Sediment Dynamics in Jordan Lake

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Central Question Addressed in this Report:
What is the fate of sediments entering Jordan Lake from the Haw River

- Where do they go spatially (throughout the lake)?
- How do they move temporally (throughout the year)?

Why do we care?

- An important fraction of nutrients and contaminants are associated with particles and follow particle pathways.
- Once particles settle to the lake bottom they experience a different geochemical environment (e.g. pH, O_2) and transformations can occur (release from particles).
- Particulates themselves can cause water quality issues resulting in light limitation

What are possible policy implications from this study?

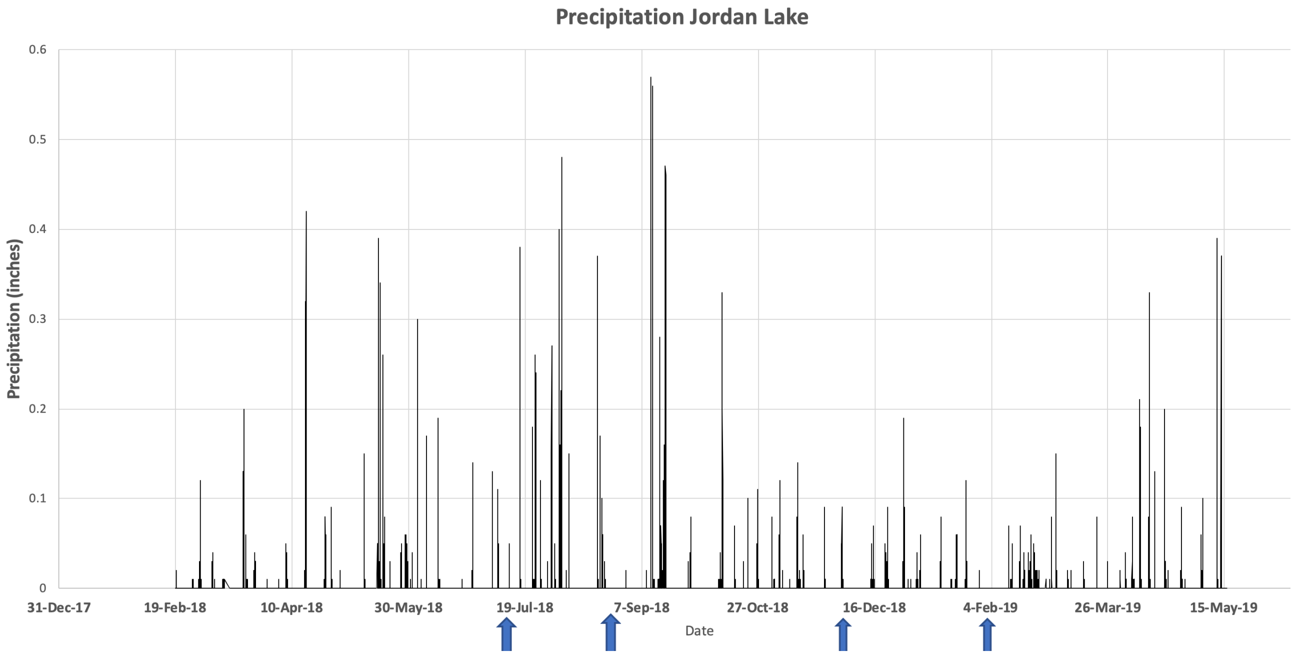
- A major objective is to better understand the extent to which Haw River sediment get to the middle lake, where municipal water intakes are located, and to better understand when that happens and what physical forces dominate (Haw River Discharge, Physical Currents within the Lake)
- It is possible to develop a predictive capability regarding how turbidity plumes get to the middle lake region.
- This study will help us better understand the dispersal of sediment-associated nutrients and contaminants.

Report Outline:

- Central Research Question and Management Implications
- Lake Setting
    - Precipitation
    - Water Discharge
    - Sediment Discharge Rating Curve
    - Lake Level
- Experimental Design
- Methods
- Results of Core Collection
    - Core Profiles
- Be-7 Inventories
    - Significance of Be-7 Inventories
    - How Inventories are calculated
- Relative Fluxes of Be-7
    - What are Relative Fluxes
    - How are they Calculated
- Sediment Depositional Fluxes
    - How are Deposition rates calculated?
    - Results sorted by stations and by dates
- Data Analysis and Interpretation
- Summary and Conclusions

Lake Setting
2018 was a record-breaking year in the Research Triangle area in terms of precipitation. The average annual rainfall totals for Raleigh, NC (1981-2018) is 46 inches with 100 days of rain. In 2018, a total of 63 inches of precipitation was recorded in the Raleigh, NC area with 137 days recording rainfall. This total was the second highest annual rainfall recorded during the past 129 years (1996 was the highest). Rainfall in 2018 was dominated by Hurricane Florence (September 13-17) and Tropical Storm Michael (October 10-11). Figure 1 shows the precipitation record at the Jordan Lake dam. Blue arrows denote the sampling dates when cores were collected (see Methods for more details).

Figure 1 Precipitation Measured at the Jordan Lake Dam (Moncure, NC)



The impact of Florence and Michael are most prominently reflected in the Haw River water discharge record at Bynum, NC (Figure 2) and the lake levels recorded at Jordan Lake (Figure 3).

