TRACING THE SOURCES, FATE, AND RECYLING OF FINE SEDIMENTS ACROSS A RIVER-DELTA INTERFACE

Corresponding author

Anna M. Jalowska
Department of Marine Sciences, The University of North Carolina at Chapel Hill
3117Y Venable Hall; Campus Box 3300 Chapel Hill, NC 27599-3300
annajalo@gmail.com
Phone number: 001.919.641.5169
Fax number: 001.919.962.1254

Author names and affiliations

Anna M. Jalowska
Department of Marine Sciences, The University of North Carolina at Chapel Hill
3117Y Venable Hall; Campus Box 3300 Chapel Hill, NC 27599-3300

Brent A. McKee, bamckee@email.unc.edu
Department of Marine Sciences, The University of North Carolina at Chapel Hill
3117J Venable Hall; Campus Box 3300 Chapel Hill, NC 27599-3300

J. Patrick Laceby, placeby@lsce.ipsl.fr
Laboratoire des Sciences du Climat et de l'Environnement (LSCE/IPSL) – Unité Mixte de Recherche 8212 (CEA, CNRS, UVSQ),
91198-Gif-sur-Yvette Cedex, France

Antonio B. Rodriguez, abrodrig@email.unc.edu
Institute of Marine Sciences, The University of North Carolina at Chapel Hill
3431 Arendell St., Morehead City, NC 28557

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Abstract

Deltaic floodplains are thought to be long-term depositional environments, however there remains a limited understanding regarding timescales of depositional and erosional events, sediment delivery pathways and sediment storage. This study uses sediment concentration and sediment fingerprinting to examine the contribution of surface and subsurface sources to suspended sediment transiting the Lower Roanoke River, North Carolina, United States. The Lower Roanoke is disconnected from its high-gradient uplands in the Piedmont and Appalachian Mountains by a series of dams, which effectively restricts suspended sediment delivery from the headwaters. Accordingly, sediments from the Lower Roanoke River basin are the primary source of suspended sediment downstream of the dams. The fingerprinting method utilized fallout radionuclide tracers ($^{210}Pb_{xs}$ and ^{137}Cs) to examine the spatial variation of sediment-source contributions to suspended-sediment samples (n=79). Three end-member sources were sampled: 1. surface sources (floodplains and topsoils; n=60), 2. subsurface sources (channel bed and banks; n=66), and 3. deltaic sources (delta front and prodelta; n=11).

The results demonstrate that with decreasing river slope and increasing influence of estuarine-driven flow dynamics, the relative contribution of surface sediments to the suspended-sediment load increases from 20% (±2%) in the upper reach, to 67% (±1%) in the Roanoke bayhead delta (BHD). At the river mouth, the surface-sediment contribution decreases, and the delta front and prodelta sediments contribute 74% (±1%) to the suspended load. These results indicate, that during the delta transgression, erosion of the lower delta provides an additional source of sediment to the upper delta. At the same time, the lower deltaic plain, considered a

sediment sink and long-term sediment-storage site, becomes erosional. The lower river and distributary network of the delta plain, which were thought to only disperse sediments in a seaward direction, may also have an important landward-directed sediment-dispersal component that provides nourishment and fortification to the upper BHD, at the cost of the eroding lower delta. Recognition of these contrasting sediment pathways in the Roanoke River highlights that these complex bidirectional processes may exist in other eroding deltas. Understanding these bidirectional processes will be necessary for the ongoing management of deltaic environments under increasing anthropogenic stress such as land use change and accelerating sea-level rise.

1. Introduction

Rivers transport particulate and dissolved materials from land to the ocean. The delivery of sediments to the coastal zone may not be direct, since sediment-transport pathways vary across temporal scales (Trimble, 1983; Walling, 1983, Harvey, 2002; Fryirs et al., 2007; Mattheus et al., 2009). Rivers transfer biogeochemically-important materials, many of which are associated with particles, including particulate carbon, nutrients, trace elements and contaminants. Furthermore, the suspended-sediment load provides essential material for building and fortifying coastlines (Blum and Roberts, 2009; Mattheus et al., 2009; Syvitski et al., 2009; Gunnell et al., 2013; Nittrouer and Viparelli, 2014).

Previous studies demonstrate that a large fraction of riverine-particulate material is transported during the rising limb of the hydrograph and is stored during the falling stages (Meade et al., 1985; Dunne et al., 1998). Globally, over 20 Pg of particulate material is transported every year by rivers (Meade, 1996); however, approximately 80-90% of the sediment eroded annually is trapped in alluvial and colluvial systems, before being delivered to the ocean (Meade et al., 1990). Particulate material may thus spend a large amount of time stored within the river system, specifically in channels and floodplains. While the spatial and temporal scales for trapping and storing particulate materials are not well quantified (Hupp, 2000), previous studies indicate that most sediment storage occurs within reservoirs, floodplains, deltas and estuaries (McKee et al., 2004, Kondolf et al., 2014). Materials in floodplains, river banks and channels can be remobilized, along with their associated constituents (e.g. carbon, nutrients and pollutants) (Hupp et al., 2015). In the lower river, channel morphology and flow change dramatically in a downstream direction, which influences sediment-transport pathways. Channels widen, channel-levee relief decreases, causing more frequent floodplain inundation, channels bifurcate into distributary networks, and the influence of water-level fluctuations in the basin on flow velocity and direction increases. Although floodplains are considered to be long-term depositional environments (Wolman and Leopold, 1957; Fryirs et al., 2007), there remains a limited understanding regarding timescales of depositional or erosional events, sediment-delivery pathways and sediment storage within bayhead delta plains (O'Connell et al., 2000). Extending knowledge regarding sediment processes in these environments would improve estimates of material fluxes to the ocean, and improve our understanding of the role that lower-river environments play in global carbon and nutrient cycles.

Over half of the world's largest river systems have been moderately to strongly impacted by dams (Nilsson et al., 2005), which often results in downstream sediment starvation, reducing further sediment delivery to the lowlands, deltas and estuaries (Meade et al., 1990; Kondolf, 1997; Vörösmarty et al., 2003; Syvitski and Milliman, 2007). Sediment retention in reservoirs has been linked to the deterioration of large deltaic systems, such as the Yangtze (Yang et al., 2011; Dai et al., 2013), Nile (Gu et al., 2011) and Mississippi rivers (Blum et al., 2009), and also small deltaic systems, such as the Roanoke River (Jalowska et al., 2015). Flow regulations eliminate the lowest and highest peaks from hydrographs, and limit overbank flows, decreasing connectivity between river channels and floodplains (Hupp, 2000; Hupp et al., 2009). Another downstream impact of dams is channel incision and subsequent channel widening through bank erosion. Consequently, below the lowest dam, the dominant sediment source of the river's suspended load changes as the influence of the dam on the graded stream profile, and the flow regime, decreases. While the physical processes behind these changes are documented, the sediment pathways and their transformation along the river gradient, including the river delta, are unknown. Accordingly, here we investigate sediment sources, pathways and sinks by monitoring total suspended matter concentrations of the river load, conducting cartographic analyses of the river basin, analyzing sediment grain-size, imaging the riverbed and applying a sediment fingerprinting technique to trace different sources. Results regarding sediment pathways and their cycling thorough the entire river-delta system are important for coastal-erosion management (flooding and erosion), dam adaptive management, and management of deltaic environments under increasing anthropogenic stress such as land use change and accelerating sea-level rise.

2. Background

2.1 Study Area

The Roanoke River was selected for this study as the history of natural and anthropogenic modifications to the system are well documented (Hupp et al., 2009; Schenk et al., 2010; Jalowska et al., 2015). The Roanoke River originates in the Valley and Ridge Province of the Appalachian Mountains in Virginia and drains into the west end of Albemarle Sound at an average annual rate of 252 m^3/s (Giese et al., 1979; Molina, 2002). The total drainage area of the River is 25,123 km^2. Albemarle Sound and the Roanoke bayhead delta (BHD) are located in Northeastern North Carolina (Figure 1). The Sound is separated from the Atlantic Ocean by the Northern Outer Banks barrier-island chain. Direct water exchange with the ocean has been minimal since the closing of a tidal inlet in 1833, and present exchange with the adjacent Pamlico Sound is possible only through narrow Croatan and Roanoke sounds (Jalowska et al., 2015). As a result, the salinity of Albemarle Sound is variable, being 5-15 ppt in the east, 0.5-5 ppt in the middle and < 0.5 ppt in the west, at the mouth of the Roanoke River (NOAA SEA Division, 1998). Albemarle Sound is a wind-driven estuary, and astronomical tides are negligible near the Roanoke BHD (Giese et al., 1979; Riggs and Ames, 2003; Jalowska et al., 2015). At the mouth of the Roanoke River, cyclical daily fluctuations in water levels, up to 0.6 m, have been associated with wind stress and seiching (Luettich et al., 2002).

The Lower Roanoke River is 220-km long and drains an area of 3,392 km^2 (Figure 1). The Atlantic Seaboard Fall Line is considered the western boundary of the Lower Roanoke River, as it is almost completely disconnected from the upper reaches by a series of dams located above the fall line (Figure 1). The elevation gradient of the Lower Roanoke is steepest (ca. 0.25%) from the fall line to 13 km downstream. Below that point to the BHD, the river gradually loses only 8 m of elevation. The low-gradient river facilitated the formation of an extensive, up to 9 km wide, floodplain extending from 80 km below the fall line to the BHD.

The Roanoke River watershed and Albemarle Sound have been impacted by European settlement in North America since the late 1600's AD. Between 1600 and 1900, intensive land clearing and primitive agricultural practices caused widespread erosion. Accordingly, sediment accumulated in the Lower Roanoke floodplains, banks and channel as a distinct, up to 10-meter thick layer of fine (<63 μm), orange-stained legacy sediments (Wolman, 1967; Jacobson and Coleman, 1986; Hupp et al., 2009; James, 2013, Jalowska et al., 2015), and formed the Roanoke BHD (Jalowska et al., 2015).

