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Analyzing the effects of estuarine freshwater fluxes on fish abundance using artificial neural network ensembles

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ABSTRACT

Decreased estuarine freshwater inflow can adversely impact commercially and recreationally important fisheries as many fish species utilize estuaries during a portion of their life. To ameliorate effect on estuarine fisheries, regression models using fish catch and freshwater inflow have been implemented to determine minimum flow necessary to sustain these populations. These models typically use streamflow data, with no correction for evaporation and precipitation. Our models including evaporation and precipitation developed using artificial neural network (ANN) ensembles had nearly 50% better classification accuracy compared to regression model using flow. This ANN ensemble method was successfully applied to the Nueces Estuary in the United States. It can improve the decision-making processes of freshwater regulation and fishery management in many coastal regions.

1. Introduction

Estuaries represent the transition region between freshwater and marine systems, subjected to both terrestrial and oceanic processes by the gradients of salinity and nutrients present (Montagna et al., 2011). Estuaries are ecologically and economically important to human society, with ~16% of our food produced in the ocean, and 85% of commercially important fish species dependent on estuaries for at least one life stage (NRC, 1997). Freshwater fluxes, including freshwater inflows, precipitation and evaporation, are associated with the structure and functions of estuarine ecosystems (Gillson, 2011; Ji and Chang, 2005; Kimmerer, 2002). Amply studies have shown that estuarine water quality conditions, habitat distribution and species abundance in an estuary are sensitive to changes of freshwater fluxes (Cloern and Jassby, 2012; Koehn et al., 2011; Perez-Dominguez et al., 2012; Wikner and Andersson, 2012; Zamparas and Zacharias, 2014). Freshwater fluxes are important controls on the salinity gradient that is a critical factor for cuing reproduction as well as regulating maturation of many estuarine species (Jassby et al., 1995; Jaureguizar et al., 2004; Reyjol et al., 2007). This signal is particularly critical in shallow bays with weak connection to the ocean, where the fluctuations of salinity levels are primarily caused by the natural or manmade variations in freshwater fluxes. The regulation of freshwater inflows aimed at maintaining a preferable estuarine salinity gradient has thus become a major policy component in many coastal management strategies (Hill et al., 2011; Jassby et al., 1995; Robins et al., 2005; Sun et al., 2015; Yáñez-Arancibia and Day, 2004; Zhang and Gorelick, 2014).

Analytic methods have been substantially advanced for simulating processes of streamflow, groundwater discharge, evaporation, and storms at different scales, and examining the impacts of human interventions on such processes (Gorelick and Zheng, 2015; Moffett et al., 2015; Zhang et al., 2016; Zhang et al., 2014). The major challenge, however, lies in quantitatively translating freshwater changes to geochemical and biological responses of an estuarine ecosystem (Montagna et al., 2011). Different methods have been developed to deal with this challenge, and preference has been generally given to various statistical regression approaches and process-based hydrodynamic and ecological models that involve inflow as a component (Gillson, 2011; Kim and Montagna, 2012; Powell et al., 2002; Qiu and Wan, 2013; Robins et al., 2005; Sun and Koch, 2001; Yáñez-Arancibia and Day, 2004). However, the development, configuration and calibration of these models are often associated with substantial data requirements, time commitment and specialized personnel, which often exceeds the expectation of

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decision makers that require a quick turnaround time in comparing the impacts of different strategies.

Artificial intelligence approaches such as artificial neural networks (ANN) are an efficient tool to characterize nonlinear stress-response relationships in a variety of complex environmental systems, such as oyster norovirus outbreaks (Wang and Deng, 2016), fish abundance (Froeschke et al., 2013), $PM_{2.5}$ exposures (Di et al., 2016), occurrence of toxic algal blooms in the Great Lakes (Millie et al., 2012), and suspended sediment load (Melesse et al., 2011). These studies have shown that ANN models are an efficient data-driven method that can produce output with comparable or better performance than other methods including physically process-based models, with substantially less data and time requirements. ANN models perform best when all patterns contained in the available data are included in the training set and the models are not used to extrapolate beyond the range of the training data (Maier et al., 2010). Hansen and Salamon (1990) originally described multiple neural networks and their use as an ensemble is an effective way to improve model performance (Chan and Paelinckx, 2008; Granitto et al., 2005; Shu and Burn, 2004; Zhou et al., 2002). The ability of ANN ensembles to analyze the impacts of freshwater inflow on estuarine fish species abundance and diversity is a new application. More importantly, previous studies have not considered the combined effects of freshwater inflow, precipitation and evaporation on estuarine species. Such knowledge gaps have been a critical obstacle to the development, implementation and evaluation of freshwater polices (Buzzelli et al., 2014; Gillson, 2011; Ji and Chang, 2005; Robins et al., 2005). Without a reliable and efficient tool to determine the freshwater need of biota, ill-regulated freshwater process could result in inadequate inflow with severe damage to fishery or excessive water release that might hinder the prosperity of other water-intensive economic sectors. Ecological damage resulting from reduced food resources, such as blue-crab and fish for migratory birds such as whooping cranes or piping plovers, can be manifested by reduced reproductive success the following year (Milne, 1976).