Figure 2. Water Discharge: Haw River at Bynum

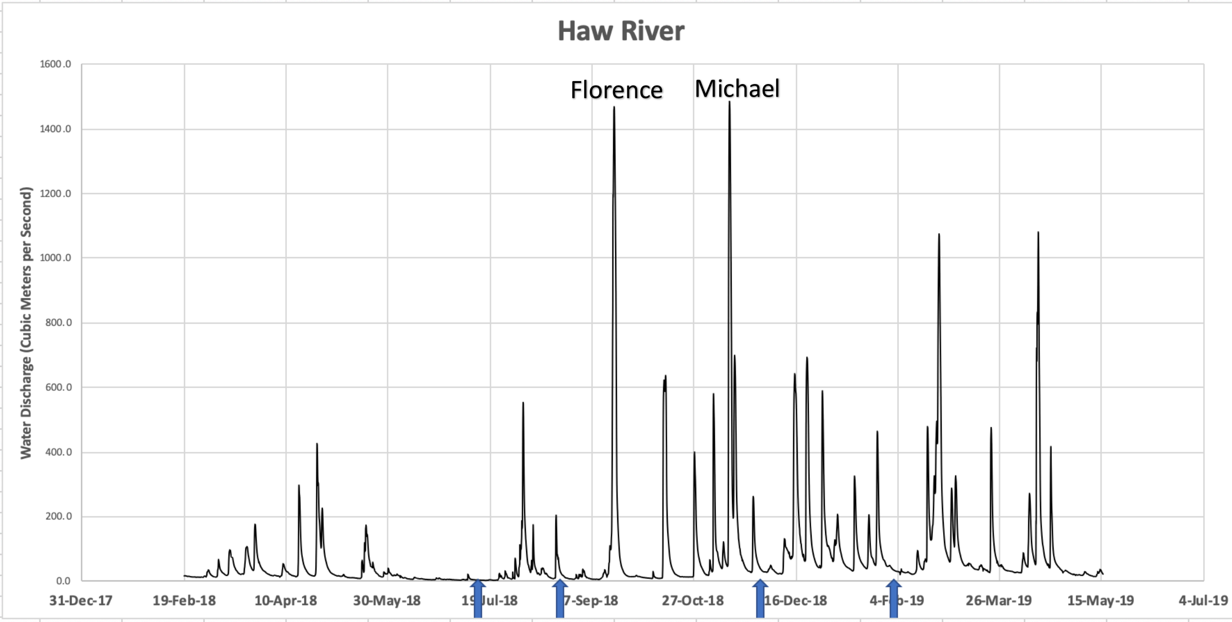
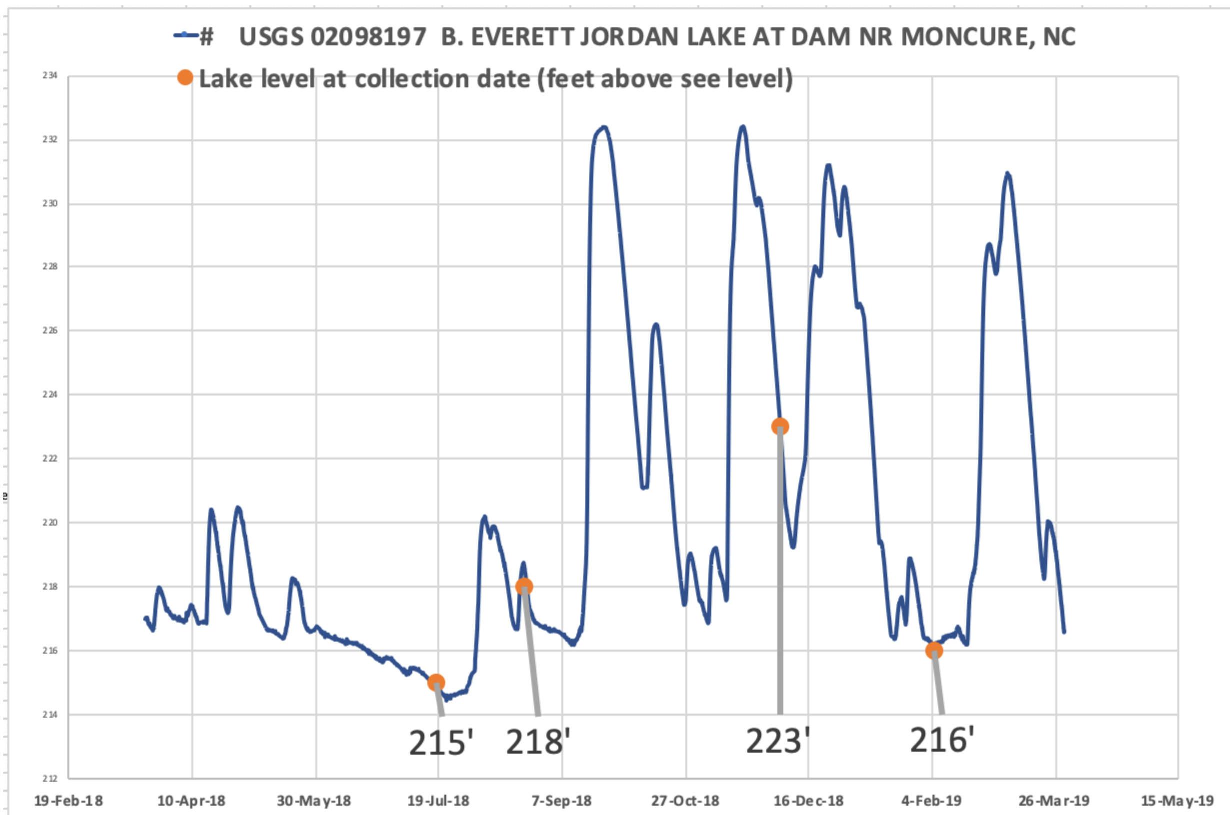


Figure 3 Lake levels during study period



Calculated Sediment Discharge using Rating Curve
In 2017, McKee et al. established a sediment rating curve based on suspended sediment concentration measured on samples collected from the Haw River (Bynum), and the corresponding water discharge rate documented by the USGS at Bynum NC. This relationship was extended with the higher water discharge values experienced in 2018 (Figure 4). Using this extended relationship, sediment discharge values for the study period were calculated and plotted in Figure 5.

