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Groundwater salinity in a floodplain forest impacted by saltwater intrusion

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ABSTRACT

Coastal wetlands occupy a delicate position at the intersection of fresh and saline waters. Changing climate and watershed hydrology can lead to saltwater intrusion into historically freshwater systems, causing plant mortality and loss of freshwater habitat. Understanding the hydrological functioning of tidally influenced floodplain forests is essential for advancing ecosystem protection and restoration goals, however finding direct relationships between hydrological inputs and floodplain hydrology is complicated by interactions between surface water, groundwater, and atmospheric fluxes in variably saturated soils with heterogeneous vegetation and topography. Thus, an alternative method for identifying common trends and causal factors is required. Dynamic factor analysis (DFA), a time series dimension reduction technique, models temporal variation in observed data as linear combinations of common trends, which represent unexplained common variability, and explanatory variables. DFA was applied to model shallow groundwater salinity in the forested floodplain wetlands of the Loxahatchee River (Florida, USA), where altered watershed hydrology has led to changing hydroperiod and salinity regimes and undesired vegetative changes. Long-term, high-resolution groundwater salinity datasets revealed dynamics over seasonal and yearly time periods as well as over tidal cycles and storm events. DFA identified shared trends among salinity time series and a full dynamic factor model simulated observed series well (overall coefficient of efficiency, $C_{eff} = 0.85$; $0.52 \leq C_{eff} \leq 0.99$). A reduced multilinear model based solely on explanatory variables identified in the DFA had fair to good results ($C_{eff} = 0.58$; $0.38 \leq C_{eff} \leq 0.75$) and may be used to assess the effects of restoration and management scenarios on shallow groundwater salinity in the Loxahatchee River floodplain.

1. Introduction

Saltwater intrusion is the invasion of fresh or brackish surface water or groundwater by water with higher salinity (USGS, 2001) and has both natural (e.g., Flynn et al., 1995) and anthropogenic (e.g., Bechtol and Laurian, 2005) drivers. Saltwater intrusion can lead to rapid and catastrophic loss of coastal wetlands (Wanless, 1989), especially where several drivers act simultaneously (e.g., deep-water canals, which increase the inland extent of saltwater inflow, combined with accelerated sea-level rise, hurricanes, or severe drought) (McCarthy et al., 2001). While sea level has cycled up and down over the millennia, the coastal ecosystems currently ringing the continents have developed over a fairly stable period of sea-level rise (Wanless et al., 1994). Relatively fast-acting natural and anthropogenic drivers are currently

Abbreviations: DFA, dynamic factor analysis; DFM, dynamic factor model; GWEC, groundwater electrical conductivity; SWEC, surface water electrical conductivity; WTE, water table elevation; SWE, surface water elevation; R_{net}, net recharge; RK, river kilometer; C_{eff}, Nash and Sutcliffe coefficient of efficiency; AIC, Akaike's information criterion; POR, period of record.

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overwhelming coastal wetlands with more frequent, longer, deeper, and saltier inundation in many areas (Burkett et al., 2001). Saltwater intrusion in coastal wetlands causes plant stress or mortality from prolonged submergence and/or high salinities; erosion of wetland substrate; conversion of freshwater habitats to brackish or saltwater habitats; and the transition of coastal saltwater habitats to open water (DeLaune et al., 1994). Barlow (2003) provides a thorough review of the causes and impacts of saltwater intrusion on the US Atlantic Coast.

In systems where the causes of saltwater intrusion are primarily anthropogenic, the development of watershed and river management and restoration plans may allow ecological impacts to be minimized or reversed, and a robust understanding of hydrological dynamics is vital to assess the potential impacts of these efforts. However, the dynamics of saltwater intrusion are controlled by the interactive effects of tidal activity, the timing and volume of freshwater discharge, wind speed and direction, and density gradients caused by salinity. With diurnal tidal cycles, stochastic annual weather patterns, and decadal climate cycles, the dynamic behavior of saltwater intrusion is highly complex (Werner et al., 2013). Interactions between surface water, groundwater, and porewater in variably saturated matrices with heterogeneous soils, vegetation, and topography (e.g., Gardner et al., 2002; Kaplan et al., 2010a; Langevin et al., 2005) often make finding direct relationships between basic hydrological inputs difficult. For example, the frequency and duration of groundwater salinity exceeding a critical ecological threshold (Jassby et al., 1995) are functions of surface water elevation and salinity, tidal range, distance from the ocean, distance from the river channel, local elevation (microtopography), volume of fresh surface water flow, and the direction, volume, and salinity of groundwater fluxes (Liu et al., 2001; Melloul and Goldenberg, 1997; Wang, 1988), as well as soil hydraulic characteristics and vegetation properties.