Before 1947, the water level and flow of the Lower Roanoke River was characterized by extreme variability in response to changes in precipitation over seasonal and event (storms) time scales (Richter et al., 1996). Between 1947 and 1963, three dams were constructed, with the most seaward dam at Roanoke Rapids completed in 1955. Dam-controlled water releases altered the hydrologic regime of the river by eliminating both the highest and lowest-magnitude flows (Richter et al., 1996; Jalowska et al., 2015). Removing high-magnitude flows caused a reduction of the hydrological capacity of the river, and the connectivity between the channel and floodplains. Additionally, the frequency of medium-magnitude flows increased over six times, which caused an increase in bank erosion (Hupp et al., 2009).

After construction of the dams, sediment delivery to the Lower Roanoke and ultimately Albemarle Sound was reduced by 99% (Simmons, 1988; Meade et al., 1990) (Figure 2), leaving the Lower Roanoke banks, channels and floodplains, which are filled with legacy sediments, as a dominant source of sediments. Previous studies in US Piedmont watersheds (Gellis et al., 2009; Devereux et al., 2010; Mukundan et al., 2010) have grouped sediment sources into two categories: surface sources, which are mainly eroded soils delivered to the river with runoff, and subsurface sources, which are associated with bank/channel and gully erosion. Hupp et al. (2009) and Schenk et al. (2010) measured bank erosion and floodplain deposition in the upper and middle reaches of the Lower Roanoke River, below the dam, using erosion pins and clay pads, respectively. The study showed that the rate of bank erosion, a subsurface sediment source, is between 0-52 cm/yr, and is most pronounced along banks >2 m high in the middle reaches of the Lower Roanoke, and then decreases downstream (Hupp et al., 2009; Schenk et al., 2010). Similar results were found in other watersheds in the region, such as in the Chesapeake Bay Watershed (Gellis et al., 2009) and North Fork Broad River, GA (Mukundan et al., 2010).

Although sediment delivery to the Lower Roanoke River and Albemarle Sound decreased after construction of the dams, floodplain deposition increased downstream of the Roanoke Rapids Dam to a maximum of 90 mm/yr recorded at the upper limits of the BHD (Schenk and Hupp, 2008, Hupp et al., 2015). That rate of floodplain deposition is comparable to sedimentation rates reported for the BHD of 20-80 mm/yr by the Environmental Protection Agency (2008) and 28-88 mm/yr measured by Jalowska et al. (2015). Jalowska et al. (2015)

reported landward movement of the Roanoke BHD shoreline, a sedimentological shift in the prodelta over the last century from depositional to non-depositional or erosional, and floodplains proximal to Albemarle Sound being net erosional. Those measurements suggested that delta retreat was associated with sea-level rise and a decrease in sediment supply resulting from improved agricultural practices and damming in the watershed. A variety of methods were utilized in this current study to investigate possible changes in river-sediment source downstream from the Roanoke Rapids Dam and upstream from the eroding BHD front.

2.2 Sediment fingerprinting approach

Tracing suspended sediment in river catchments requires identification of the various sediment sources and fates (Oldfield et al., 1985, Collins et al., 1998; Davis et al., 2009). Sediment fingerprinting assumes that a set of biogeochemical and/or physical sediment properties provide a unique signature allowing investigators to calculate the relative sediment contribution from various sources (Davis et al., 2009). Importantly, the set of unique properties should not change during erosion, transport and deposition, or should change in a predictable way (Motha and Wallbrink, 2002, Laceby et al., 2015).

The use of fallout radionuclide tracers, particularly ^{137}Cs and ^{210}Pb$_{xs}$ is common in sediment fingerprinting (Walling and Woodward, 1992; Olley et al., 1993, 2013; Wallbrink et al., 1998, 1999; Walling et al., 1999). ^{137}Cs ($t_{1/2}$=30y) is present in the environment as a result of fallout from the testing of nuclear weapons, primarily from 1954–1968. In natural areas, watershed surface soils are enriched in ^{137}Cs (Olley et al., 2013) because of direct exposure to the fallout. In agricultural areas, the surface soil values may be lower than undisturbed soils, due to mixing associated with tillage. Consequently, the absence of ^{137}Cs indicates that sediments were not derived from sources that were exposed to fallout, such as subsurface sources. ^{137}Cs is strongly associated with particles in fresh-water environments, while in saline environments ^{137}Cs desorbs from particles (Olsen et al., 1989, Hong et al., 2012). During the sampling period, the most seaward sampling site- the delta front/prodelta - always recorded a salinity of 0 ppt (measured in-situ), thus the restraints associated with a potential ^{137}Cs desorption do not apply. Accordingly, this study region provides a unique environment to apply a sediment fingerprinting approach in a freshwater-deltaic environment.

^{210}Pb ($t_{1/2}$=22y) is a naturally-produced radionuclide, formed by the decay of ^{238}U, which is present in the Earth's crust (Curie et al., 1898; Rutherford, 1904). It has two pathways of becoming associated with lithogenic particles. First, is the in-situ contribution through the ^{238}U decay chain in the particle's matrix referred to as background ^{210}Pb. Second, is through wet and dry fallout, associated with the escape of ^{222}Rn (also part of the ^{238}U decay chain) from soils to the atmosphere, and its decay to ^{210}Pb, referred to as the 'excess' ^{210}Pb ($^{210}Pb_{xs}$) after its subsequent fallout. Surface soils have high $^{210}Pb_{xs}$ values, due to recent exposure to the fallout, while subsurface sources typically have low $^{210}Pb_{xs}$ activities (Walling and Woodward, 1992). In this study, the prodelta/delta front sediments have very low $^{210}Pb_{xs}$ activities because of the erosional state of the environment. The pro-delta sediments were deposited prior 1875 AD but have patches of younger sediments flushed from the river system during a hurricane in 1940 (Jalowska et al., 2015).

3. Methodology and Sampling

3.1 Land use, Elevation, Stream Discharge, and Total Suspended Matter

The slope of the river and channel width were measured using a digital elevation model (DEM; 6 m grid-cell spacing) obtained from NC DOT-GIS Unit (North Carolina Department of Transportation, 2003) and processed in ArcMap software (ESRI (Environmental Systems

Resource Institute), 2015). Land use in the Lower Roanoke watershed was obtained from the Earth Satellite Corporation land cover dataset (Earth Satellite Corporation (EarthSat), 1997) and mapped using ArcMap software (ESRI (Environmental Systems Resource Institute), 2015) (Figure 1B, Table 1).

Discharge data for the Roanoke River USGS station at Roanoke Rapids (station number 02080500), and gage height data for Hamilton (station number 02081028), Williamston (station number 02081054), Jamesville (station number 02081094) and NC45 NR Westover, NC (station number 0208114150, located downstream from Plymouth) were obtained from the USGS Water Data website (United States Geological Survey, 2012) (Figure 1). These data were used to calculate minimum, maximum and average water levels at the stations. To understand the influence of the dam on the hydrology downstream, hydrographs for stations in Hamilton, Williamston, Jamesville and Plymouth were compared to the hydrograph from Roanoke Rapids, and the correlation coefficients between discharges from Roanoke Rapids and water level at each station were derived for the sampling period (Table 2).

Total suspended matter (TSM) concentrations were measured between February 20th 2009 and November 16th 2013 at 11 locations in the Lower Roanoke River (Figure 1B). To measure TSM concentrations, river water samples were collected periodically (every two weeks-3 months) in 1 L, acid-cleaned bottles at each station, and vacuum-filtered through pre-weighed 0.22 μm, nitrocellulose filters. After filtering, samples were flushed with 1L of deionized water. The filters were then dried in a 40^{o}C oven for 48h, and weighed again. TSM concentrations were recorded as mg/L.

Despite its local importance, no continuous record of suspended-matter concentrations exists for the Roanoke River. Previous studies provided single sets of measurements (Meade et al., 1990; Alexander et al., 1998), and used Secchi disk observations as a proxy for suspended-matter concentrations (Hupp et al., 2009; Schenk et al., 2010). Non-continuous, historical data of suspended matter concentration were obtained from the EPA STORET website (United States Environmental Agency, 2007), and used to validate results from this study (stations and time periods are listed in Table 3).

3.2 Collection, Sampling Frequency and Processing of Fluvial Deposits

Sediment samples (n=245) were collected mostly in calm weather conditions and no sampling occurred during event conditions (e.g. tropical storms). Between February 2009 and March 2012, materials from subsurface (86 samples) and surface (60 samples) sources were collected from both erosional and depositional environments, including: floodplains (surface; n=58), agricultural topsoils (surface; n=2), river-channel beds (subsurface; n=17), banks (subsurface; n=33), and gullies (subsurface; n=16; Figure 3). The eroding delta front and prodelta were categorized as a separate suspended sediment source and sediment from these environments was collected at the river's mouth (n=11). Samples from floodplains, agricultural fields and dry gullies were collected by integrating the top 30-mm layer of short 100-mm diameter cores. Subaqueous samples from the channel bed and submerged banks were collected with a bottom grab sampler or in short 100-mm diameter cores. In both cases, the top 30-mm layer was integrated into a sample. Samples from the banks were collected with a spatula, and similarly to the other sources, the top 30-mm layer of sediment was integrated into a sample. Suspended sediment samples (n=78) were collected at 13 locations, 8 of which were at USGS water-level monitoring stations (Figure 1A). USGS stations in Jamesville, Williamston and Plymouth were sampled biweekly for bulk suspended sediment and sediment concentration. The remaining sampling stations were sampled bimonthly or annually due to limited accessibility

(Figure 1A and B). Water samples for suspended sediment were collected in 70 L acid-cleaned plastic carboys, and particles were harvested from the water through continuous flow centrifugation.

3.3 Grain-size Distribution and Side Scan Sonar Data

Channel sediment subsamples (n=56) were analyzed for grain size using a CILAS 1180 to measure particle sizes from 0.04 to 2500 mm in 100 size classes by laser diffraction. Grain sizes were binned into coarse (>62μm), and fine (<62μm) classes.

To explore the subaqueous geomorphology of the Roanoke River channel, side-scan sonar data were collected using an Edgetech 4200 dual-frequency (120/410 kHz) system. Data were collected using 410 kHz, at a 50-m range and in a discontinuous grid pattern. Data were processed by applying a time-varying gain and mosaicked using Chesapeake Technology Inc. SonarWiz software.

