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Off-river waterbodies on tidal rivers: Human impact on rates of infilling and the accumulation of pollutants

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ABSTRACT

Cut-off meanders, backwater ponds, and blocked valley coves are all common features along the tidal reaches of lowland rivers. While significant progress has been made to understand sediment dynamics in similar off-river environments above the head of tides, less is known about the processes driving transport and sedimentation within these systems when tidally influenced. To provide insight we combine sedimentological observations with flux analyses for a series of tidal off-river waterbodies along the Lower Connecticut River spanning the river's entire 100 km tidal reach. Sedimentation rates exhibit a clear seaward increase with growing tidal influence, and are an order of magnitude higher than accumulation rates obtained previously from neighboring marsh and subtidal environments. A simplified mass balance can relate time-series measurements of water level and suspended sediment concentration to observed trends in sedimentation, and support flood-dominated asymmetry in tidal sediment flux (i.e. tidal pumping) as the primary mechanism for enhanced trapping. Relatively steady rates of deposition are observed in off-river waterbodies over the last century, with little evidence of deposition dominated by extreme events. Suspended sediment concentrations rise significantly in the main tidal river with increasing river discharge, while tidal range is damped with rising freshwater flow. The net result is an optimal freshwater discharge for maximizing the tidal pumping of sediment from the main river into tidal off-river waterbodies, with more routine discharge events largely responsible for driving long-term trends in deposition. A sudden shift in lithology towards more inorganic, fluvial derived sediment is commonly observed towards the end of the 19th century, along with over an order of magnitude increase in the rate of deposition. The timing of the onset of rapid infilling occurs contemporaneous with the documented creation and/or deepening of tidal tie-channels, followed shortly after by a rapid rise in heavy metal concentrations related to industrial activity along the river. Results point to the creation and routine maintenance of tidal inlets increasing the connectivity of off-river waterbodies to the main tidal river in recent centuries, and enhanced sediment trapping along the floodplain at the most favorable time for capturing legacy contaminants introduced during the industrial era.

1. Introduction

Understanding how sediment is transported, trapped, and remobilized in low-lying rivers and their respective estuaries is of broad geomorphic significance, fundamental to quantifying river inputs to the ocean, constraining internal inventories, and predicting the evolution of low gradient landscapes (e.g. Meade, 1982). A great deal of research describes the transport and trapping of sediment along low-lying rivers at locations above the tidal reach (e.g. Allison et al., 1998; Aalto et al., 2008; Day et al., 2008; Swanson et al., 2008), and further downstream within the brackish waters of an estuary (e.g. Geyer et al., 2001; Woodruff et al., 2001; Klingbeil and Sommerfield, 2005; Galler and Allison, 2008; Ralston and Geyer, 2009). By comparison, less is known about the mechanisms for transport and storage between these two environments within the freshwater tidal river, or the perimarine zone (e.g. Hageman, 1969; Plater and Kirby, 2006). This freshwater tidal reach can constitute a significant portion of a low-gradient river's overall extent, particularly for low-lying rivers along the eastern seaboard of North America, where tides frequently extend upriver from the mouth on the order of 100-to-200 km (Fig. 1).

The predominant location for long-term (decadal-to-centennial), fine-grained storage in a river above the head of tides (tidal limit) is often considered to be the floodplain, (e.g. Trimble, 1983; Allison et al., 1998; Goodbred and Kuehl, 1998; Walling et al., 1998, 1999),

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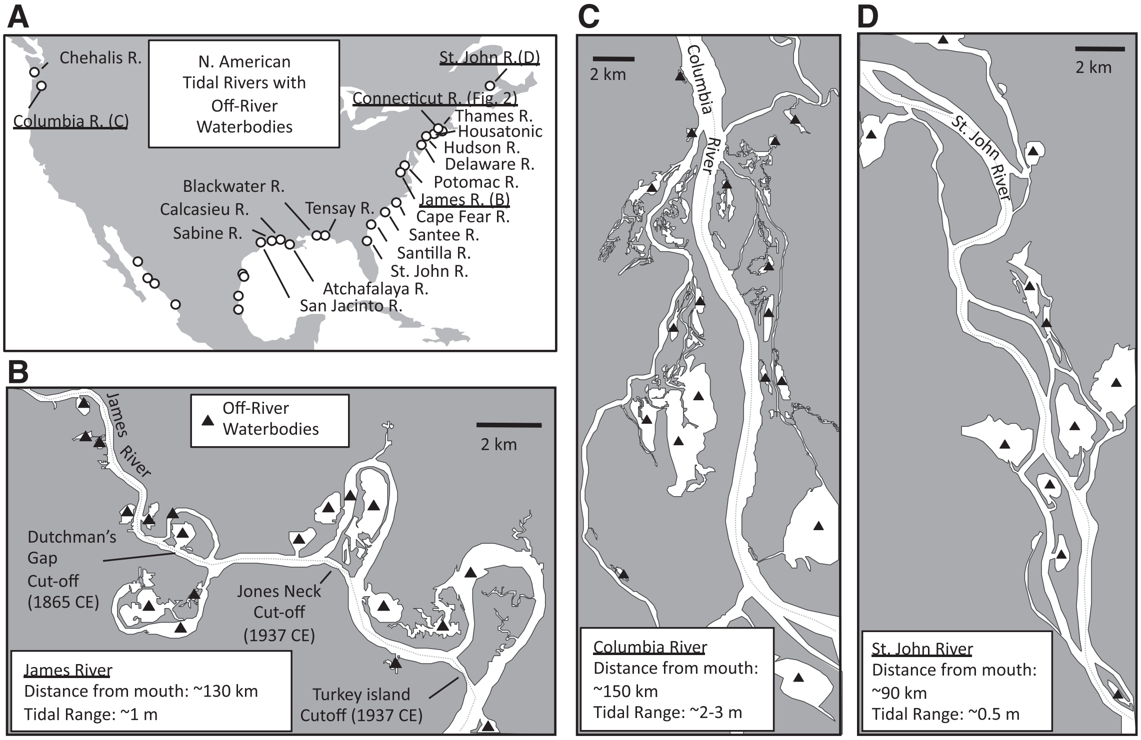

