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Environmental flow assessments for transformed estuaries

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SUMMARY

Here, we propose an approach to environmental flow assessment that considers spatial pattern variations in potential habitats affected by river discharges and tidal currents in estuaries. The approach comprises four steps: identifying and simulating the distributions of critical environmental factors for habitats of typical species in an estuary; mapping of suitable habitats based on spatial distributions of the Habitat Suitability Index (HSI) and adopting the habitat aggregation index to understand fragmentation of potential suitable habitats; defining variations in water requirements for a certain species using trade-off analysis for different protection objectives; and recommending environmental flows in the estuary considering the compatibility and conflict of freshwater requirements for different species. This approach was tested using a case study in the Yellow River Estuary. Recommended environmental flows were determined by incorporating the requirements of four types of species into the assessments. Greater variability in freshwater inflows could be incorporated into the recommended environmental flows considering the adaptation of potential suitable habitats with variations in the flow regime. Environmental flow allocations should be conducted in conjunction with land use conflict management in estuaries. Based on the results presented here, the proposed approach offers flexible assessment of environmental flow for aquatic ecosystems that may be subject to future change.

1. Introduction

An estuary is a partly enclosed coastal body of brackish water, defined by mixing of freshwater from rivers and saltwater from seas. Freshwater inflows serve a variety of important functions in estuaries, including maintenance of salinity gradients, sediment and nutrient transport, and provision of habitats for estuarine species (Kurup et al., 1998; Kim and Montagna, 2009; Lamberth et al., 2009). The growth and distribution of many migratory species is influenced by freshwater inflows, which are related to both hydrodynamic and nutrient dynamic processes (Alber, 2002). However, the intense regulation of water resources has altered the natural flow of rivers significantly worldwide (Döll et al., 2009), and has resulted in negative impacts on environmental gradients and species distribution and the quality and quantity of many ecosystem habitats, particularly in estuaries (Even et al., 2007; Bianchi and Allison, 2009). Environmental flows, which describe the quantity, quality, and timing of water flows required to sustain freshwater and estuarine ecosystems and the human populations that depend on them, have become an important tool for ecosystem restoration, water resource management, and reservoir management (Arthington et al., 2006; The Brisbane Declaration, 2007;Poff and Matthew, 2013; Acreman et al., 2014).

Various methodologies for environmental flow assessment have been developed, including hydrological, hydraulic, habitat, and holistic methods (Tharme, 2003). However, applications of these methodologies have been limited in estuaries owing to the complex and individually distinct structures and functions of estuaries, and the environmental flow requirements of estuaries have received attention only in recent years (Alber, 2002; Sun et al., 2008, 2013; Yang et al., 2014; Adams, 2014). Determining ecological responses to hydrological alterations is a critical issue in environmental flow assessments (Arthington et al., 2006; Poff et al., 2009; Petts, 2009). Adams (2014) believed that the environmental flow requirements of estuaries have typically been ignored, owing primarily to the lack of long-term monitoring data or incomplete understanding of responses to changes in freshwater inflow.

In general, the methods and frameworks used to determine the environmental water requirements of estuaries have been classified as inflow-, resource-, and condition-based (Alber, 2002; Adams, 2014).The percent-of-flow approach proposed by Flannery et al. (2002) is a typical inflow-based method. According to this approach, it is suggested that, if a reduction in daily flow does not exceed 10%, then a reasonable natural discharge allocation can be maintained that should be sufficient for ecosystem

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requirements. As a typical resource-based method, Powell et al. (2002) described a series of relationships between historic monthly inflow and the catch of various fish species, utilizing the TxEMP model to arrive at an optimized inflow–harvest relationship. In a separate study, three sea grass species sensitive to salinity changes were selected as indicators to determine the minimum required freshwater inflow for the Caloosahatchee Estuary (Doering et al., 2002). Subsequently, Robins et al. (2005) developed a framework to determine the environmental flows required to sustain estuary-dependent fisheries, whereas Arhonditsis et al. (2007) examined spatial and temporal patterns in phytoplankton communities to report ecosystem variation influenced by river flow fluctuations in the Neuse River Estuary.

