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Human effects on ecological connectivity in aquatic ecosystems: Integrating scientific approaches to support management and mitigation

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HIGHLIGHTS

- Human effects on ecological connectivity in aquatic ecosystems are reviewed.
- Threats include: habitat loss, altered hydrology, invasive species, and climate change.
- Case studies show improved understanding from multi-disciplinary approaches.
- Data on autecology, population structure, movement and physiology are critical.
- Planning requires data synthesis across life histories and temporal/spatial scales.

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ABSTRACT

Understanding the drivers and implications of anthropogenic disturbance of ecological connectivity is a key concern for the conservation of biodiversity and ecosystem processes. Here, we review human activities that affect the movements and dispersal of aquatic organisms, including damming of rivers, river regulation, habitat loss and alteration, human-assisted dispersal of organisms and climate change. Using a series of case studies, we show that the insight needed to understand the nature and implications of connectivity, and to underpin conservation and management, is best achieved via data synthesis from multiple analytical approaches. We identify four key knowledge requirements for progressing our understanding of the effects of anthropogenic impacts on ecological connectivity: autecology; population structure; movement characteristics; and environmental tolerance/phenotypic plasticity. Structuring empirical research around these four broad data requirements, and using this information to parameterise appropriate models and develop management approaches, will allow for mitigation of the effects of anthropogenic disturbance on ecological connectivity in aquatic ecosystems.

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1. Introduction

Animal populations and ecosystems are connected via a range of physical, biological and biochemical pathways. These connections influence biodiversity, productivity, energy fluxes, species assemblage compositions and food web dynamics (Taylor et al., 1993; Lowe and Allendorf, 2010), and define the spatio-temporal scales at which management and conservation initiatives will be most effective (Pringle, 2001; Lindenmayer et al., 2008).

Understanding the drivers and implications of altered ecological connectivity has become a key concern with respect to biodiversity conservation. Globally, few terrestrial and aquatic ecosystems remain unaffected by anthropogenic fragmentation and the resulting loss of connectivity among populations and habitats (Pringle, 2001; Lindenmayer and Fischer, 2006). Humans are fundamentally changing connections within and between ecosystems over a wide range of spatial scales and habitat types. The effects of human activities are not unidirectional, and may result in either increased or decreased levels of connectivity. Such changes can pose direct threats to biota, but may also create novel environments that alter the evolutionary trajectories of populations and species (Allendorf et al., 2013).

In this review, we examine the effects of anthropogenic activities on ecological connectivity as it pertains to the movement and dispersal of aquatic organisms. We recognise, however, the critical importance of other forms of connectivity in aquatic ecosystems that are not specifically considered — for example, the flow of nutrients and energy across space, whether mediated by organisms or physical processes (Polis et al., 2004). Our primary aim is to identify and describe the main anthropogenic effects on ecological connectivity in aquatic ecosystems, and to explore their consequences for biota both within and between populations. A series of case studies illustrates how integration of multiple methodological approaches can increase our understanding of the potential effects of human activity on connectivity in aquatic ecosystems. Based on these considerations, we propose a series of key knowledge requirements for future research in this area.

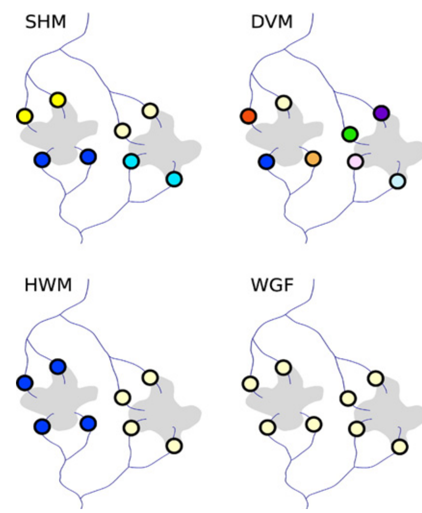
1.1. Movement and dispersal in aquatic ecosystems

Aquatic ecosystems encompass a diverse array of physical configurations, ranging from 'open' systems like oceans, to isolated waterholes in arid landscapes. Based on the spatial structure and physical characteristics of marine, freshwater and estuarine habitats, one might expect different 'rules' for ecological connectivity among ecosystems. The oceans and seas that cover around 70% of the earth's surface provide considerable possibilities for variability in the direction and extent of movement, although factors such as oceanic currents, bathymetry, land boundaries and seabed type can exert strong influences on the movements of many species (Gaspar et al., 2006). Freshwater systems, conversely, cover only ~0.8% of the earth's surface and are typically organised into networks of hierarchically branching streams and rivers, occasionally punctuated by lakes and wetlands (Grant et al., 2007). The complex structure of freshwater ecosystems can create isolation among populations at much smaller spatial scales than would be expected in marine systems; for example, when nearby populations occupy habitats that are not connected via the river network (Hughes et al., 2009). Four general models of ecological connectivity have been proposed to describe the unique constraints imposed by hierarchical network structure in freshwater ecosystems (Text Box 1).

Whilst the different physical attributes of aquatic ecosystems place limitations on the movements of resident organisms, their behavioural responses are not always intuitive with respect to the apparent openness of the environment. For many years, the pelagic larval stages of marine organisms were considered as passive particles that disperse widely under the influence of oceanic currents. This assumption led to a long-held paradigm in which local populations were considered highly mixed and demographically open (Jones et al., 2009). However,

Text Box 1
Models of ecological connectivity in streams.

The *stream hierarchy model* (SHM, Meffe and Vrijenhoek, 1988) predicts that freshwater species will be connected in a way that reflects the dendritic nature of the stream network. Sites within the same stream will be most connected, sites sharing the same subcatchment will be more connected than those in other subcatchments, and so on following the hierarchically branching nature of streams. Under the SHM, zero connectivity would be expected between sites occupying completely isolated stream networks (such as opposite sides of a continental divide). The SHM can apply to animals such as fish, many of which are highly mobile within the water column but have no capacity to move outside of the water column.



The four models can be visualised as above, with dots of the same colour representing connected populations. Populations occupy four sub-catchments with headwaters in two higher-altitude headwater regions (the grey areas).

The *Death Valley model* (DVM, Meffe and Vrijenhoek, 1988) describes extreme isolation experienced by animals that are similarly restricted to aquatic habitat but are confined to small patches of disconnected habitat. Under the DVM, habitat patches are extremely isolated either physically, due to a permanent lack of hydrological connectivity (e.g., springs in a desert), or functionally, due to a high degree of habitat specialisation for a sparsely distributed habitat type within a river network (e.g., cold headwater streams).

The *headwater model* (HWM, Finn et al., 2007) describes a pattern of ecological connectivity that is essentially opposite to the SHM. The HWM applies to animals that specialise on a particular habitat type, often associated with small headwater streams in a river network, but have some capacity to disperse terrestrially, typically by crawling or weak flight. Animals following the HWM pattern typically disperse readily among nearby headwater streams, whether or not these streams are physically connected in a river network.

Widespread gene flow (WGF) occurs in species that either have a highly mobile terrestrial phase (e.g., many aquatic beetles, Coleoptera) or are adapted to have temporary associations with highly mobile terrestrial animals (e.g., zooplankton attached to birds' legs, Maguire, 1963). For freshwater animals following the WGF pattern, the geometric structure of the river network has little influence on potential ecological connectivity.