Figure 4 Sediment Rating Curve for Haw River Water Discharges

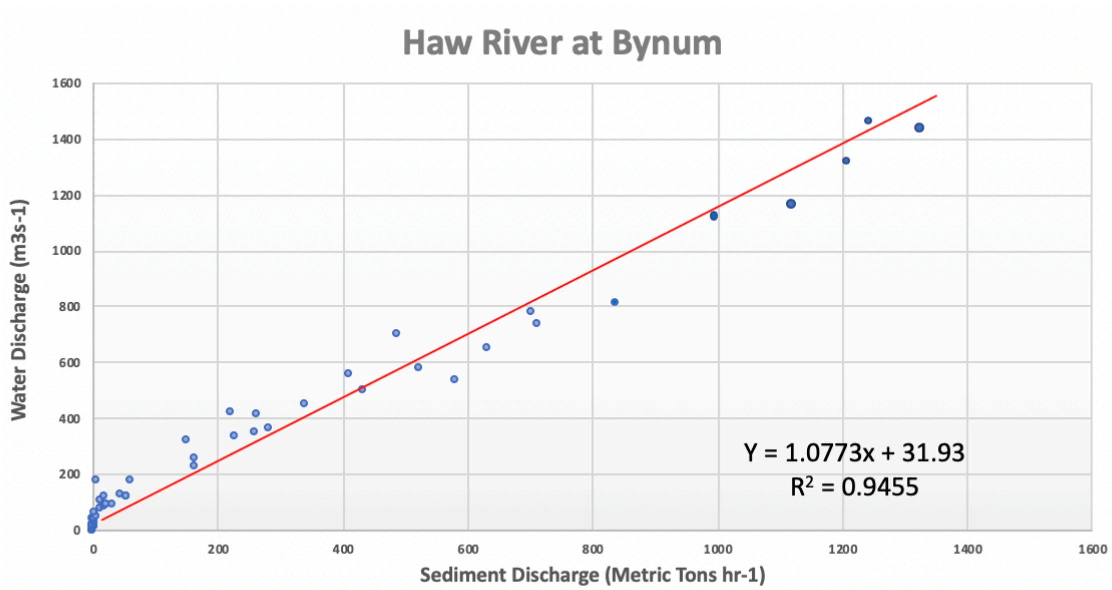
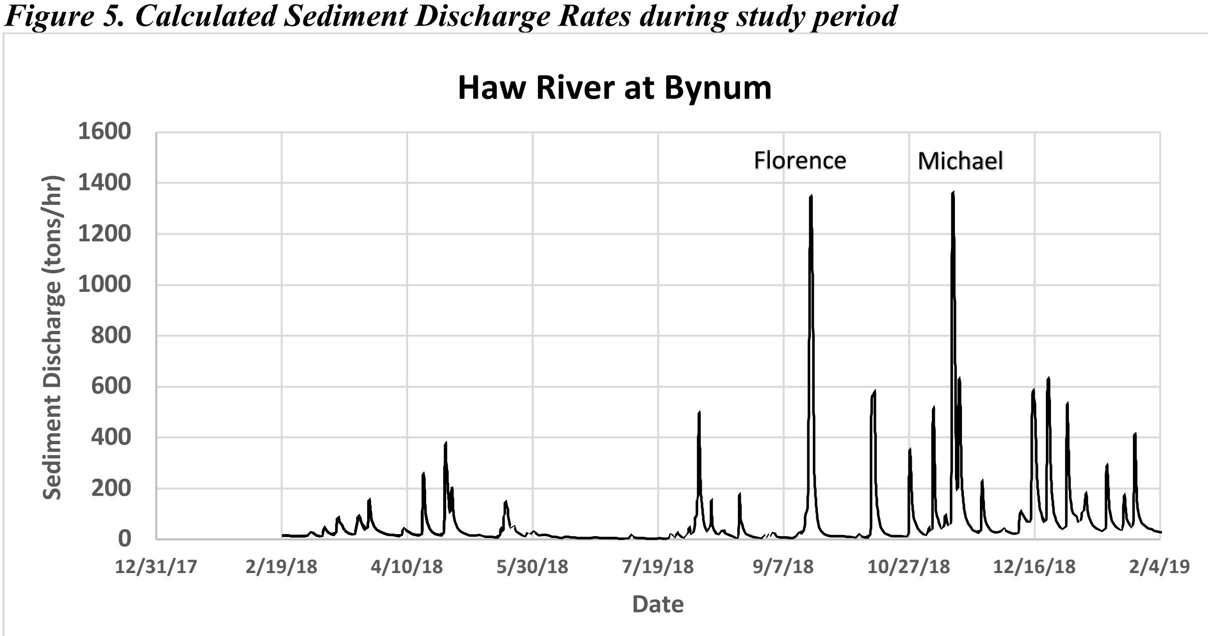


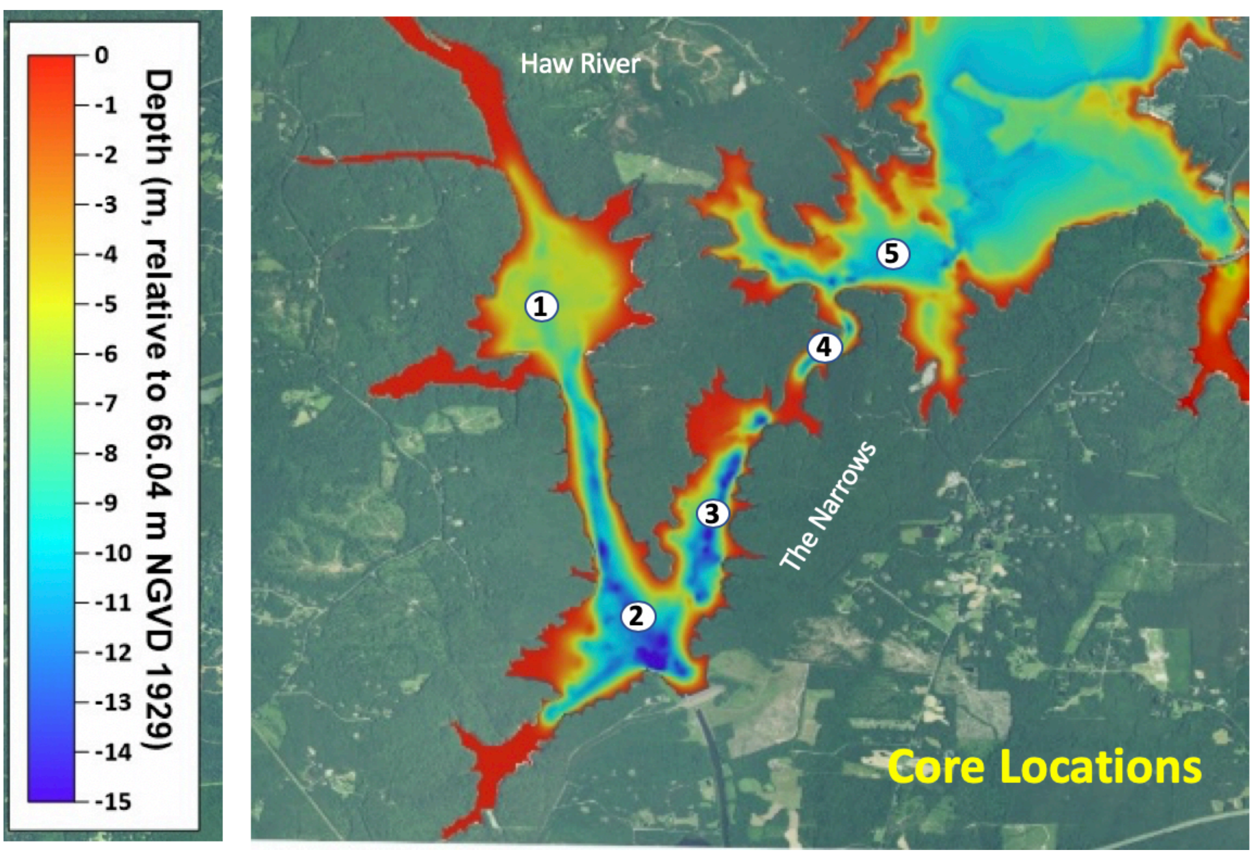
Figure 5. Calculated Sediment Discharge Rates during study period