The objectives of this study were to: (i) develop an ANN ensemble method to analyze the linkages between freshwater fluxes and estuarine fish abundance; (ii) apply this method to nine commercially and recreationally important fish species in an estuary of the Gulf of Mexico; and (iii) compare this method to statistical regression models currently used to develop freshwater polices. The findings of this study would benefit decision-making processes aimed at species that ecologically or economically valuable, improving our ability to ensure estuary health, productivity and resilience.

2. Methods and materials

2.1. Study area and data

The study area covers the Nueces Bay (177.78 km^2) and Corpus Christi Bay (37.87 km^2) of the Nueces Estuary in south Texas (Fig. 1). The estuary is separated from the Gulf of Mexico by the Mustang Island, except for a ship channel at Port Aransas and a smaller exchange point at Packery Channel. It mainly receives freshwater inflow from its major contributing river, the Nueces River, having a drainage area of 43,200 km^2. Other inflows include the Oso Creek and return flows from wastewater treatment plants and industrial water users distributed in the City of Corpus Christi and surrounding communities (total population of ∼516,000). Land use surrounded the estuary is dominated by both developed and agricultural land. The estuary has a humid sub-tropical climate with hot summers and short, mild winters. Annual average temperature is 22.3 °C and annual total precipitation is 805.9 mm. Both the Nueces Bay and the secondary Corpus Christi Bay are shallow with an average depth of 2.3 m and 3.0 m, respectively. Tidal variation is small (<1 m) and water level is responsive to meteorological forcing, especially strong winds. The average salinity across the estuary is 22 ppt. Designated by the Environmental Protection Agency as an estuary of national significance, the Nueces Estuary is ecologically and economically vital to the surrounding coastal communities, serving as a key habitat for a range of fish, shellfish and bird species. The estuary is situated in the middle of southwest-northeast gradients of rainfall, freshwater inflow and salinity along the Texas Gulf Coast (Longley, 1994; Montagna et al., 2011) and is the most southern part of the Central Flyway critical for migratory birds (Morrison et al., 1993). These birds utilize freshwater resources and spend a significant portion of their life (up to 10 months annually) overwintering. Ample high quality food resources are critical for bird survival after their arrival in south Texas and for building fat reserves to afford reproductive success after returning northward. An improved understanding of freshwater-species linkages in this estuary would provide insights into functional relationships between freshwater and ecological indicators across a broad spectrum of estuarine systems in the Gulf of Mexico and other subtropical coastal regions.

Data of freshwater fluxes were obtained from the Texas Water Development Board (TWDB) database of coastal hydrology (Schoenbaechler et al., 2011), consisting of of monthly total surface inflow to the estuary, total evaporation from the estuary surface and total precipitation on the estuary surface (Fig. 2a). Total surface inflow included observed streamflow of the Nueces River at a USGS stream gage (station ID: 08211000), simulated streamflow from ungauged drainage areas using the Texas Rainfall-Runoff (TxRR) model (Schoenbaechler et al., 2011), and reported diversion and return flows from varied water users along the estuarine shoreline. Evaporation was calculated by multiplying the total estuarine area by an estimated lake evaporation rate derived from the nearest TWDB pan evaporation station. Precipitation was calculated based on four NWS stations using Thiessen weighted polygons. As the original precipitation datasets were calculated for the whole Nueces Estuary, they were scaled to the total areas of the Nueces Bay and the Corpus Christi Bay. In 1980–2009, the average annual freshwater inflow, precipitation and evaporation were 602, 463 and 880 million cubic meters (MCM), respectively. These fluxes changed significantly at seasonal and annual levels, resulting in a highly-variable freshwater budget. For example, the standard deviation of annual inflows was larger than their mean; the maximum annual inflow (observed in 1989) was 48 times greater than the minimum annual inflow (observed in 2002). The statistics of freshwater fluxes are shown in Table 1.

Fish biomass data includes catch rates of nine important fish species that are relatively abundant in the estuaries of the Gulf of Mexico: Atlantic croaker (*Micropogonias undulatus*), Black drum (*Pogonias cromis*), Blacktip shark (*Carcharhinus limbatus*), Bull shark (*Carcharhinus leucas*), Red drum (*Sciaenops ocellatus*), Sand trout (*Cynoscion arenarius*), Sheephead (*Archosargus probatocephalus*), Southern flounder (*Paralichthys lethostigma*), and Spotted seatrout (*Cynoscion nebulosus*). Catch rate, defined as the number of a particular species caught per unit of effort (CUE), is a globally accepted index of population abundance in fishery. The data were collected by Texas Parks & Wildlife Department (TPWD) using monofilament gill nets that have been systematically deployed within the nine major bay systems in Texas since the 1970s. The gill nets were 182.88 m (600 feet) long and 1.22 m (4 feet) deep. For each spring and fall season in each bay, a number of gill nets were set out overnight with early morning retrieval (TPWD, 2016). In the Nueces Estuary, the annual total catch rate of the nine selected species was 2.91 ± 0.83 CUE. Dominant species were Atlantic croaker, Black drum, Red drum, and Spotted Seatrout, accounting for 94% of the