3.4 Radionuclide Analyses

Bulk sediment samples were freeze-dried, subsampled for grain-size analyses, packed into standardized vessels and petrie dishes, and sealed for three weeks to allow ^{222}Rn equilibration. Radionuclide tracer activities were measured by gamma spectrometry. Gamma counting was conducted on one of four low-background, high-efficiency, high-purity Germanium detectors (Coaxial-, BEGe-, and Well-types) coupled with a multi-channel analyzer. Detectors were calibrated using a natural matrix standard (IAEA-300) at each region of interest in the standard counting geometry for the associated detector. Activities were corrected for self-adsorption using a direct transmission method (Cutshall et al., 1983). Total ^{210}Pb and ^{137}Cs activity was directly determined by measuring the 46.5-KeV and 661.64-KeV gamma photopeaks respectively. To calculate the $^{210}Pb_{xs}$ values, a background ^{210}Pb activity was subtracted from total ^{210}Pb activity. The background levels of ^{210}Pb (^{226}Ra activity) were determined by measuring the gamma activity of ^{226}Ra granddaughter ^{214}Bi (609 KeV).

3.5 Mixing Model

A common method used in modeling the relative contribution of endmembers to the observed suspended load is a multivariate mixing model (Haddadchi et al., 2013). In this study, we used a distribution modelling approach, proposed by Laceby and Olley, (2015), that quantifies source contributions through minimizing mixing model difference (MMD) when solving Equation 1:

$$MMD = \sum_{i=1}^{n} \left| \left(C_i - \left(\sum_{s=1}^{m} P_s \, S_{si} \right) \right) / C_i \right| \qquad (1)$$

where n is the number of tracers included in the model; C_i is the normal distribution of tracer parameters ($_i$) in the suspended sediment sample; m is the number of sediment sources used in the model; P_s is the percentage contribution of the sediment source ($_s$); S_{si} is the normal distribution of the tracer parameter ($_i$) in the sediment source ($_s$). The proportional contribution from each source (P_s) was modelled as a normal distribution ($0 \leq x \leq 1$) with a mixture mean (μ_m) and standard deviation (σ_m) (Caitcheon et al., 2012; Olley et al., 2013, Laceby and Olley, 2015).

Haddadchi et al., (2014) reported that this is one of the more accurate modelling approaches. Further, the use of tracer-specific correction factors (Collins et al., 1996) or an individual source elemental concentration correction factor (Collins et al., 2010, 2012) were not found to improve model performance (Laceby and Olley, 2015). Thus, these correction factors were not included in the model.

Prior to modelling, $^{210}Pb_{xs}$ and ^{137}Cs were tested for non-conservativeness, to ensure sediment radionuclide concentrations plotted within the source concentration range (Collins et al., 1996). The mean and standard deviation of each source and in-stream sediment tracers were used to define their normal distributions. To incorporate the tracer distributions, the mixing model was optimized with the OptQuest algorithm that is a part of Oracle's Crystal Ball software (Oracle, 2015). The OptQuest algorithm is used to search for, and find optimal solutions in Monte Carlo simulation models.

With this software, each source's contribution (P_s) distribution (both μ_m and σ_m) was repeatedly varied when simultaneously solving Equation (1) 5000 times with 5000 stratified samples drawn from each suspended sediment (Ci) and source (S_{si}) distribution. The median MMD was minimized in the model when solving Equation (1). A constraint for the optimization was that the sum of the proportional contributions of the sources (P_s) must equal one. This process of deriving the optimal source contribution mixture distribution (P_s) for all 5000 randomly-generated simulations was repeated 5000 times. The median P_s from these additional 5000 simulations is reported as the source contribution. Source-contribution uncertainty was calculated by summing modelled standard deviation of the mixture, plus the median absolute deviation (MAD) of the modelled standard deviation for an additional 5000 simulations, plus MAD of the individual sources median proportional contribution for 5000 simulations (Laceby et al., 2015).

4. Results

4.1 Land cover, discharge and Total Suspended Matter Concentration

Results demonstrate that land cover for the Lower Roanoke River basin is 39% forest and shrubs, 33% wetlands and water bodies, 27% cultivated and 1% urban (Figure 1, Table 1). Land proximate to the river channel is mostly forested floodplain and connectivity with the cultivated and urban parts of the watershed is limited.

The river elevation changes from 66 to 0 meters above sea level (MASL) (NAD1983) over the entire 152-km distance below the Roanoke Rapids Dam (Figure 4). TSM concentration increases along the river's highest gradient, between the dam and km 105 (Figure 4). Below that marker, the concentration of TSM gradually decreases. TSM concentrations slightly increase again around the eroding delta front/prodelta. Data collected during the study period are consistent with the data recorded by the EPA (Figure 4).

The Roanoke River water level time series at each of the sampling stations were compared to water levels at the Roanoke Rapids Dam. The derived correlation coefficients (r expressed as a percentage) were used to examine the primary forcing mechanisms of water-level fluctuations in the Roanoke River. Between the Roanoke Rapids Dam and Hamilton, water level was controlled by dam releases over 91% of the study period (Figure 5). When the river reaches the elevation of 0 MASL, dam releases become less of a controlling factor for the water level. The water level at Williamston (km 155, elevation 0 MASL) is controlled by dam releases 88% of the time, and nearby at Jamesville (km 186, elevation -1 MASL), water level is controlled by dam releases only 69% of the time. The Jamesville transition marks the upstream boundary of the BHD. Decreasing influence of the dam on water levels, in a downstream direction, with a concurrent lack of tributaries, suggests the dominance of other controls on water level, such as changes in channel and floodplain morphology, which implies an increase in connectivity between the river channel and floodplains. The river widens seaward from Jamesville (Table 3). The influence of water-level fluctuations in Albemarle Sound (i.e., wind stress and seiching) on water level in the river also becomes more pronounced downstream, and is a major forcing factor at Plymouth (km 208, elevation -1 MASL), where the correlation with discharges from the dam decreases to 12% of the time (Figures 4 and 5) (Table 2). Indeed, the hydrograph at Plymouth shows a seasonal pattern and semi-diurnal fluctuations in water level, suggesting that wind stress and seiching from Albemarle Sound is the primary forcing mechanism for water-level fluctuations at the BHD. These changing controls of river flow likely influence sediment sources and pathways in the Roanoke River system.

4.2 Spatial distribution of channel-bed sediment classes

Grain size analyses of the channel sediments show a clear, 10-km long transition between the Lower Roanoke River and the BHD (Figure 6). Channel-bed sediments between river km 150 and 186 are composed of ~80% coarse material (fine sands). Along this reach, riverbanks, channel walls and the beds of rills and floodplain channels are composed of >70% fine-grained material. At km 180, the grain size of the channel bed sediment starts decreasing, and the channel bed below km 190 is composed of <20% sand. The shift in bottom-sediment type was also examined with side-scan sonar data, showing the presence and absence of channel bed forms upstream and downstream, respectively. The location of the transition to a mud-dominated channel bed corresponds with the upstream boundary of the BHD, and a change in elevation from 0 to -1 MASL (Figure 6).

4.3 Sediment Fingerprinting

Radionuclide activities of samples grouped by source are provided in Table 4. Surface-sediment samples had a mean $^{210}Pb_{xs}$ activity value of 134.0 (standard deviation (SD) 53.0) Bq/kg and mean ^{137}Cs of 9.0 (SD 4.0) Bq/kg. Subsurface sediments representing banks, channels and gullies (Figure 3) had a mean $^{210}Pb_{xs}$ activity value of 10.0 (SD 16.0) Bq/kg and a mean ^{137}Cs of 1.0 (SD 1.0) Bq/kg. The eroding delta front/prodelta, considered to be a sediment source for deposition at the mouth of the river, had a mean $^{210}Pb_{xs}$ activity value of 27.0 (SD 20.0) Bq/kg and mean ^{137}Cs of 6.0 (SD 2.0) Bq/kg.

Floodplain samples (n=58) recorded ^{137}Cs activities between 0 and 35 Bq/kg (mean 9.0 Bq/kg). These values were higher than agricultural sources. To contextualize the activity range, the results from floodplain samples were compared to those from depositional environments in coastal North Carolina, where there is a preserved original or focused layer of sediments exposed to the fallout. The maximum peaks for ^{137}Cs varied from 3.0-135.3 Bq/kg with a mean of 39.4 Bq/kg (Ritchie, 1962; Benninger and Wells, 1993; Giffin and Corbett, 2003; Corbett et al., 2007; Mattheus et al., 2009; Pruitt et al., 2010; Lagomasino et al., 2013) (data decay corrected to 2009). Values reported in this study for surface sediments fit within that range reported in the literature.

For the distribution modeling, surface sediments were represented by floodplains (n=58), and agricultural topsoils (n=2). To verify if the activities of the two agricultural-topsoil samples (3.0-5.0 Bq/kg) were representative, their values were compared with values reported for other places in the region. Surface Piedmont soils ^{137}Cs concentrations in the Chesapeake Bay watershed range between 1.8 and 9.5 Bq/kg (Gellis et al., 2009, Clune et al., 2010) (all data decay corrected to 2009), which encompass the measurements reported here.

Subsurface, surface and delta front/prodelta sediment sources (Figure 3) were best discriminated by $^{210}Pb_{xs}$ activity, which was highest in surface soils. Mann-Whitney U-tests indicate statistically-significant differences between all sources at $p < 0.001$. Activity of ^{137}Cs was also highest in surface soils, significantly discriminated between subsurface and surface sources, between subsurface and delta front/prodelta sources ($p < 0.001$), but not between surface and delta front/prodelta sources (Table 5 and Figure 7).