Experimental Design

The Haw River is the dominant source of sediments delivered to Jordan Lake, accounting for 89% of the sediment load to the lake. During the study period, an average of 67 tons of sediments were delivered to Jordan Lake each hour, including 2 peak events that exceeded 1200 tons/hr, corresponding to Hurricane Florence and Tropical storm Michael (Figure 5). Five coring locations were established, and lake bottom sediment cores were collected at each site during four sampling periods within the study. A central focus of this study was to understand the fate of sediments entering the lower arm of Jordan Lake from the Haw River. Of special interest was to determine how much sediment from the Haw entered the middle lake, where municipal water intakes are located. For Haw River sediments to be delivered to the middle lake, they have to traverse the narrow and tortuous section of the lake called "The Narrows" (see Figure 6). A transect of coring sites ranging from proximal to the Haw River input (Station 1) to the middle lake (Station 5) were selected to examine the transport of sediment into and through the Narrows. Sampling dates were July 17, August 23 and December 4 in 2018 and February 5 2019. Sediment dynamics during the study was tracked using the naturally occurring radioisotope Be-7. Sediments were monitored 53 days (one half-life of Be-7) prior to July 17 and during the subsequent period between sampling dates (36, 96 and 63 days, respectively). An addition sampling date was selected between August 23 and December 4, 2018 but Jordan Lake levels were extremely high during this entire period and boat access to the lake was difficult. Only once was core collection successful at Station 4 due to difficulties collecting cores in sandy sediments, and therefore Station 4 is not included in our results.

Figure 6. Coring Locations within the lower Jordan Lake. Base map displays water depths.

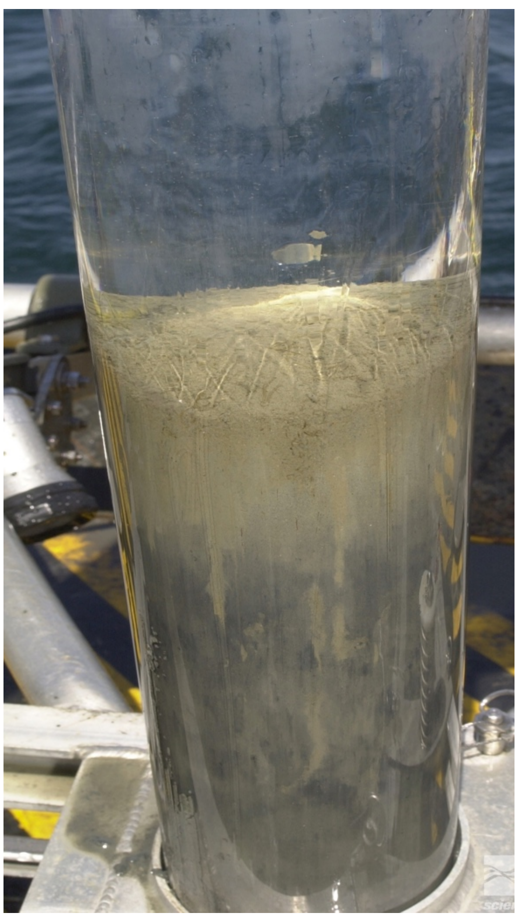


The main tracer used to track sediment deposition rates during the experiment was Be-7 which is naturally produced in the atmosphere and quickly sorbs onto particulates in the water of rivers and lakes. Once it is sorbed onto sediments it can be used to follow the pathways of particulate materials. Be-7 has a half-life of 53.3 days and therefore is very useful for tracking sediment deposition on month time scales.

Methods

Sediment cores were collected using a modified Eckman grab sampler that consistently retrieved an intact undisturbed surface sediment sample approximately 15 cm deep. Subsequently sub-cores were collected from each grab using a 4" diameter core tube. Upon return to the lab, each sub-core was extruded and sliced at precise 1 cm intervals downcore (Figure 7). Each sample was weighed wet, then frozen and freeze dried and re-weighed to determine sediment bulk density. Dried sediment was packed into vials and were counted by direct gamma spectroscopy on an intrinsic germanium planar detector. All isotopes displayed in Figure 8 below (Be-7, Pb-210, Cs-137, Ra-226, K-40, U-238) were determined by direct gamma spectroscopy.