Fig. 1. (A) North American map showing the distribution of tidal rivers with known off-river waterbodies. Portions of rivers underlined in (A) are enlarged in (B), (C), (D), and Fig. 2. Off-river waterbodies in B–D are identified with triangles. A number of the most prominent off-river waterbodies along the James River (shown in B) are man-made, due to navigation cut-offs beginning in the mid-1860s.

where sediment is transported and trapped primarily during seasonal high river discharge events (e.g. Wolman and Miller, 1960; Mertes, 1994; Walling et al., 2003). In contrast, provided that an estuary has sufficient accommodation space, significant amounts of fine-grain sediment can also be trapped and stored within the estuarine channel itself, both seasonally (e.g. Woodruff et al., 2001; Traykovski et al., 2004; Galler and Allison, 2008) and on decadal and centennial time scales (e.g. Klingbeil and Sommerfield, 2005). Similar to locations above the influence of tides, non-ephemeral depocenters of fine-grained sediment within the fresh water tidal reach are generally located along the floodplain rather than the channel itself (e.g. Patton and Horne, 1992; Varekamp et al., 2003), in part because the main channel often lacks the accommodation space required for significant amounts of long-term, fine-grained sediment storage.

Off-river waterbodies, such as cut-off meanders, backwater lakes, and drowned valley coves serve as prominent depocenters for the focused sedimentation of fine-grained sediment along the floodplain, primarily because these systems present significantly more vertical accommodation space than neighboring subaerial wetland environments. These floodplain waterbodies function as unique and essential habitats for flora and fauna (e.g. Simpson et al., 1983), provide sheltered harbors and recreational areas (e.g. Maloney et al., 2001; Jacobs and O'Donnell, 2003), serve as an important sink for nutrients, organic carbon and associated contaminants (e.g. Bubb et al., 1991, 1993; Loomis and Craft, 2010), and are a key ecohydrological component of the perimarine floodplain (e.g. Plater and Kirby, 2006). Critical to managing all of these important functions is an understanding of the mechanisms by which off-river waterbodies infill.

A number of recent papers have provided valuable insight into the processes governing the transport and trapping of material in floodplain waterbodies when located in a strictly fluvial environment (Rowland et al., 2005; Day et al., 2008; Constantine et al., 2010). These works highlight the importance of seasonal discharge events to the infilling of these environments. They also emphasize the significance of tie-channels that connect off-river waterbodies to the main river, and the important role these tie-channels play in diverting sediment loads from the main river to the floodplain.

Off-river waterbodies are also prevalent along the tidal reach of many of low-lying rivers throughout the world, and are particularly prominent along the western Atlantic Slope (e.g. Fig. 1). Here we provide a new empirical data set for understanding how these tidal off-river waterbodies infill. More specifically the study is focused on assessing: i) the relationship between tidal magnitude and rates of infilling, and ii) how human alterations to tidal off-river waterbodies have affected sediment trapping in recent centuries.

2. The Connecticut River

Examples of notable North American rivers that contain prominent tidal off-river waterbodies are presented in Fig. 1 and include (with the length of their approximate tidal reaches in brackets): the Saint John River in New Brunswick, Canada [140 km], the Connecticut River [100 km], the Hudson River [250 km], the Delaware River [200 km], the Potomac River, [164 km], the James River [160 km], the Santee River [60 km], the St. John River in Florida [180 km], the San Jacinto River [260 km], and the Columbia River [220 km]. In particular, the lower reach of the Connecticut River exemplifies a system with prominent tidal off-river waterbodies (Fig. 2). The river has long been recognized for its extended tidal environment, dating back to its early documented history when Native Americans originally referred to the Connecticut as "Quinnetukut," meaning long tidal river (Horne and Patton, 1989). Tides begin at the mouth of the river at Long Island Sound with a semi-diurnal range of 1.1 m, and propagate upstream roughly 100 km to just below Thompsonville, CT (Fig. 2A). A majority of the tidal river is fresh, with the salinity intrusion typically extending up the estuary 5 to 15 km during periods of high and low river discharge, respectively (Garvine, 1975; Howard-Strobel et al., 1996).

Estimates of total fine grain sediment load for the river range from 250,000 tonnes/yr (Milliman and Farnsworth, 2011) to 760,000 tonnes/yr (Patton and Horne, 1992), of which a sizable