The distribution model was applied to suspended sediment samples at five different stations along the river to predict source contributions. 80% (±2%) of suspended sediments collected in Hamilton (km 118) were modeled to be derived from subsurface sediments. The subsurface contribution decreases downstream with decreasing river gradient, and in Williamston their contribution was modeled to be 63% (±1%). The suspended sediment at the next downstream sampling station in Jamesville, located just 4 km above the transition zone with the BHD, was modeled as being composed of 53% (±1%) subsurface sediment. Within the BHD at the sampling station in Plymouth, we see a dramatic shift in the source of suspended sediment, with a modeled subsurface input of only 33% (±1%) and a substantial increase in the contribution of surface sediments to 67% (±1%). Suspended sediment at the river mouth, modeled with surface and subsurface sources, resulted in an increase in the contribution of subsurface sediments (60%). Suspended sediment at previous stations showed a strong decreasing trend in subsurface-sediment contribution with increasing distance downstream, thus the increased input of the subsurface source at the last station was unexpected. As previous studies showed erosion of the delta front and prodelta, the suspended sediment at the river mouth was modeled with surface and delta front/prodelta sources to determine if that distal deltaic sediment was part of the river's load. The river mouth station exhibited a much lower contribution from surface sediments and a dominant, 74% (± 1%), contribution of particles from the eroding delta front/prodelta (Figure 8).

5. Discussion

This study demonstrated a downstream trend of decreasing contributions from subsurface inputs to the suspended load of the river from 80% to 33% in the BHD. This trend demonstrates that material from the Lower Roanoke River channel is likely not transported to the BHD because controlled dam releases do not provide enough energy to the system to move the coarser sediments (Figure 6). A corresponding rise in surface sediment contribution is, in turn, associated with increased hydrologic connectivity between the river channel and the floodplain along the Lower Roanoke River. Within the BHD, the increased connectivity is facilitated by the lack of gradient, low or non-existent banks, and flooding due to changing water-levels in Albemarle Sound.

Previous studies reported the highest incidence of bank erosion (subsurface source) 95–137 km below the dam (Hupp et al., 2009). Bank erosion is strongly featured in the modeling results from the Hamilton station, located at river km 118, where 80% (± 2%), of the suspended sediment was contributed from subsurface sources (Figure 8, Table 2). An additional factor controlling the relative sediment contributions at the Hamilton site is the high banks (mean bank height 4.1 m (Hupp et al., 2009)), that effectively limit hydrologic connectivity between floodplains and the channel. With decreasing bank height (mean bank height 1.7 m between km 138 and 175 (Hupp et al., 2009)) and decreasing river gradient (Figure 4), the river between Hamilton and Williamston has a significant ~38% reduction in bank erosion (from 63.3 mm/yr to 24.2 mm/yr (Hupp et al., 2009)). The modeling results, presented here, corroborate the findings of Hupp et al. (2009) by showing a reduction in the contribution of subsurface sediments; however, the decline is not as pronounced. In Hupp et al. (2009), the reduction in bank erosion between Hamilton (km 118) and Jamesville (km 182) is ~61% while in this study it is 27% (±1%) (Figure 8). The discrepancy in the magnitude of the subsurface-sediment contribution to the suspended load between Hupp et al. (2009) and our study indicates that in addition to bank erosion, other subsurface sources, which have not been monitored, contribute to the suspended-sediment load, such as sediment from channel incision or gully erosion.

Concentrations of TSM decrease downstream, which can be associated with a loss of sediment to deposition with the funnel/bottleneck effect observed in freshwater, bidirectional (tidal) environments (Kroes et al., 2007; Ensign, et al., 2015), or dilution from an increase in water volume due to widening of the river below Jamesville and water exchange with Albemarle Sound (from 120 m wide in Jamesville to 200 m wide at the transition, Table 2). The decrease in the subsurface contribution to the suspended load in Plymouth (km 202), coincides with increasing floodplain deposition below Jamesville (km 189), reported by Hupp et al. (2015). That study demonstrated that the highest floodplain sedimentation rates were in the backswamps between Williamston (km 155) and Jamesville (km 189), where a rate of 56 mm/yr was recorded (Hupp et al., 2015). The furthest downstream location in that study (at km 193), within the upper BHD, recorded rates of 23 to 28 mm/yr. That rate is close to the lower range of sedimentation reported for the delta plain by Jalowska et al. (2015), the EPA Remediation Study (2008) and also by Hupp et al. (2009) between km 151 and 193 (28 mm/yr, 20 mm/yr and 25 mm/yr, respectively).

Modeling results show that suspended sediment collected at the mouth of the Lower Roanoke is mostly composed of sediment derived from the eroding delta front/prodelta (74% ± 1%) and connectivity with the floodplain is low. These results suggest that sediments from the river are not all released into proximate waters of the Albemarle Sound, but a fraction is dispersed inland with river back-flow and are being redeposited within the upper portions of the BHD. The role of the lower delta floodplain and the delta front/prodelta likely shifts from being a sediment sink to a sediment source when delta-evolution shifts from being regressive to transgressive.

The discrepancy between reported floodplain deposition in the upper BHD (Hupp, 2000; Schenk and Hupp, 2008) while simultaneously observed higher contribution of floodplain sediments to the suspended load in the lower BHD (this paper), suggests an unaccounted floodplain-channel connectivity, an internal sediment redistribution function of the BHD floodplains or a sediment shadow effect associated with the river bottleneck mechanism (Ensign, et al., 2015) (Figure 9). The upper BHD floodplains accrete with sediment mainly sourced from the lower delta plain, and the delta front/prodelta, as opposed to sediment from upstream (Figure 9). Eroded material from the lower parts of the BHD is likely transported upstream during high water level events associated with the wind stress in Albemarle Sound, and redeposited in the upper BHD floodplains. This sediment recycling in the BHD tempers transgression by nourishing the upper BHD with eroded delta front/prodelta and lower delta plain sediment, fortifying the upper BHD against inundation. This BHD sediment recycling process highlights the importance of sediment-transport pathways during BHD transgression and challenges the source to sink paradigm in fluvial deltaic systems, which are heavily biased towards upstream sources and downstream sinks.

Additional studies of the described sediment-recycling process and its role in delta retreat are required. Importantly, the presence of sediment recycling during delta retreat in other types of deltas, including open-ocean deltas, needs to be investigated. BHDs are commonly the smallest of all the deltas, which increases their vulnerability to even minor changes in land-use, and sea-level rise. The small size of BHDs makes them good study sites, or testing sites for restoration efforts of deltaic systems. Unlike in the Roanoke BHD, large ports and cities are commonly constructed near or on BHDs (Port of Houston, TX, San Jose, CA), where hard structures within the delta additionally hinder natural sediment-transport processes.

Understanding sediment pathways in modified deltas may offer clues as to where coastal restoration efforts should be focused, whether to enhance natural processes that control river flow and sediment transport at higher elevations or to fortify eroding delta-front shorelines.

Conclusions

The Lower Roanoke River has been extensively dammed causing significant downstream geomorphological changes to its channel and floodplains. Our research demonstrates a downstream trend of increasing surface-sediment input and decreasing subsurface-sediment input to the suspended load of the river. Consequently, the contribution of material from subsurface sources is significantly reduced downstream and is being replaced by sediments from the eroding prodelta and delta front, and from the lower delta plain.

Major and minor dammed rivers around the world do not have enough sediment supplied from upstream reaches and tributaries to nourish and fortify deltas. Without increasing sediment supply, deltas cannot outpace sea-level rise and they will retreat. The results of this study suggest that during the retreat process, deltas recycle sediment from the eroding parts of the lower delta to build the upper delta. Upstream sediment transport during transgression results in delta rollover, where the delta and its floodplains are a source and sink for sediments at the same time. This largely unaccounted for process would lead to an overestimation of sediment and nutrient budgets for deltaic environments and downstream basins. Further research focused on mechanisms and time scales of the floodplain retreat, pathways and dynamics of sediment redistribution in BHD systems are required. Understanding the scale of these processes is important for management practices as it would allow restoration and conservation efforts to focus on those upper parts of the delta wetland that are being naturally nourished by eroded sediments from the lower delta.

Tables

Table 1. Land use in the Lower Roanoke River.

Land use type and subtypes	**Area (km^2)**	**Percentage**
Forest and shrubs (Broadleaf Evergreen Forest, Deciduous Shrubland, Evergreen Shrubland Mixed Hardwoods/Conifers, Mixed Shrubland, Southern Yellow Pine, Other Needleleaf Evergreen Forests, Mixed Upland Hardwoods, Needleleaf Deciduous)	1327	39%
Wetlands (Unmanaged Herbaceous Wetland, Oak/Gum/Cypress, Bottomland Forest/Hardwood Swamps)	1052	31%
Cultivated (Unmanaged Herbaceous Upland, Unconsolidated Sediment, Managed Herbaceous Cover, Cultivated)	919	27%
Water	64	2%
Developed (Low Intensity Developed, High Intensity Developed)	30	1%
Total	3392	100%

Table 2. Discharges, water level data and correlation with dam releases during the sampling period.

USGS monitoring station	Distance below the dam (km)	Drainage area below the dam (km^2)	Water level range (m)	Mean water level (m)	Discharge (m^3s^{-1})	Mean discharge (m^3s^{-1})	Correlation coefficient (r) with discharges from Roanoke Rapids Dam
Roanoke Rapids	0	0	NA	NA	45 to 810	187	NA
Hamilton	118	1311	0.05 to 0.50	0.21	NA	NA	0.91
Williamston	155	1777	0.68 to 3.52	2.04	NA	NA	0.88
Jamesville	182	2243	-0.20 to 1.68	0.51	NA	NA	0.69
Plymouth (NC45)	208	3305	-0.21 to 1.98	0.41	NA	NA	0.12

Table 3. Sample location information including number of total suspended sediment concentration samples and channel width.

Station Location	Channel width (m)	Number of TSM observations in this study	Date Range of EPA observations	Number of EPA TSM observations
Roanoke Rapids, NC Km 0	~60	1	02/20/1997 - 11/28/2007	69
Weldon, NC Km 11	~130	3	NA	NA
Scotland Neck, NC Km 57	~90	NA	02/20/1997 - 11/28/2007	49
Oak City, NC Km 105	~90	8	NA	NA
Hamilton, NC Km 118	~90	11	NA	NA
Williamston, NC Km 155	~90	27	03/11/2008 - 09/04/2013	20
Jamesville, NC Km 182	~120	29	NA	NA
Welch Creek near	~330	NA	02/24/2008 -	11

Plymouth, NC Km 199			07/17/2012	
Plymouth, NC Km 202	~160	25	NA	NA
NC 45 at Sans Souci Km 208	~480	6	03/18/1997 - 11/14/2007	70
Eastmost River Km 212	~50	13	NA	NA
Albemarle Sound at Batchelor Bay Near Black Walnut	~370	NA	03/18/1997 - 04/18/2007	62
Prodelta Km 214	NA	8	NA	NA

Table 4. Fingerprinting properties of sediment sources and suspended sediment per station.