Figure 7. Core collection, extrusion and sub sectioning



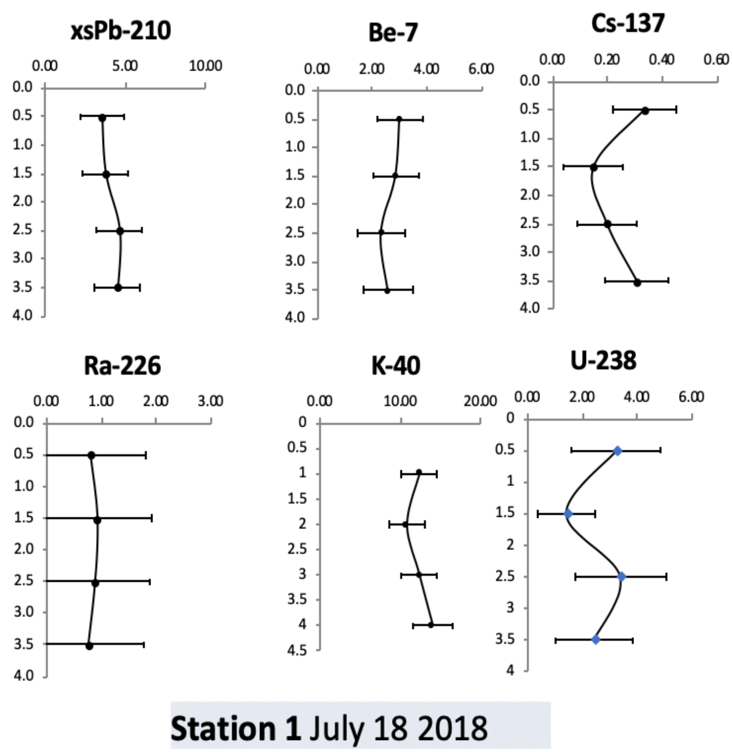
Results of Core Collection

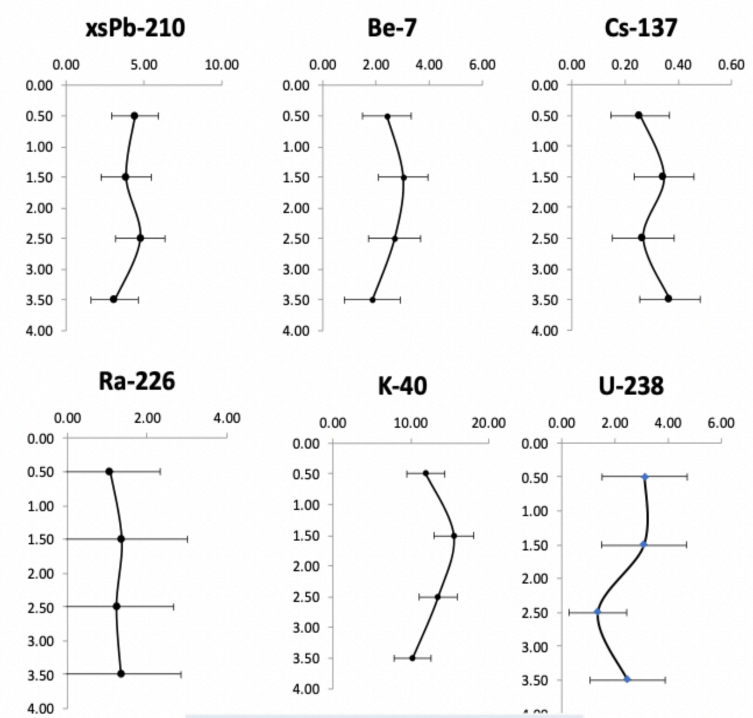
Core Profiles

Figures 7 displays the downcore profiles of Be-7 along with xsPb-210 (a longer-lived tracer with a 22.3-year half-life), which is used here as a contrast to the rapidly decaying Be-7 tracer. Also displayed are K-40, Ra-226 and U-238, which are useful in detecting possible changes in sediment sources during our experiment.

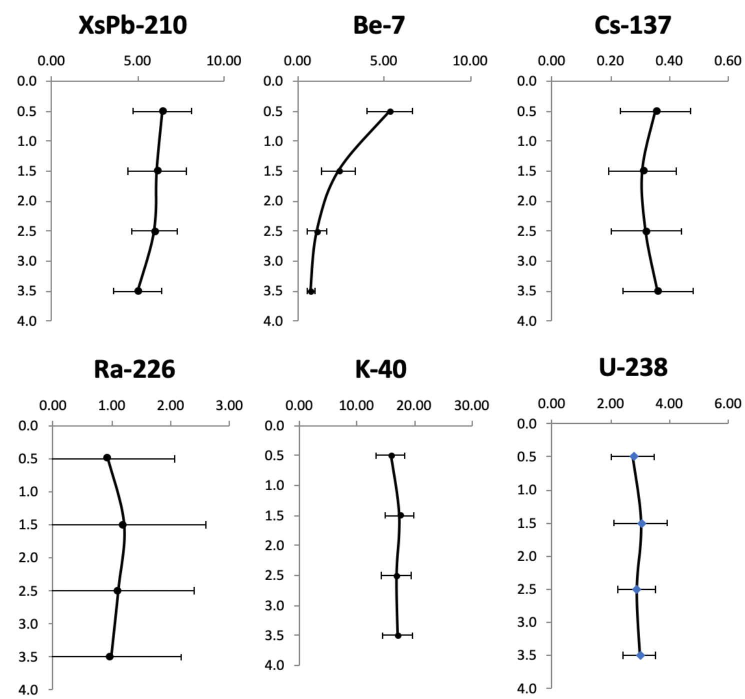
Features to note for each set of profiles are the following: (a) changing Be-7 concentrations both downcore and between stations and sampling times; and, (b) nearly constant values (within error) of xsPb-210, Cs-137, Ra-228, K-40 and U-238 downcore and between stations and sampling times. Be-7 changes are due to both decay and changes in the rate of sediment deposition and erosion. The other parameters are indicators of different sources of particulates and for all sampling times and station display very little change, indicating that the sediments being deposited were relatively constant during all sampling times, and are characteristic of terrestrial inorganic particles (ie., from the Haw River). This is important since it indicates that Haw River sediments dominate the study area (confirming sediment input data) and there appears to be very little dilution from plant and organic matter. Therefore, the changes documented for sediment deposition rates correspond to changes in Haw River sediment supply to each sampling site at specific locations and times. The deepest Be-7 concentration displayed in each figure represent the deepest layer in which Be-7 was detectible. The Be-7 profiles are used to determine sediment focusing and sediment deposition for each location and date.

