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Hydrodynamic behavior of the Cape Fear River and estuarine system: A synthesis and observational investigation of discharge–salinity intrusion relationships

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ABSTRACT

Transport of constituents in partially mixed estuaries depends on the relative strengths of dominant forcing mechanisms which may include tides, river input, and wind. In this study, we investigated the major physical mechanisms that influence the salinity structure in the Cape Fear River Estuary (CFRE), a partially mixed estuary that is representative of river-dominated estuaries along the southeast Atlantic coast of the U.S. Based on analysis of observed hydrographic and hydrodynamic data, we first describe differences in velocity, salinity, and stratification at along-channel sections of the estuary for relatively low-flow conditions. We then investigate the influence of river inflow on the salinity intrusion (defined by the 1-salinity contour near the bottom), based on six methods of choosing discharge in order to identify an appropriate means of incorporating flow history into the discharge value.

Our analyses indicate: 1) 92 percent of the variability in the length of the salinity intrusion over a five-year period can be explained based on the Hydrologic Flood Method identified in this work, 2) the salinity intrusion depends more weakly on discharge than predicted by classic analytical relationships for exchange-dominated systems in which the intrusion varies with discharge to the power of ($-1/3$), and 3) intra-tidal and tidal-range differences based on a 29-day modulation significantly influence the salinity structure.

Our results suggest that the salinity intrusion location is dependent upon the hydrologic "flood," defined by a peak in the river-discharge hydrograph. The analysis indicates that the new method used to determine discharge in the CFRE can more accurately explain river inflow–salinity relationships than previously investigated methods. In river-estuary systems in which hydrologic flood peaks are large relative to base flow, we hypothesize the hydrologic flood model offers a useful tool for predicting the estuarine salinity response to river inflow.

1. Introduction

Transport in estuaries depends strongly on their physical hydrodynamic characteristics. Factors including tides, river discharge, atmospheric forcing, and local geomorphology determine the transport of salt, nutrients, dissolved oxygen, and other constituents and their impact on environmental conditions. Along the North Carolina shoreline (Fig. 1, inset) differences in morphological and hydrodynamic features of estuaries may explain certain environmental characteristics of these water bodies. For example, the Neuse River Estuary is almost completely surrounded by barrier islands and represents a nearly enclosed, restricted environment in which water-level variations and circulation patterns are primarily determined by winds at short time scales and river discharge at longer time scales (Luettich et al., 2002). These factors largely determine the degree of stratification and many ecologically important quantities such as dissolved oxygen distributions (including areas of hypoxia and anoxia) (Reynolds-Fleming and Luettich, 2004).

The Cape Fear River Estuary (CFRE), in contrast, exhibits notably different morphological and hydrodynamic features (Fig. 1). The CFRE receives freshwater from the largest and most industrialized watershed in North Carolina via a major piedmont river (the Cape Fear River) and two "black-water" streams (the Black and Northeast Cape Fear Rivers) that originate in swamps high in organic material. The CFRE has a relatively open mouth that allows tidal currents to propagate well into the system including parts of riverine sections of the Cape Fear and Northeast Cape Fear Rivers upstream of

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Fig. 1. Cape Fear River Watershed.

Wilmington. The result is a partially mixed to well mixed estuary (Welch and Parker, 1979) which may share hydrodynamic characteristics of tidally energetic systems such as the Hudson River (Nepf and Geyer, 1996; Geyer et al., 2000; Bowen and Geyer, 2003), the James River (Pritchard, 1956), or Northern San Francisco Bay estuaries (Monismith et al., 1996, 2002).

While the CFRE system is generally considered non-eutrophic as a result of sufficient flushing (Ensign et al., 2004), its water quality has degraded with agricultural, industrial, and metropolitan development (Mallin, 2000; Mallin et al., 2000). Dissolved oxygen levels in the CFRE system have frequently fallen below the state standard (5 mg L^{-1}), in particular, during warm, low-streamflow summer conditions and after severe storms (Mallin, 2000; Mallin et al., 2003). Research suggests dissolved oxygen patterns in the estuary may be strongly influenced by hydrodynamic factors including the strength of density-driven flow and river inputs (Lin et al., 2006).

In order to assess the impact of anthropogenic and natural changes in a river–estuarine system, the dominant forcing mechanisms and the time scales during which they act must first be identified and understood. The purpose of this research is to provide a synthesis of the dominant physical influences on the CFRE through analysis of observed hydrographic and hydrodynamic data.

Physical forces include tides (whose associated currents advect saline water along the estuary and enhance mixing), river flow (which is a source of buoyancy, enhances stratification, and imposes a barotropic longitudinal pressure gradient along the estuary and a baroclinic pressure gradient due to density differences between salt and freshwater) and wind stress (which may act as a remote forcing in the coastal ocean or a local forcing over the estuary). Because the coastal region is characterized by estuaries in which tides and river flow are important physical mechanisms (Dame et al., 2000) and preliminary data analysis supports this characterization, this research primarily focuses on the influence of these two physical mechanisms on the estuarine salinity and circulation structure.

First, we characterize the tidal environment when river inflow is reasonably low, i.e. mean daily discharge less than 65 $m^3\ s^{-1}$, compared to mean daily discharge of about 161 $m^3\ s^{-1}$ based on a long-term (35-year flow) record on the main-stem Cape Fear River. In particular, differences in tidal excursions and salinity characteristics at along-channel sections of the estuary and variations in salinity characteristics for different temporal scales (ebb versus flood tide and low versus high tidal ranges) are discussed. Next, we investigate the influence of sub-tidal variations in river discharge on the location of the salinity intrusion including consideration of the most appropriate means of incorporating the flow history into the discharge value based on regression and hydrograph analysis. Finally, we provide a synthesis of effects of tidal and sub-tidal variability in the estuarine system and discuss the implications of our preferred discharge–salinity intrusion relationship.

2. Background

2.1. Study area

The CFRE is representative of estuaries along the southeast Atlantic coast of the U.S. in which tides and river inflow are important physical drivers (Dame et al., 2000; Mallin et al., 2000). The Cape Fear Estuary receives most of its freshwater from the Cape Fear River. The entire Cape Fear River basin (Fig. 1) extends from near Greensboro, NC, to the coastal waters south of Wilmington. Industry and agriculture are significant land uses; contaminants from non-point sources include pesticides, fertilizers, and herbicides (Mallin et al., 2000). In addition, waste from industrialized animal operations contributes to low-oxygen conditions and fish kills during intense storm events (Mallin, 2000). Three lock and dam structures that exist along the river (Fig. 1) are used to lock vessels and fish (for spawning) (Moser et al., 1998) and do not affect the general flow into the estuary.

The estuarine and lower river regions considered in this study stretch from Lock and Dam 1 (Fig. 1) to the mouth of the estuary,