Sediment Sources		Mean $^{210}Pb_{xs}$ activities (Bq/kg)	Mean ^{137}Cs activities (Bq/kg)
	Surface (n=60)	134 (SD 53)	9 (SD 4)
	Subsurface (n=66)	10 (SD 16)	1 (SD 1)
	Eroding Prodelta (n=11)	27 (SD 20)	6 (SD 2)
Suspended Sediment (Surface water 0-0.5 m depth)	Hamilton (n=6)	77 (SD 68)	3 (SD 2)
	Williamston (n=22)	91 (SD 66)	7 (SD 5)
	Jamesville (n=21)	130 (SD 81)	7 (SD 6)
	Plymouth (n=17)	155 (SD 88)	12 (SD 6)
	Prodelta (n=13)	75 (SD 60)	8 (SD 5)

Table 5. Results of Mann-Whitney U-test

	$^{210}Pb_{xs}$ (p-value)			^{137}Cs (p-value)		
	Subsurface	Surface	Prodelta	Subsurface	Surface	Prodelta
Subsurface						
Surface	< 0.001			< 0.001		
Prodelta	< 0.001	< 0.001		< 0.001	0.342	

Acknowledgments

We would like to thank our colleagues at University of North Carolina Sherif Ghobrial, John Gunnell, Kristen Jarman, Shelby Marshal, Gráinne O'Grady, and Ethan Theuerkauf for help in the field and the lab, and Patricia Rodriguez for grain size analyses. We would also like to thank Cliff Hupp from US Geological Survey, Reston, VA, and Jean Richter from US Fish and Wildlife Service, Roanoke River National Wildlife Refuge, Windsor, NC for invitation to the field trip that allowed access to Lower Roanoke River floodplains, and sample collection, and sharing their knowledge about the system. The authors would like to thank Scott Wilkinson and Olivier Evrard for constructive modeling comments, Dr. Gert Verstraeten, Dr. Cliff Hupp and two others anonymous reviewers for their constructive comments and feedback on the original manuscript.

This work was supported by the North Carolina Sea Grant, grant number 10-HCE-B-10 and by the U.S. Department of Energy's Office of Science (BER) through the Coastal Center of the National Institute for Climatic Change Research at Tulane University.

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Figure 1. A. Lower Roanoke Basin elevation map with USGS monitoring stations B. Map of the land use in the Lower Roanoke basin with sampling locations. The insets show the location of the catchment within the United States.

Figure 2. River suspended sediment discharge during two periods, circa 1910 and circa 1980 showing the decrease in sediment loads associated with dam placement (based on (Meade et al., 1990)).

Figure 3. Sources of sediment to suspended load

Figure 4. Upper panel: Suspended sediment concentrations presented as mean (solid line) and minimum and maximum values (dashed lines) at the station in the sampling period 2/20/2009 to 11/16/13.The open circles represent mean sediment concentrations from EPA STORET for period 02/20/1997 - 11/28/2007. Lower panel: Slope of the Lower Roanoke River.

Figure 5. Hydrographs at four stations, compared with discharges from the Roanoke Rapids Dam. Correlation coefficients (r) are provided in a left upper corner of each panel.

Figure 6. Grain size data of the channel bed and gullies by river km. Transition between Lower Roanoke River and bayhead delta is highlighted with a dashed line. Above the plot are examples of the bedforms characteristic for the Lower Roanoke River above the transition and for the fine-grained, flat channel bed in the bayhead delta

Figure 7. $^{210}Pb_{xs}$ and ^{137}Cs activities in source sediments with the error bars representing one standard deviation of the mean.

Figure 8. Results of the multivariate mixing model showing relative contributions of surface and subsurface sediments to the suspended load (uncertainty in parenthesis).

Figure 9. Conceptual diagram of the sediment sources and fate in the Lower Roanoke River and bayhead delta (Symbols for diagrams courtesy of the Integration and Application Network ian.umces.edu/symbols and Dunne et al., 1998).

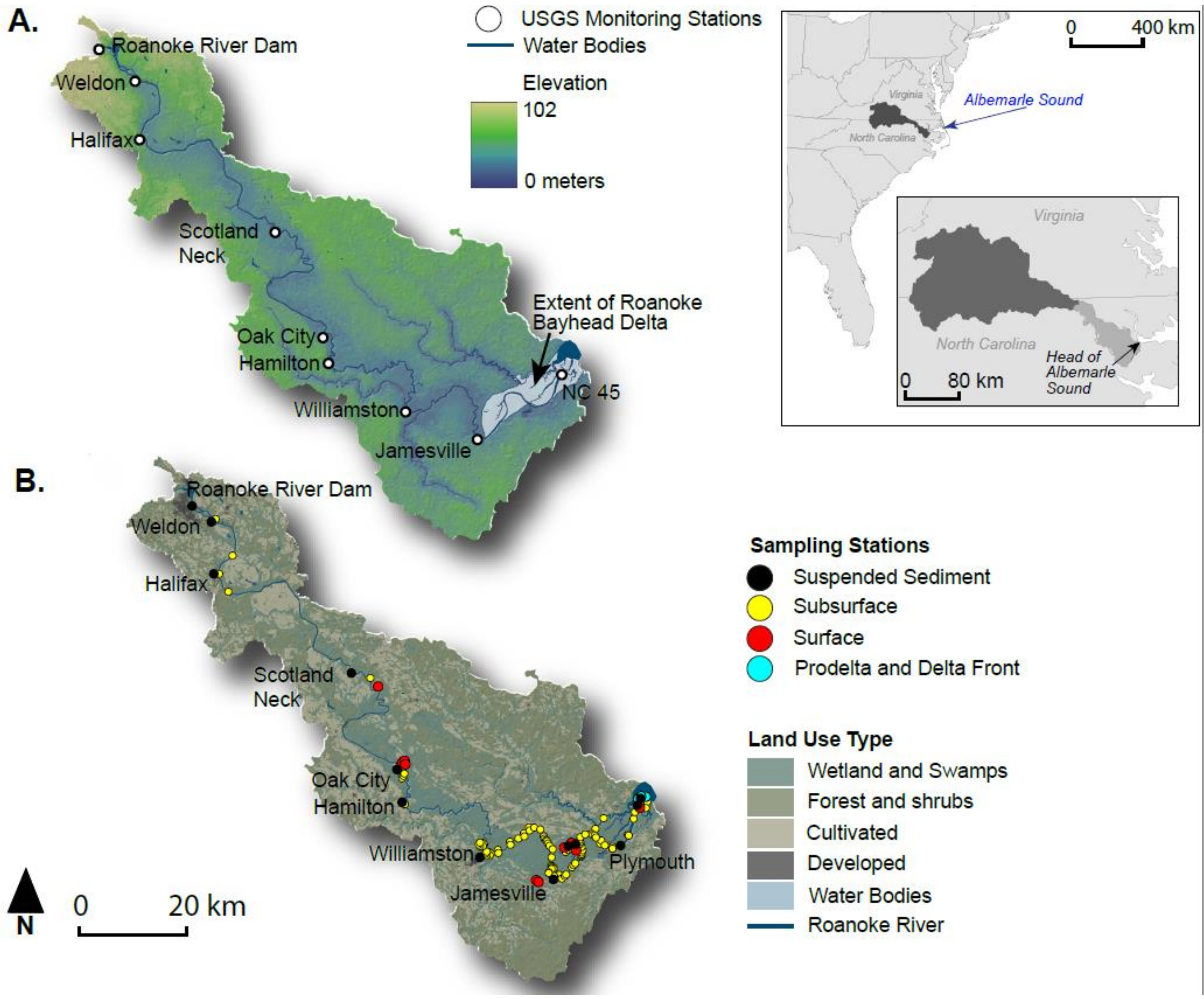
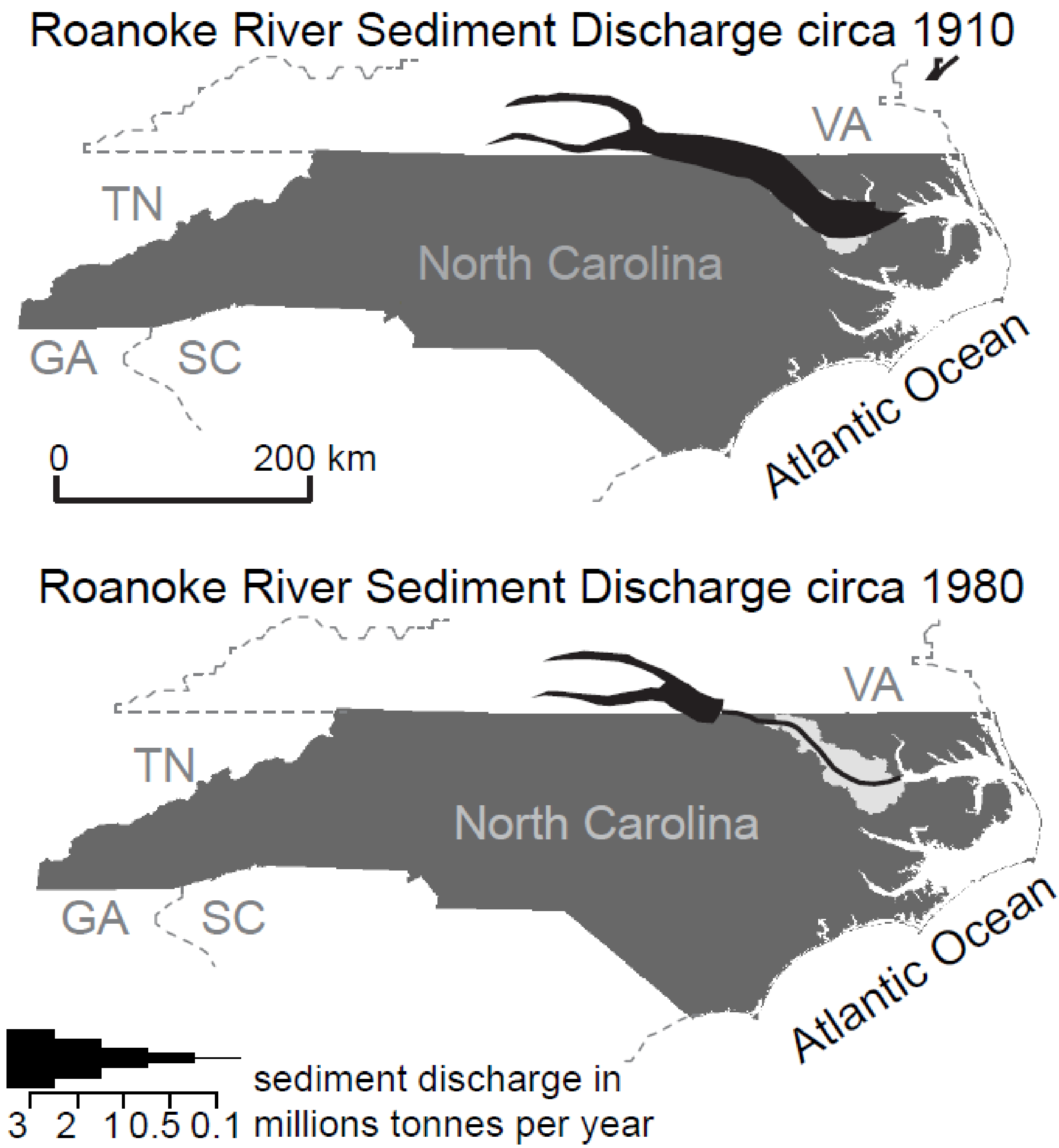