Figure 8 Profiles of xsPb-210, Be-7, Cs-137, Ra-226, K-40 and U-238

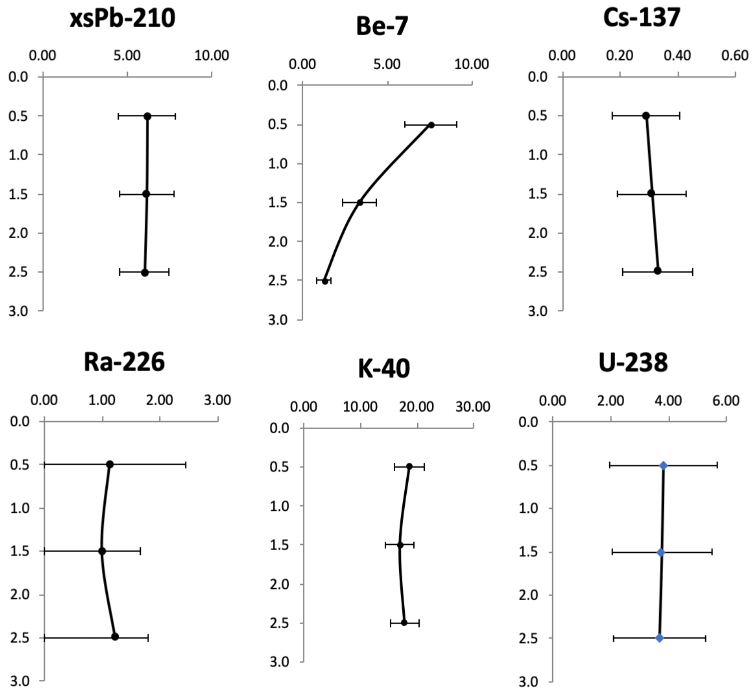




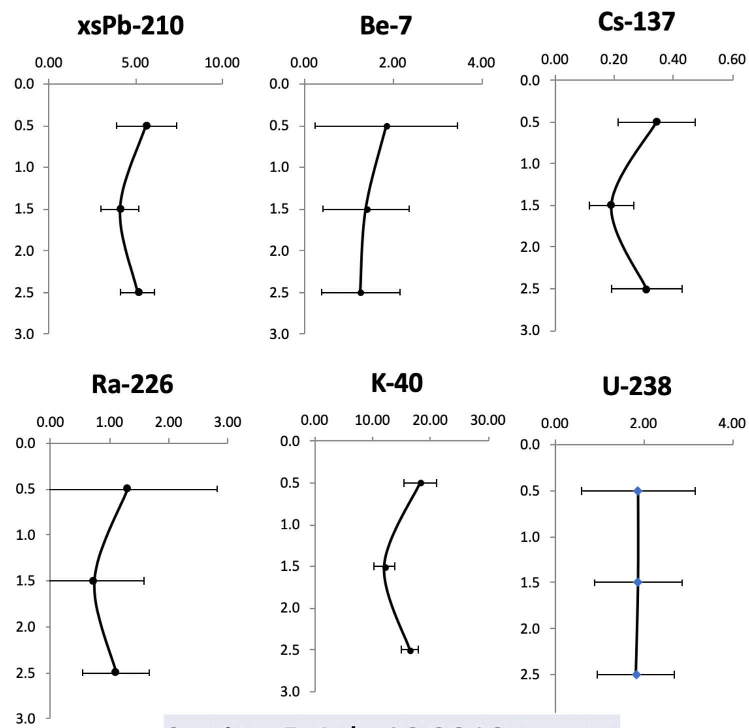
Station 2 July 18 2018



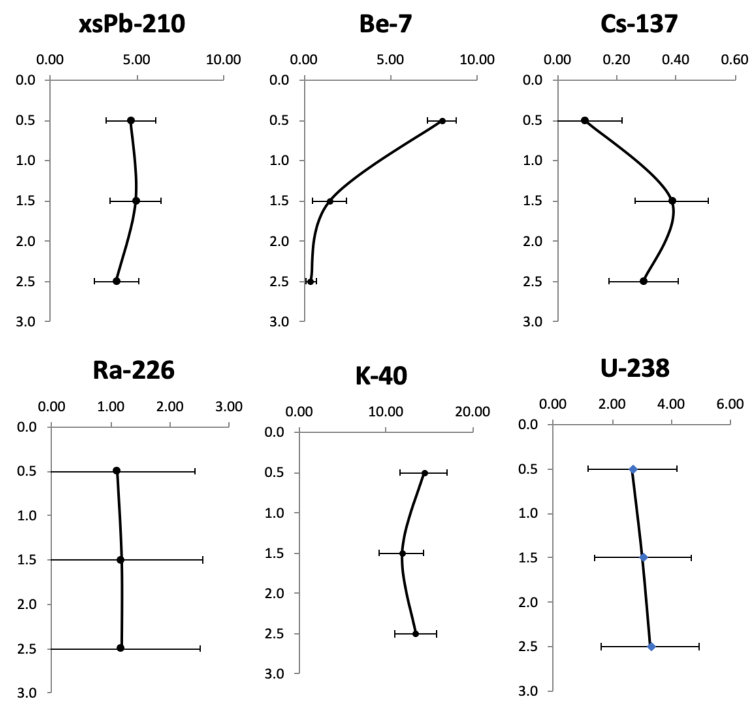
Station 3 July 18 2018



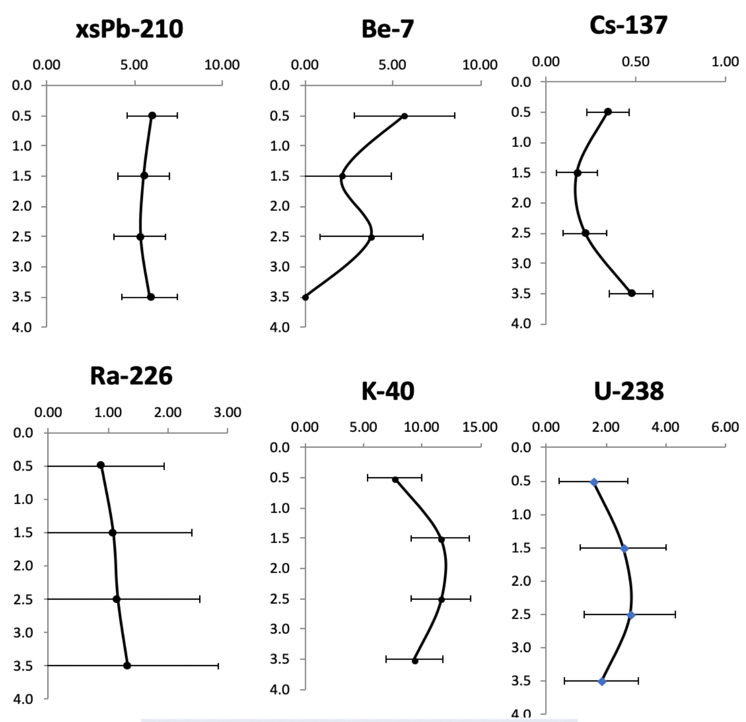
Station 4 July 18 2018



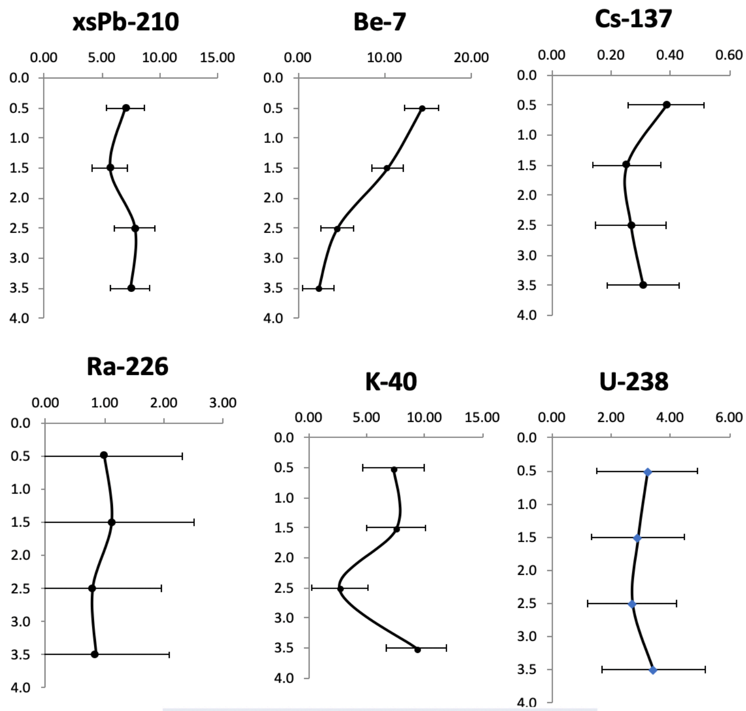
Station 5 July 18 2018



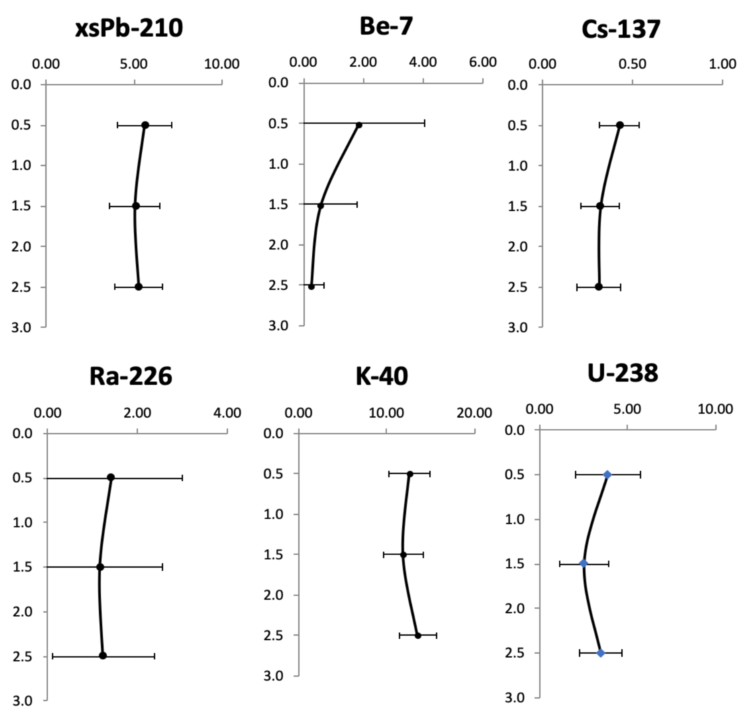
Station 2 August 23 2018



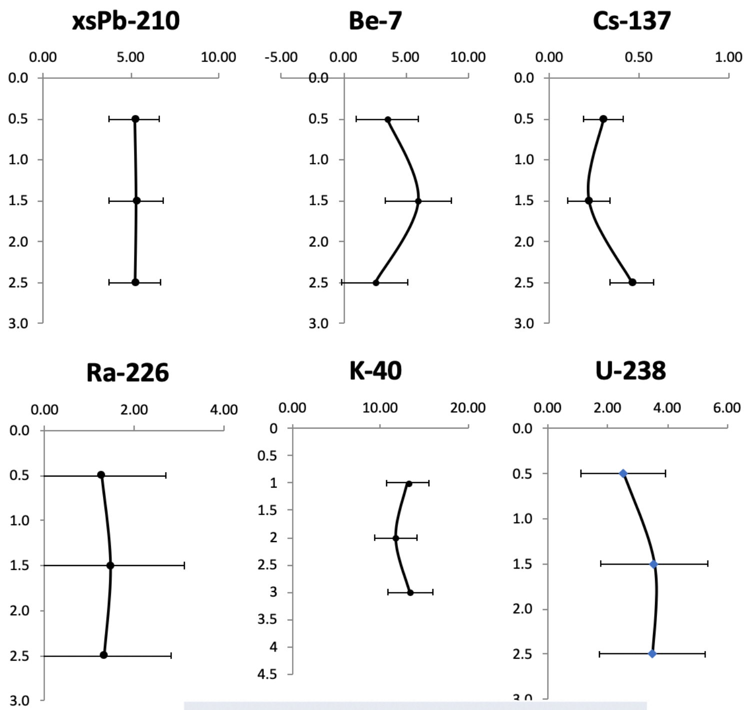
Station 3 August 23 2018



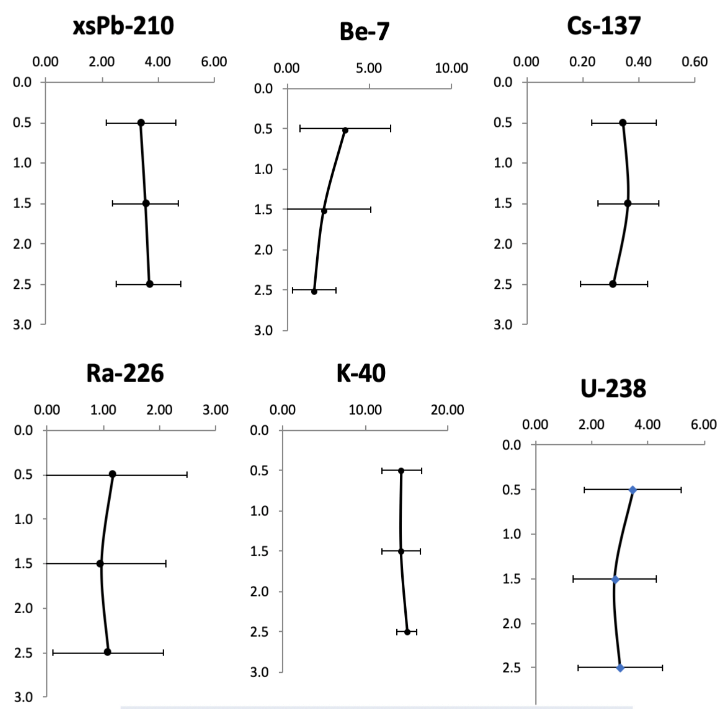
Station 5 August 23 2018



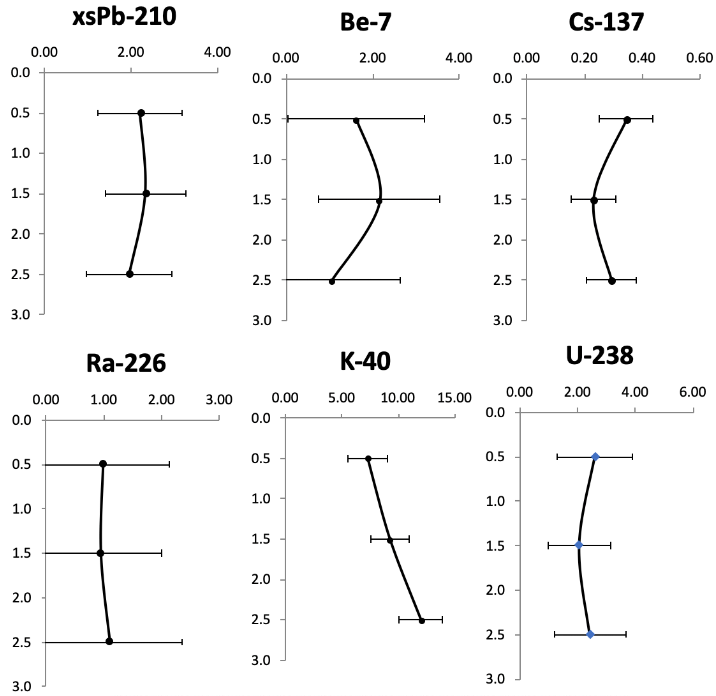
Station 1 December 4 2018



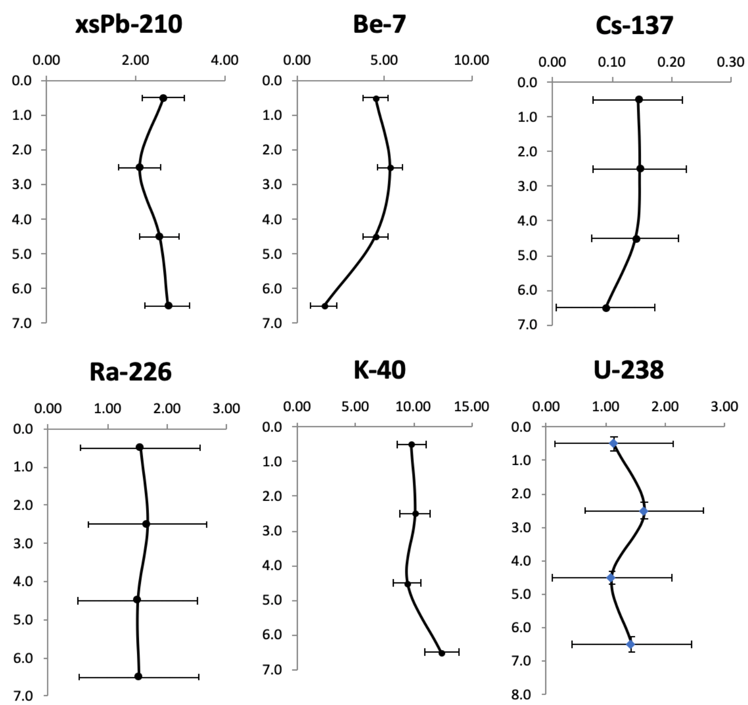
Station 2 December 4 2018



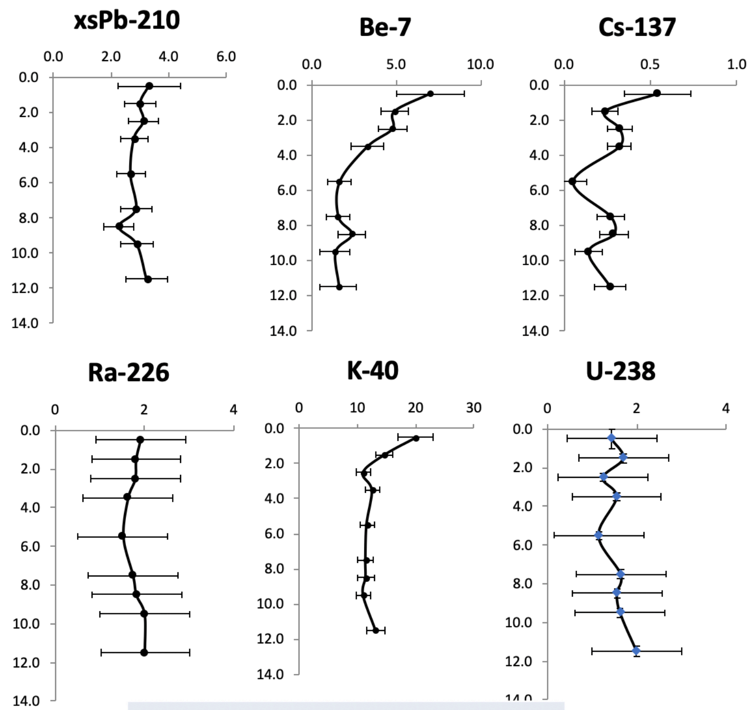
Station 3 December 5 2018



