, and ecoregion. Of the identified indicator species, predominantly warmwater, large river, and/or lentic species were positively associated with stream network fragmentation, whereas cold and coolwater lotic species were negatively associated with fragmentation. These results suggest a combination of downstream thermal effects and upstream influences from impoundments generated by dams. Variance partitioning analyses based on identified indicator species revealed greater upstream-dominated dam influences in headwaters than mid-sized streams, and a greater relative influence of dams vs. other non-dam anthropogenic influences in cold streams than warm streams. Overall, a combination of localized and cumulative fragmentation metrics, as well as upstream and downstream-oriented measures, were influential in indicator species responses, emphasizing the importance of selecting a diversity of fragmentation metrics when assessing effects of dams on stream fishes. Understanding multiple dam influences on stream fishes, including localized effects from individual dams and cumulative effects from all dams within a river basin, would provide useful information for a variety of management activities, including dam operation and dam removal prioritization. Dams significantly affect conservation and management options for stream fishes, with identification of multi-scale dam influences on fishes being critical to restoration and maintenance of aquatic biodiversity throughout the world.

1. Introduction

Dams constitute spatially complex anthropogenic disturbances to riverine systems, altering habitat both upstream and downstream of dams within stream networks. Often alterations on habitat are multi-faceted, affecting hydrology, stream temperature, channel morphology, water chemistry, and hydrologic connectivity, making isolation of individual mechanisms of habitat alteration difficult. In addition, the type and magnitude of habitat alterations observed at individual dams often depend on their location within the stream network, how they are managed, and their age (Ward and Stanford, 1983; Poff et al., 1997; Poff and Hart, 2002). Furthermore, habitat alterations can be localized, resulting from individual dams, or cumulative, stemming from an aggregation of effects of all dams along a stream network within a river basin or large region (e.g., Pringle, 2001; Bosch, 2008). These diverse

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influences underscore the need for multiple, spatially-explicit dam measures to characterize effects of dams on fluvial habitat and biota. Ultimately, understanding local and cumulative sources of stream habitat degradation depends on characterizing the location and intensity of each degradation source, as well as the regional context in which disturbances may occur (Utz et al., 2010).

Numerous studies have documented effects of dams on stream fishes, typically by sampling fish or abiotic habitat above and below dams, by comparing surveys between dammed and undammed streams, or by sampling along individual stream networks containing a series of dams (e.g., Lessard and Hayes, 2003; Guenther and Spacie, 2006; McLaughlin et al., 2006; Slawski et al., 2008). In some cases, studies have described fish assemblage changes by surveying streams before and after dam removals (e.g., Catalano et al., 2007). Such studies have provided valuable knowledge on the localized effects of individual dams on fishes, including decreased abundance of coldwater species below dams from thermal shifts, increased prevalence of lentic species upstream of reservoirs, and overall species composition changes due to habitat alteration by dams. Relatively few studies have incorporated both localized and cumulative dam measures to investigate influences of dams on fishes across large geographic regions, such as entire river networks, ecoregions, or multi-state regions. Such studies could identify patterns of dam influences unobservable at smaller spatial extents, or alternatively, could determine if observations made in localized studies are evident across larger regions. Information provided by large-scale studies could be used for prioritizing dam management actions and ultimately improving fisheries conservation and management efforts, especially across broader geographic extents.

Of the few studies that have investigated dam influences on fishes over large regions, most have used one or two dam measures, typically representing habitat fragmentation and/or temporal isolation of habitats identified from dam construction dates (e.g., Fukushima et al., 2007; Hall et al., 2011). Other studies have focused on how dams alter free-flowing stream lengths, exploring the relationship between stream fragment size and responses of individual species or reproductive guilds (Bain and Wine, 2010; Perkin and Gido, 2011; Perkin et al., 2015). Two recent studies have used several dam metrics to investigate the influence of localized and cumulative effects of dams within river networks. Wang et al. (2011) used spatially-explicit measures of fragmentation, including distances to dams, total upstream dam density, and upstream/downstream mainstem dam densities to examine the influence of dams on stream fish community metrics in Michigan and Wisconsin, USA. Similarly, Van Looy et al. (2014) used dam measures from multiple scales, ranging from local reach to upstream catchment, to investigate dam influences on community-based fish and invertebrate metrics for the Loire River basin, France. Results from these two multi-metric studies suggest that key measures of stream fish communities are responsive to dam influences in both upstream and downstream directions and in both a localized and cumulative context.