A.
USGS Monitoring Stations
Water Bodies
Elevation
102
0 meters
Roanoke River Dam
Weldon
Halifax
Scotland Neck
Oak City
Hamilton
Williamston
Jamesville
NC 45
Extent of Roanoke Bayhead Delta
0
400 km
Virginia
North Carolina
Albemarle Sound
0
80 km
Head of Albemarle Sound
B.
Roanoke River Dam
Weldon
Halifax
Scotland Neck
Oak City
Hamilton
Williamston
Jamesville
Plymouth
Sampling Stations
Suspended Sediment
Subsurface
Surface
Prodelta and Delta Front
Land Use Type
Wetland and Swamps
Forest and shrubs
Cultivated
Developed
Water Bodies
Roanoke River
N
0
20 km

Figure 1



Roanoke River Sediment Discharge circa 1910
VA
TN
North Carolina
GA
SC
Atlantic Ocean
0
200 km
Roanoke River Sediment Discharge circa 1980
VA
TN
North Carolina
GA
SC
Atlantic Ocean
sediment discharge in
millions tonnes per year
3
2
1
0.5
0.1

Figure 2

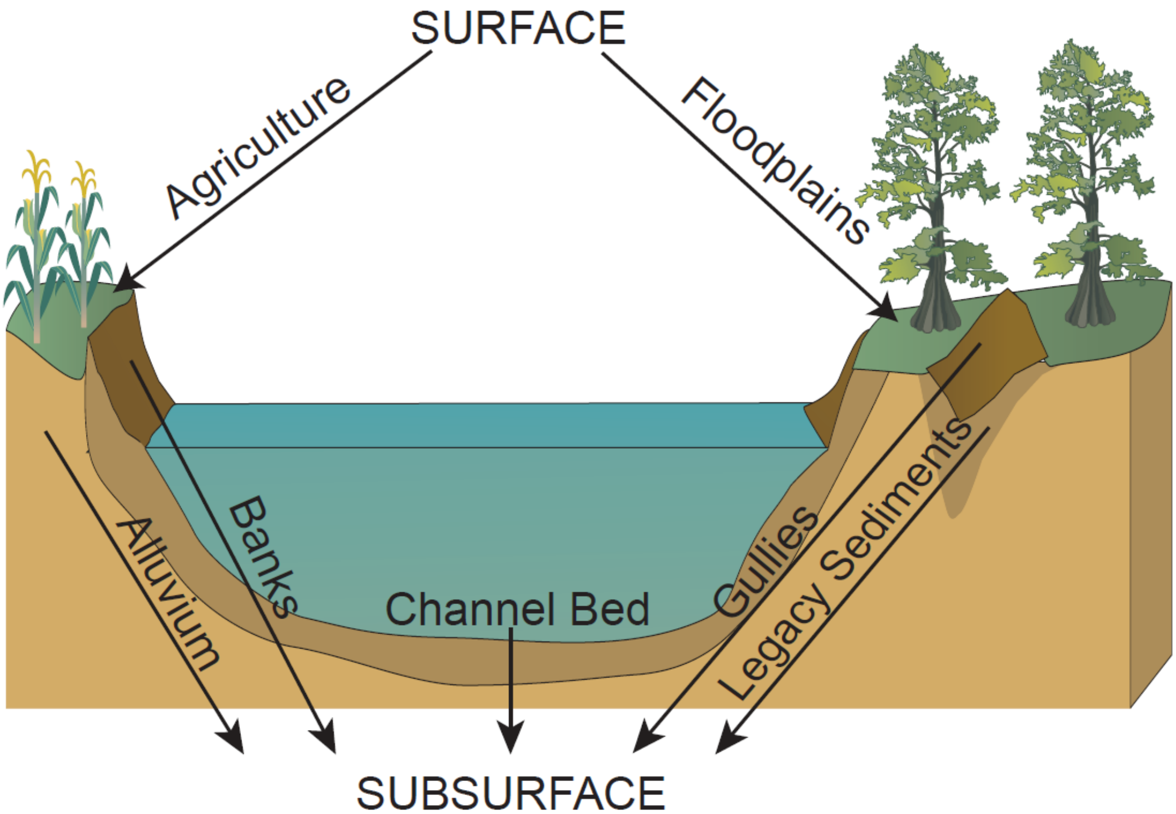

SURFACE
Agriculture
Floodplains
Banks
Alluvium
Channel Bed
Gullies
Legacy Sediments
SUBSURFACE

Figure 3

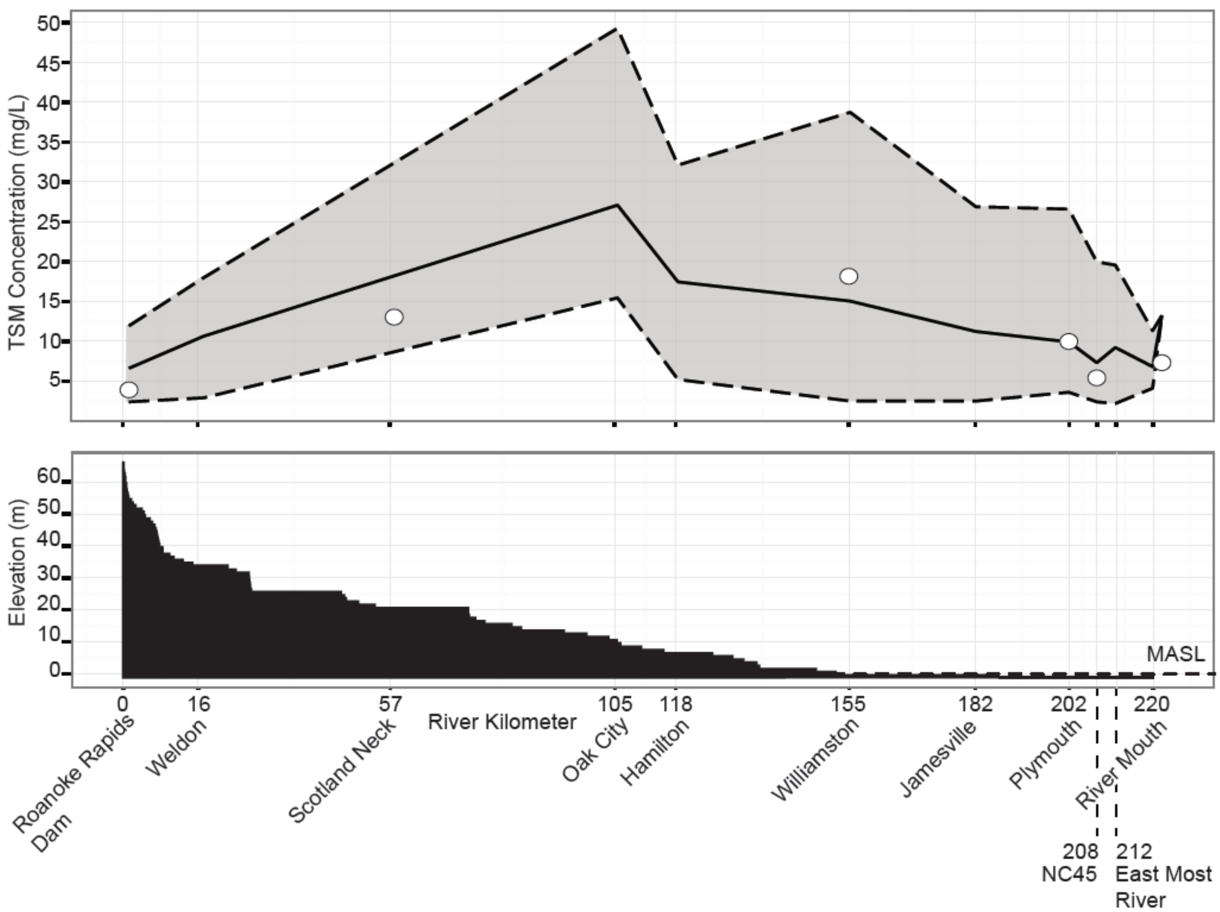

TSM Concentration (mg/L)
50
45
40
35
30
25
20
15
10
5
Elevation (m)
60
50
40
30
20
10
0
MASL
0
16
57
105
118
155
182
202
220
River Kilometer
Roanoke Rapids Dam
Weldon
Scotland Neck
Oak City
Hamilton
Williamston
Jamesville
Plymouth
River Mouth
208 NC45
212 East Most River