In contrast to the direct links between flow and the species responses observed in experimental research, condition-based methods and habitat simulation models often incorporate preferred (i.e., optimal) habitats for target species as an intermediate step in addressing environmental flow requirements (Sun et al., 2009, 2012).For example, Jassby et al. (1995) managed freshwater inflow strategies to maintain a 2 ppt salinity habitat at a specific location in the San Francisco Bay delta. Sun et al. (2012, 2013) defined environmental flows in estuaries based on salinity and water depth simulation in critical habitats with alterations of freshwater inflows. It should be noted that diversity in ecological responses may be induced by alterations to the freshwater inflow regime caused by water use conflicts in a river basin or by serious land use contradictions in estuaries and coastal areas (Lotze et al., 2006; Alvarez-Romero et al., 2011; Langevin et al., 2005; Gattacceca et al., 2009; Milzow et al., 2010). Under conditions in which long-term monitoring data are sparse and the complex relationships between ecosystem responses and hydrological alterations are poorly understood, the method used to define or predict environmental flows in estuaries with potential variations in ecosystem structure and ecological responses to hydrological alterations (which are often influenced by human activity and climate change) has become a critical issue in ecosystem protection and sustainable development in our transformed estuaries (Sun et al., 2013; Pang et al., 2014; Adams, 2014; Acreman et al., 2014).

Rather than defining environmental flows based on typical objectives in an ecosystem protection framework, the present study offers an approach to environmental flow assessments that involves integrating the diversity requirements of potential suitable habitats for different species in an estuary. In particular, based on simulation of critical environmental factors under the action of river flows and tidal currents, variations in potential suitable habitats for typical species were mapped for different levels of the Habitat Suitability Index (HSI) using fuzzy logic. We also employed the Habitat Aggregation Index (HAI) to understand variations in potential habitats considering the internal patch structure and fragmentation of the estuarine habitat. Our approach was applied in the Yellow River Estuary, China, and strategies were proposed for environmental flow management in estuaries.

2. Methods

To define environmental flows in estuaries with complex eco-hydrological processes, we propose an approach to environmental flow assessment based on a consideration of spatial pattern variations in potential habitat suitability. The approach comprises four steps: identifying and simulating distributions of critical environmental factors for suitable habitats of typical species; mapping of suitable habitats based on the HSI and utilizing the HAI to understand the fragmentation of potential suitable habitats; defining variations in environmental flows in estuaries through trade-off analysis of different objectives for ecosystem protection; and recommending environmental flows considering the compatibility or conflicts of freshwater requirements for different species (Fig. 1).

2.1. Characterizing critical environmental factors

To date, it has proven difficult to identify all objectives for environmental flows at different temporal scales owing to scarcity of data. In the approach described here, objectives for ecosystem protection are identified by combining the requirements of habitats in critical seasons with temporal variation objectives of natural river discharge. In estuaries, habitats that are utilized during the breeding and growth periods for typical migratory species are usually located at shallow water depths. Accordingly, water depth, water temperature, and salinity for typical migratory species during pivotal life-stage seasons (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., 2012). After integrating natural flow variations into the environmental flow assessment, it is possible to define environmental flows that satisfy not only the desired ecological objectives in critical seasons but also those in other seasons, which may not be included in typical environmental flow assessments.

When investigating the responses of selected environmental factors to changes in river discharge, temporal and spatial variations in water depth, salinity, and water temperature at different locations can be simulated based on hydrodynamic and water quality models as a combined function of river discharge and tidal currents. In the present study, the Environmental Fluid Dynamics Code (EFDC)was applied to simulate the distribution of water depth, salinity, and temperature under the combined action of river inflows and tidal currents; this code has been adopted by many researchers as a simulation tool (e.g., Seo and Ahn, 2012).Based on the simulated distributions of environmental factors in the estuary, the suitability of habitats at different locations for typical species can be defined by integrating different requirements of environmental factors using fuzzy logic inference.

With temporal variations in hydrological and biological processes, environmental flows that maintain certain functions or services in ecosystems usually exhibit temporal variability at various scales. On daily or shorter temporal scales, biological processes may respond to variations in factors such as water level, river flow velocity, and water quality. Conversely, on seasonal or monthly scales, biological populations have different requirements in terms of their physical environments or habitats, and the structure and function of ecosystems may be altered by human activity or global climate change on yearly or longer scales. Considering the close relationships between hydrological and biological processes in natural ecosystems, temporal variations in natural river discharge may be used to estimate the temporal variation in environmental flows that can be considered acceptable to maintain a natural flow regime. This temporal variation can be expressed as the ratio of the monthly or daily river discharge to the annual discharge (Sun et al., 2009, 2013),

$$R_i = \sum_{j=1}^{n} W_{ji} \Big/ \sum_{j=1}^{n} W_j \quad (1)$$

where R_i is the ratio (%) of the monthly (or daily) river discharge in month i (or day i) to the annual discharge; W_j is the annual river discharge (m^3) in year j, and W_{ji} is the river discharge (m^3) in month i (or day i) of year j.