Full-scale, density-dependent, numerical models of water table elevation and groundwater salinity such as SEAWAT (Guo and Langevin, 2002) and MOCDENS3D (Essink, 2001) can be useful for improving our understanding of physical systems (Langevin et al., 2005) and for assessing the potential effects of proposed management scenarios (Nassar et al., 2007), but require extensive subsurface stratigraphy and hydrogeology data to populate the model domain and often rely on simplifying assumptions to estimate model boundary conditions (Motz and Sedighi, 2009) and initial conditions (Lin et al., 2008). These models also focus almost exclusively on deeper groundwater systems, and may not be as useful for describing shallow groundwater, which can be in direct contact with coastal wetlands directly vía the root zone (Skalbeck et al., 2008) or through upward or lateral seepage (e.g., Gardner et al., 2002; Moffett et al., 2008). On the other hand, collection of long-term, high-resolution shallow water table elevation and salinity data can describe the dynamics (i.e., magnitude, range, daily, seasonal and interannual variation, etc.) and spatial variation of these variables (e.g., Lyons et al., 2007). However, using visual inspection and comparative statistics to develop relationships between multivariate time series can be difficult, subjective, and may not improve our understanding of the hydrological relationships that characterize the system (Ritter et al., 2007). Thus, an alternative method for sifting through complex datasets to identify possible shared trends and relationships is required.

In this study, we applied dynamic factor analysis (DFA), a multivariate times series dimension reduction technique, to investigate the complex groundwater salinity dynamics observed in the floodplain wetlands of the Loxahatchee River, a managed coastal river in southeastern Florida (USA). DFA is a statistical model, such that dynamic factor models (DFMs) produced by DFA are driven by measured data. Thus, the approach requires no a priori information about the physical system being modeled. The ability to model time series as a combination of common trends (representing unexplained variability) and explanatory variables is especially useful for analyzing complex environmental systems, where DFA can help assess what explanatory variables (if any) affect the time series of interest, and thus may be worthy of closer attention. DFA was initially developed to analyze variation in economic time series (Geweke, 1977) and was later adapted to include explanatory variables to improve understanding of variation in a variety of hydrological and ecological systems, including studies of: groundwater level and quality (Kaplan et al., 2010b; Kovács et al., 2004; Kuo and Chang, 2010; Márkus et al., 1999; Muñoz-Carpena et al., 2005; Ritter and Muñoz-Carpena, 2006; Ritter et al., 2007); soil moisture dynamics (Kaplan and Muñoz-Carpena, 2011; Ritter et al., 2009); commercial fisheries (Addis et al., 2008; Erzini, 2005; Tulp et al., 2008; Zuur and Pierce, 2004); maximum precipitation trends (Kuo et al., 2011); and most recently large-scale vegetation change (Campo-Bescos et al., 2013).

In this study, DFA was applied to study the interactions between floodplain groundwater salinity and other hydrological variables in the floodplain wetlands of the Loxahatchee River (Florida, USA), where watershed modifications and management have reduced freshwater flow and led to saltwater intrusion into historically freshwater ecosystems. This changing hydrology has been associated with a transition to salt-tolerant, mangrove-dominated communities as salt water advanced upstream (South Florida Water Management District [SFWMD], 2006). While intensive data collection and modeling efforts have been directed at developing appropriate surface water management and restoration goals (SFWMD, 2002, 2006), groundwater salinity has been largely overlooked. Thus, the specific objectives of this research are to: 1) investigate shallow groundwater salinity in the floodplain of the Loxahatchee River along several transects perpendicular to the river (from upriver, freshwater areas through downriver, tidal areas) and 2) apply DFA to investigate interactions between the groundwater salinity time series and other hydrological variables to identify (a) important common trends among the series and (b) external hydrological factors that most fully explain observed variation in the time series.

2. Materials and methods

2.1. Study site and experimental setup

The Loxahatchee River is located on the southeastern coast of Florida, USA (26° 59′ N, 80° 9′ W; Fig. 1) and was