Figure 4

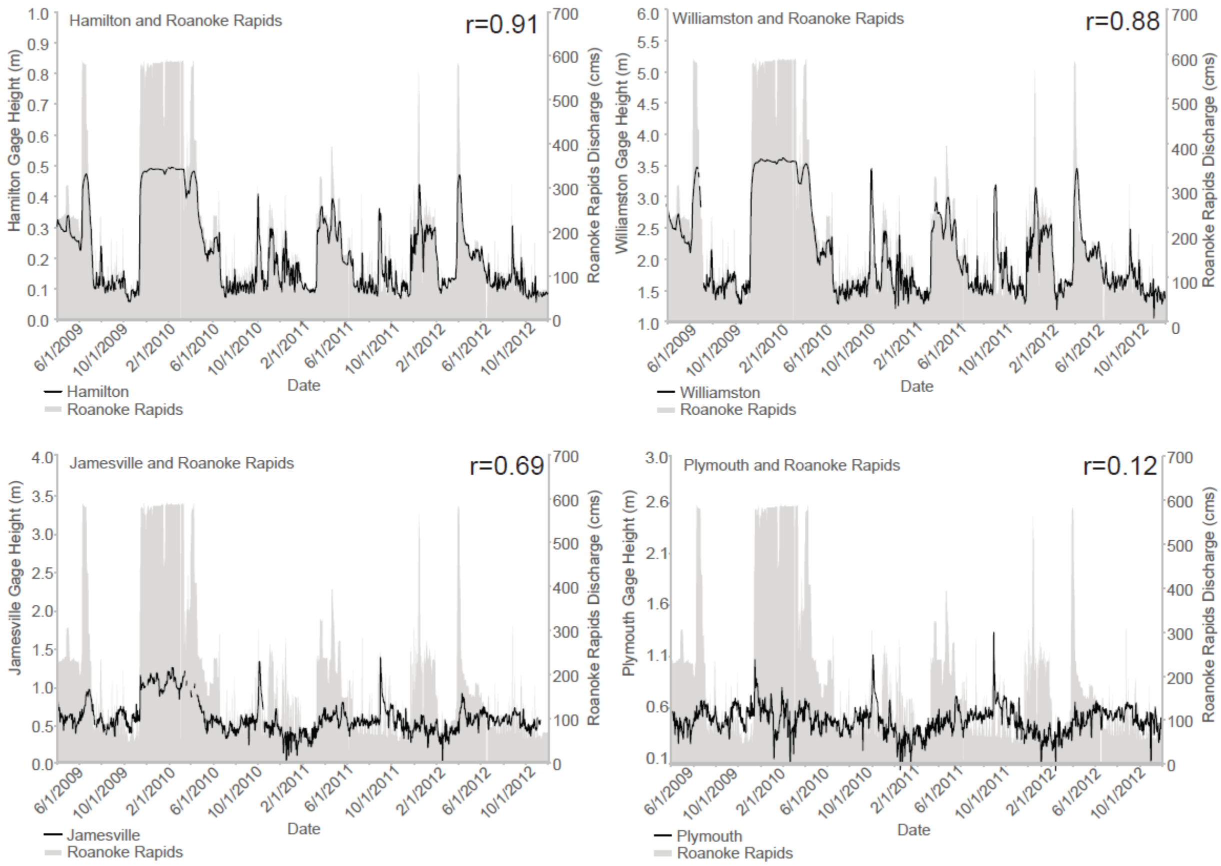
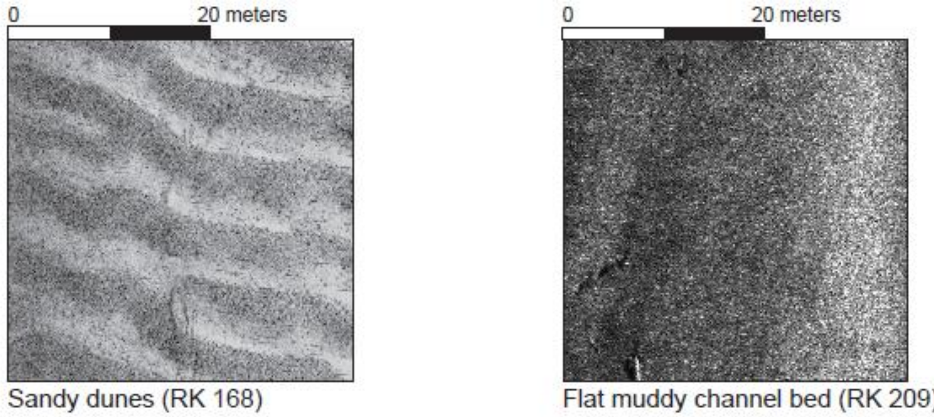
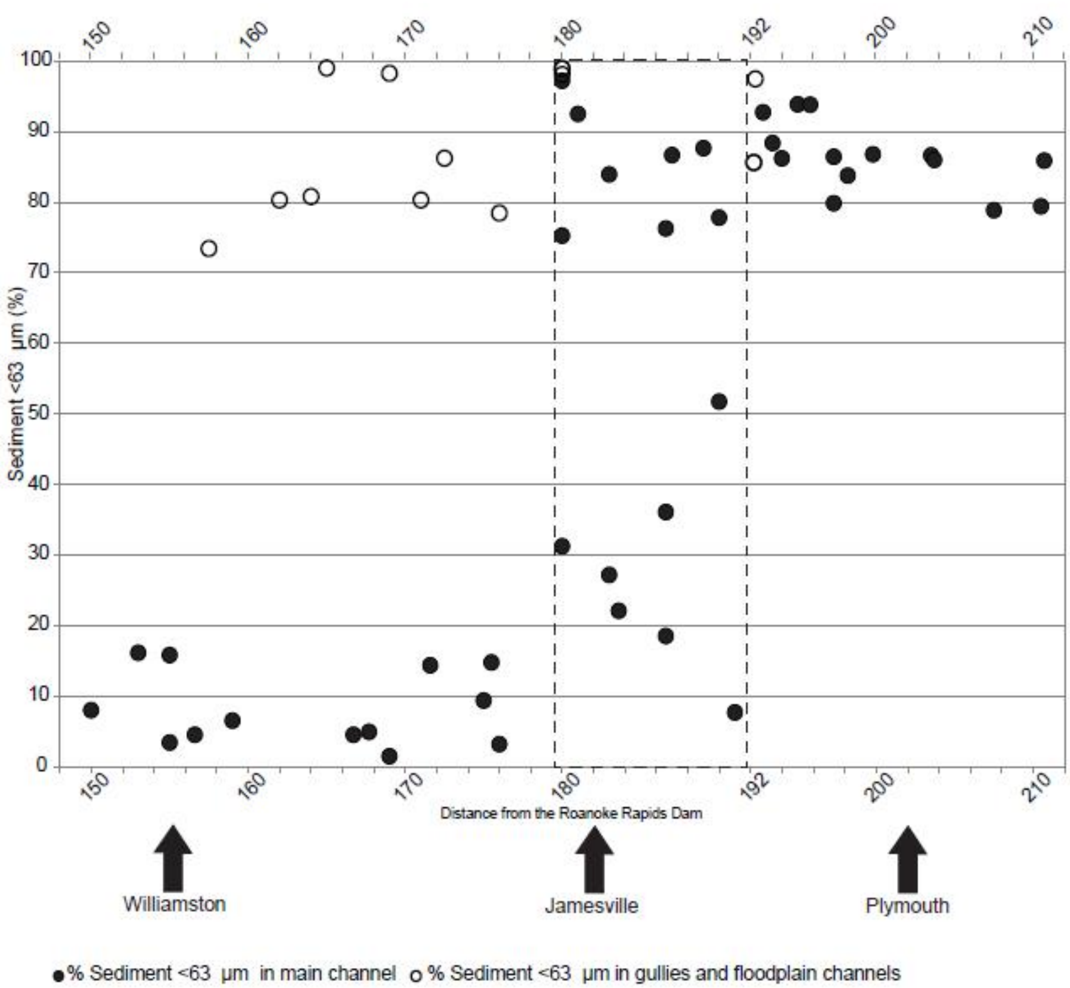

Hamilton and Roanoke Rapids
r=0.91
Hamilton Gage Height (m)
Roanoke Rapids Discharge (cms)
Date
Hamilton
Roanoke Rapids
Williamston and Roanoke Rapids
r=0.88
Williamston Gage Height (m)
Roanoke Rapids Discharge (cms)
Date
Williamston
Roanoke Rapids
Jamesville and Roanoke Rapids
r=0.69
Jamesville Gage Height (m)
Roanoke Rapids Discharge (cms)
Date
Jamesville
Roanoke Rapids
Plymouth and Roanoke Rapids
r=0.12
Plymouth Gage Height (m)
Roanoke Rapids Discharge (cms)
Date
Plymouth
Roanoke Rapids
6/1/2009
10/1/2009
2/1/2010
6/1/2010
10/1/2010
2/1/2011
6/1/2011
10/1/2011
2/1/2012
6/1/2012
10/1/2012

Figure 5



0
20 meters
Sandy dunes (RK 168)
0
20 meters
Flat muddy channel bed (RK 209)



Sediment <63 µm (%)
Distance from the Roanoke Rapids Dam
Williamston
Jamesville
Plymouth
% Sediment <63 µm in main channel
% Sediment <63 µm in gullies and floodplain channels