Despite such advancements in our understanding of dam influences on fish, measuring fragmentation by dams and river connectivity as a whole continues to present challenges to stream ecologists and managers (Wang et al., 2006; Steel et al., 2010). In particular, few studies have investigated influences of multiple dam metrics, including localized and cumulative metrics, on individual fish species across a large geographic region. Although community trait-based or diversity-based measures are typically used in monitoring and condition assessments (e.g., Esselman et al., 2013; Daniel et al., 2015), knowledge of how individual species respond to dam influences can provide more relevant information to managers and policy makers focused on species-based conservation and management. Developing, and implementing, an approach to identify species-level fish indicators of dam fragmentation would provide information for discerning the relative importance of complex dam effects, as well as understanding in these effects on fish assemblage structure along the river network. Despite the pervasive threat of dams to lotic systems, dams represent a unique restoration opportunity, one that would be informed by understanding indicator fish responses to landscape-scale dam effects.

This study represents a detailed evaluation of influences of multiple network-based dam metrics on individual fish species in the states of Michigan, Wisconsin, and Minnesota. We present an approach to identify fish indicators of fragmentation by dams that is consistent, provides information at multiple levels of organization, and is reproducible in other regions. We apply this approach within the study region to: (1) identify fish species that can be used as indicators (both positive and negative) of fragmentation within stream networks, (2) identify key fragmentation metrics as they relate to indicator species responses, and (3) examine the relative influence of stream fragmentation by dams and non-dam covariates on indicator fish species, including a comparison of upstream vs. downstream-oriented dam influences.

2. Materials and methods

2.1. Study region

This study encompassed the states of Michigan, Wisconsin, and Minnesota, USA, covering approximately 514,000 km^2 and containing nearly 262,000 km of streams (Fig. 1). This region has been heavily influenced by glaciation and lacustrine deposition (e.g., Farrand and Bell, 1982), leading to diverse surficial geology deposits that vary widely in texture (e.g., coarse vs. fine) and landform (e.g., moraine, outwash plain, lake plain). This complexity results in highly variable groundwater discharge, including groundwater-dominated streams characterized by stable flow and thermal regimes as well as streams driven primarily by surface runoff with "flashy" flow regimes and variable water temperatures (Zorn et al., 2002; Wehrly et al., 2009). This region also varies greatly in the distribution and intensity of landscape-based anthropogenic disturbances, including land uses, with relatively least-disturbed northern areas dominated by forest and wetlands to highly altered southern areas typified by agriculture and urbanization (e.g., Wang et al., 2008).

2.2. Stream reaches, catchments, and associated data

The stream network used for this study region was the 1:100,000 scale National Hydrography Dataset Plus Version 1 (NHDPlusV1; USEPA and USGS, 2005), a dataset consisting of confluence-to-confluence stream reaches and their corresponding local catchments, defined as the land area draining to each reach. Network catchments represent the cumulative upstream land area draining to a reach, including a reach's local catchment. We used stream network topology, along with a suite of variables representing both natural and non-dam anthropogenic data layers, to assemble network catchment attributes by upstream aggregation of local catchment data (Tsang et al., 2014). A subset of network catchment attributes were chosen for use in analysis based on previous landscape-based fish community studies (e.g., Wang et al., 2011; Esselman et al., 2013), including catchment area and slope, precipitation, base flow, and coarse-textured lithology, and non-dam anthropogenic variables representing urban and agricultural land uses, population density, and road crossings and densities (Table 1).

To measure stream fragmentation by dams, we used a previously defined set of 14 fragmentation metrics (Cooper,