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Environmental flow assessment in estuaries taking into consideration species dispersal in fragmented potential habitats

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ABSTRACT

Here, we propose an approach to environmental flow assessment that pays attention to species dispersal among fragmented potential habitat patches affected by river inflow and tidal currents in estuaries. The approach consists of three steps. In step one, potential suitable habitats were mapped and the Habitat Aggregation Index (HAI) was determined to understand the fragmentation of potential suitable habitats by integrating the requirements for critical environmental factors that have temporal and spatial variability. In the second step, an individual-based model was developed to simulate the dispersal of target species among potential habitat patches. The model provided the species distributions for altered hydrological processes. In the third step, environmental flows were defined by comparing the occupancy of suitable habitat patches by individual organisms and habitat aggregation for varying freshwater inflows. This approach was tested using a case study in the Yangtze River Estuary. We stressed the ecological importance of flood pulse, rather than average discharge, and recommend a Gaussian-type flood pulse, as provides a win–win point for both the numbers of individuals that could occupy suitable habitat and the HAI. We also demonstrated the importance of the peak flow and flood pulse duration in terms of affecting species distribution. Based on the results presented here, the proposed approach offers a flexible assessment of environmental flow for aquatic ecosystems.

1. Introduction

Estuaries and coasts are important transitional environments connecting the land to the sea. They have high ecological and biodiversity functional values, as well as diverse cultural and economic values (Roy et al., 2001; Lotze et al., 2006; Piehler and Smyth, 2011; Brush et al., 2016). Freshwater inflow can serve a variety of important functions through maintenance of salinity gradients, sediment and nutrient transport, and provision of habitats for estuarine species (Crump et al., 2004; Lamberth et al., 2009; Valdemarsen et al., 2015). However, both climate change and intense regulation of water resources has significantly altered the natural flow regimes of rivers worldwide (Döll et al., 2009; Yang et al., 2015), and thus has negatively affected their hydrodynamic processes, environmental gradients, and species distributions, particularly in the case of estuaries (Bianchi and Allison, 2009; Allison and Meselhe, 2010; Korus and Fielding, 2015; Liu et al., 2016). In order to define the quantity, quality, and time required to maintain water use balance between human activities and ecosystems in estuaries, environmental flow assessments have been undertaken. These assessments are important tools for informing ecosystem restoration, water resource management, and reservoir management (Tharme, 2003; Yang et al., 2009; Walsh et al., 2013; Cruzeiro et al., 2016).

A critical issue in environmental flow assessment is the understanding of ecological responses to hydrological alterations. By considering the complex interactions between ecological and hydrological processes, habitat simulation models can quantitatively analyze the ecological effects of hydrological processes through a contrasting relationship between freshwater inflow and environmental factors that are critical to restricting suitable habitats, and hence have been widely used in estuarine environmental flow assessments (Jassby et al., 1995; Tharme, 2003; Li et al., 2009; Sun et al., 2013, 2015). Despite this, many major stressors in estuarine and coastal ecosystems can result in either decreased suitable habitat area or habitat fragmentation (Thrush et al., 2008; Zhang et al., 2016; Lefcheck et al., 2016). Habitat fragmentation has been recognized as a major threat to terrestrial and marine ecosystems (Young et al., 1996; Fahrig, 2003; Lindenmayer and Fischer, 2013; Zhang et al., 2016). Increased habitat fragmentation reduces connectivity among habitat patches, obstructs species diffusion, reduces established populations, hinders species dispersal

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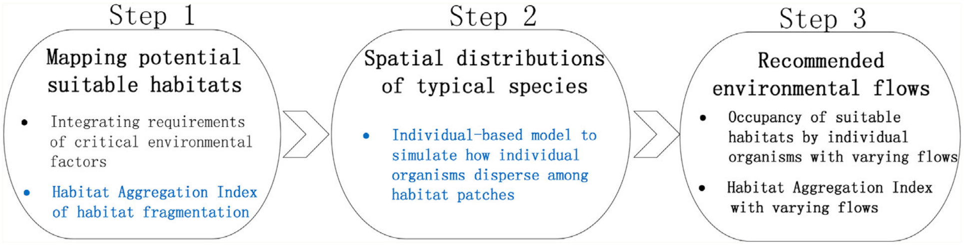

Fig. 1. Approach for environmental flow assessments in estuaries.

and migration activities (Bierregaardet et al., 1992; Elgar and Clode, 2001; Layman et al., 2004), and has a direct impact on species distribution and biogenetic structure. Habitat simulation models focus on potential habitats for species in altered freshwater inflows. Nevertheless, individual organisms frequently move among complex landscapes (Dover and Settele, 2009; Rabinowitz and Zeller, 2010), and even among fragmented habitat patches (Antongiovanni and Metzger, 2005; Lees and Peres, 2009; Dorchin et al., 2013).