Figure 6

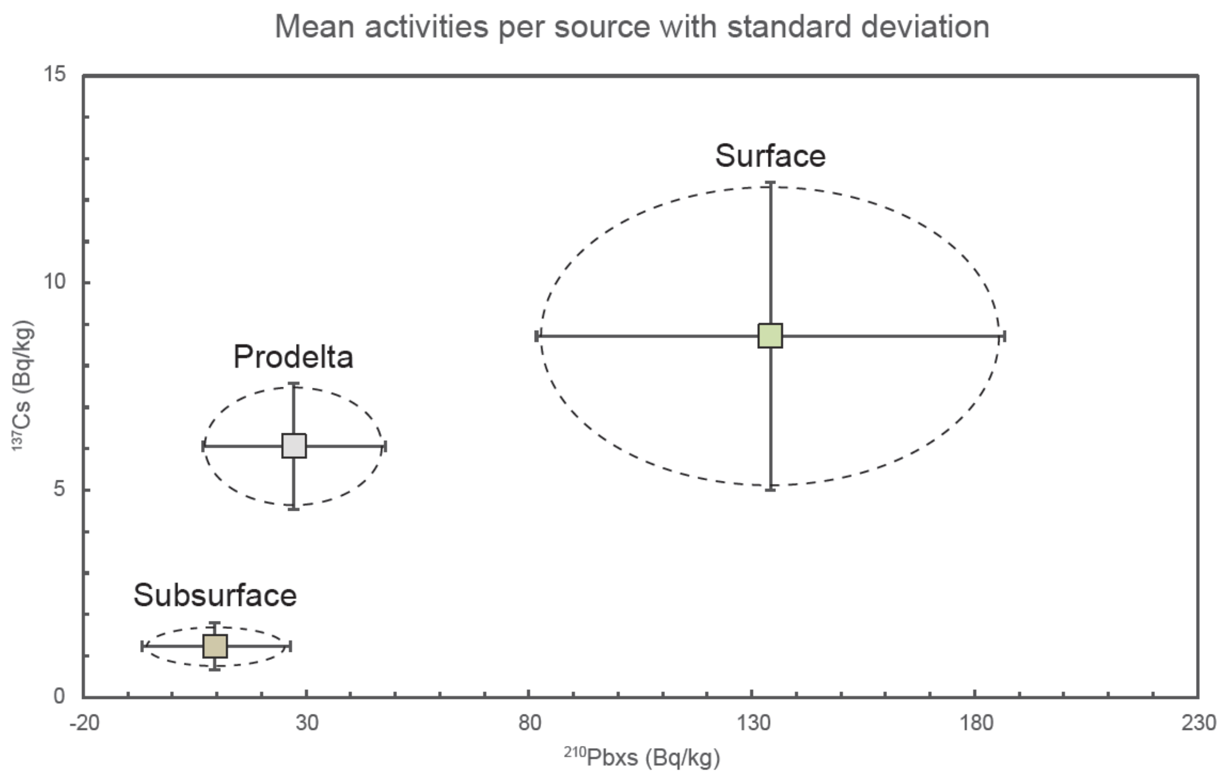

Mean activities per source with standard deviation
15
10
5
0
-20
30
80
130
180
230
137Cs (Bq/kg)
210Pbxs (Bq/kg)
Surface
Prodelta
Subsurface

Figure 7

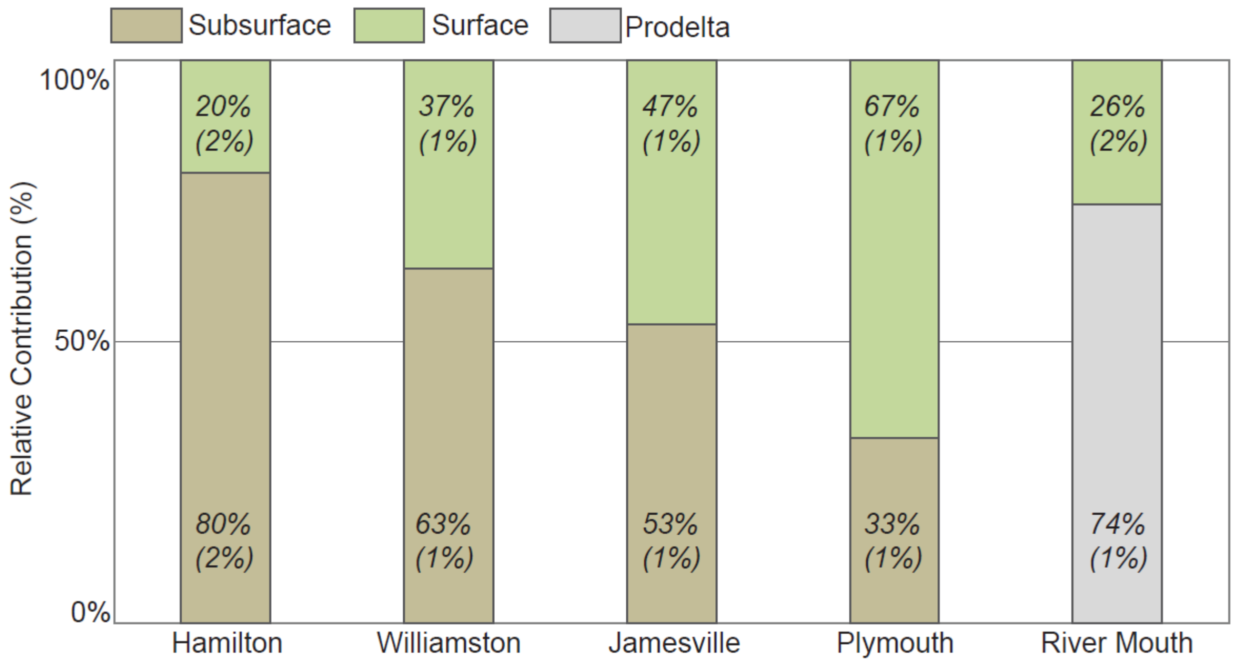

Subsurface
Surface
Prodelta
100%
50%
0%
Relative Contribution (%)
20%
(2%)
37%
(1%)
47%
(1%)
67%
(1%)
26%
(2%)
80%
(2%)
63%
(1%)
53%
(1%)
33%
(1%)
74%
(1%)
Hamilton
Williamston
Jamesville
Plymouth
River Mouth

Figure 8

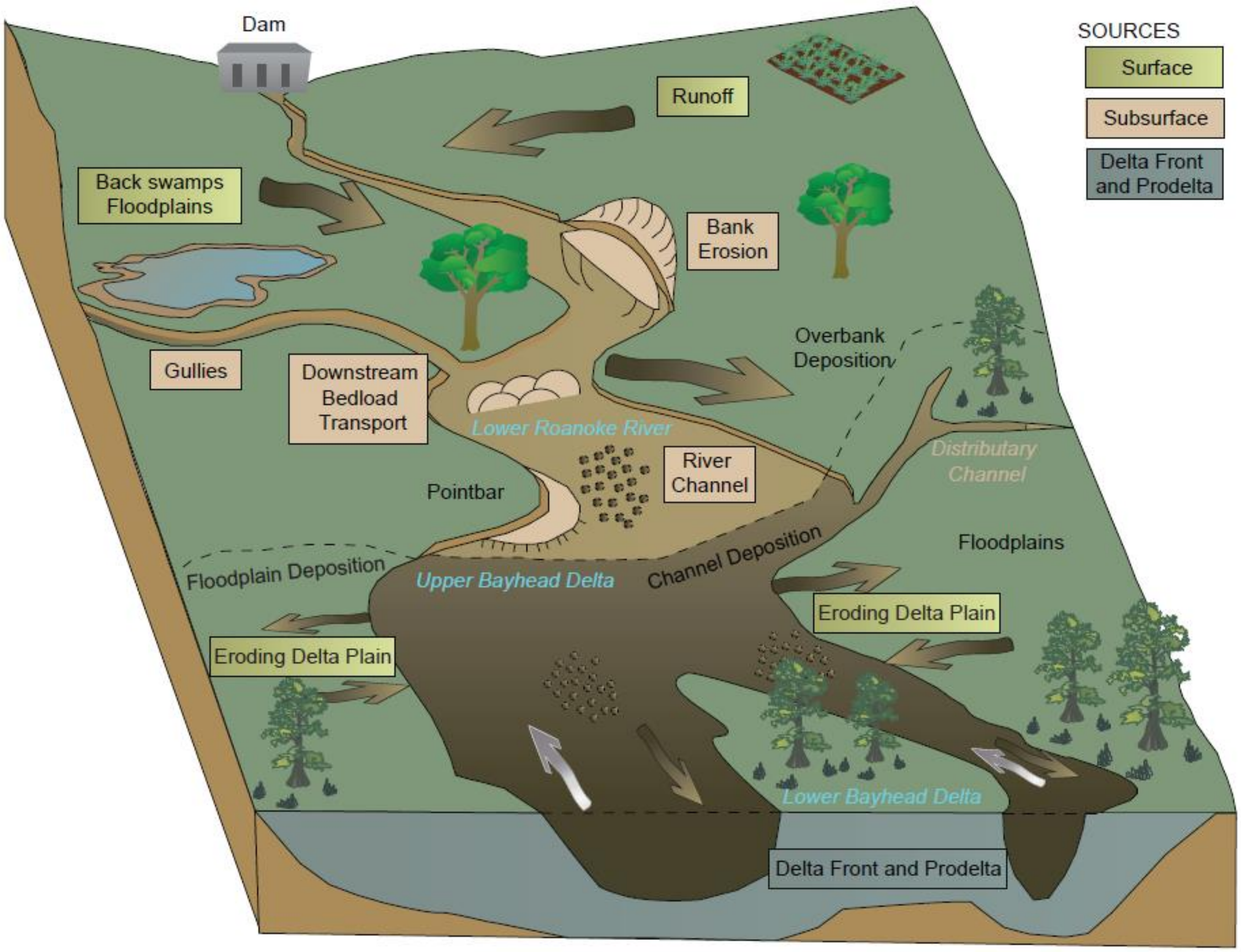

Dam
SOURCES
Surface
Subsurface
Delta Front and Prodelta
Runoff
Back swamps Floodplains
Bank Erosion
Overbank Deposition
Gullies
Downstream Bedload Transport
Lower Roanoke River
River Channel
Pointbar
Distributary Channel
Floodplains
Floodplain Deposition
Upper Bayhead Delta
Channel Deposition
Eroding Delta Plain
Eroding Delta Plain
Lower Bayhead Delta
Delta Front and Prodelta

Figure 9