The adaptation of individual behaviors under stress caused by the fragmentation of potential suitable habitats has seldom been included in environmental flow assessments. Rather than defining environmental flows based on potential suitable habitats, the present study focused on species distribution in fragmented estuarine habitat patches with hydrological alteration. In particular, an individual-based model was built to simulate how target organisms disperse individually among fragmented habitat patches. The dispersal preferences were defined using the suitability and spatial distribution of potential habitat patches under the action of different river flows and tidal currents, which were mapped through a suitable habitat evaluation model based on the fuzzy logic method.

2. Methods

2.1. Mapping potential habitat distributions

To define environmental flows in estuaries with complex eco-hydrological processes, here we propose an approach to environmental flow assessment based on species spatial distributions, taking into consideration of their dispersal among potential habitat patches with alterations in freshwater inflow. The approach consists of three steps (Fig. 1). In the first step, potential suitable habitat was mapped and the Habitat Aggregation Index (HAI) was used to understand the fragmentation of potential suitable habitats based on the integration of critical environmental factors that have temporal and spatial variability. In the second step, an individual-based model was developed to simulate the dispersal of target species among potential habitat patches. The species distribution with altered hydrological processes was obtained from this model. In the third step, environmental flows in estuaries were compared for varying freshwater inflows based on the occupancy rates for suitable habitat patches by individual organisms and the HAIs.

In estuaries, habitats that are utilized during the breeding and growth seasons for typical migratory species are usually located in shallow water. Water depth and water salinity for typical migratory species during pivotal life-stages (e.g., reproduction and juvenile growth) are usually selected to indicate habitat suitability for species in estuaries (Kurup et al., 1998; Koch, 2001; Robins et al., 2005; Poff and Zimmerman, 2010; Sun et al., 2015). In addition, fluctuations in water salinity that are affected by the combined action of freshwater and seawater have important impacts on aquatic organisms (Wang, 2012), especially on larvae survival (Cheng, 1997). Proper salinity fluctuation can stimulate aquatic organisms to spawn, although aquatic organisms can also suffer extensive mortality rates due to instantaneous variations in water salinity (Browne and Wanigasekera, 2000; Calliari et al., 2008). Accordingly, in this study, we selected water depth, water salinity, and water salinity fluctuation rates as the critical environmental factors required for mapping suitable habitats for target species. Salinity fluctuation rates were calculated based on the temporal variation in salinity, which can be expressed as a standard deviation formula:

$$F = \sqrt{\frac{1}{N}\Sigma_{i=1}^{N}\left(x_i - \frac{1}{N}\Sigma_{i=1}^{N}x_i\right)^2} \quad (1)$$

where x_i represents salinity at moment i, and N represents the tidal fluctuation time. The standard deviation reflects the data set dispersion measures, so that within the same time frame, a higher fluctuation rate value reflects a more intense salinity fluctuation.

Temporal and spatial variations in water depth and salinity can be simulated as a combined function of river discharge and tidal currents using hydrodynamic and water quality models. The responses of target environmental factors to changes in river discharge were thus quantified and the salinity fluctuation rates calculated at different locations. The Environmental Fluid Dynamics Code (EFDC), which has been adopted by many researchers as a simulation tool, was applied to simulate the space-time distribution of environmental factors (Liu et al., 2008; Seo and Ahn, 2012; Kang et al., 2015). Based on the simulated distributions of water depth, salinity, and salinity fluctuation rate in the estuary, the suitability of habitats at different locations for target species could be defined by integrating the different requirements for the environmental factors using the fuzzy logic method. The suitability of each habitat was classified using the Habitat Suitability Index (HSI) with four degrees of suitability (0–0.25 for very unsuitable, 0.25–0.5 for unsuitable, 0.5–0.75 for suitable, 0.75–1 for very suitable). Additionally, the HAI was adopted to investigate the fragmentation of potential suitable habitats (Xue et al., 2016).

2.2. Spatial distributions of typical species by the individual-based model

An individual-based model was built through the application of cellular automata (CA) to simulate the dispersal of individual organisms among habitat patches. The spatial distribution of species with hydrological alteration was obtained from the model. The modeling space was divided into several two-dimensional square cells, and each cell was composed of three elements: habitat suitability (*HSI*), number of individual organisms (*S*), and carrying capacity (K, $K = K_{max} * HSI$). The state of a certain cell at time (t) was decided by both its original state and the state of neighborhood at time ($t-1$). Cells with different states transformed based on the same rules in divergent space and time. Rules for individual dispersion were determined by the dispersal rate, dispersal direction, and dispersal quantity for each cell (Fig. 2).

2.2.1. Density-dependent dispersal rate

The influence of individual density on the dispersal rate depends on the relationships between individuals. Density negatively affects dispersal when individuals being aggregation to against predators,