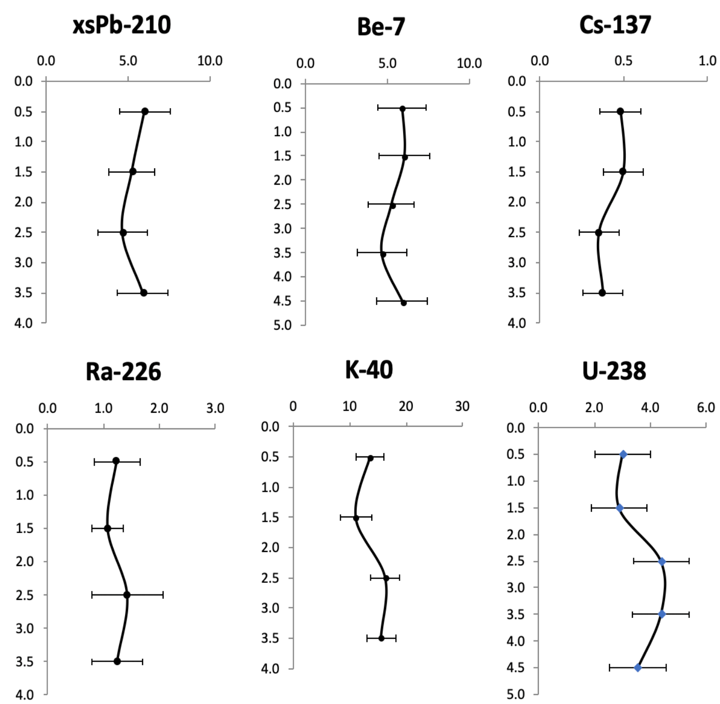
Station 5 December 5 2018



Station 1 February 5 2019



Station 2 February 5 2019



Station 5 February 5 2019

Features to note for each set of profiles are the following: (a) changing Be-7 concentrations both downcore and between stations and sampling times; and, (b) nearly constant values (within error) of xsPb-210, Cs-137, Ra-228, K-40 and U-238 downcore and between stations and sampling times. Be-7 changes are due to both decay and changes in the net rate of sediment deposition. The other parameters are indicators of different sources of particulates and for all sampling times and stations display very little change, indicating that the sediments being deposited were relatively constant during all sampling times, and are characteristic of terrestrial inorganic particles (i.e., from the Haw River). This is important since it indicates that Haw River sediments dominate the study area and very little dilution from plant and organic matter is present. Therefore, the changes documented for sediment deposition rates correspond to changes in Haw River sediment supply at the location and time. The Be-7 profiles are used to determine sediment focusing and sediment deposition for each location and date.

Be-7 Inventories and Fluxes

The mean atmospheric supply of Be-7 to North Carolina is 0.05 $dpm/cm^2/day$ (Figure 9). The presence of Be-7 in collected cores is usually restricted to the top few centimeters since the source of Be-7 is atmospheric. The sum of all Be-7 (in all layers within the core) is referred to as the “Be-7 inventory”. The Be-7 flux from the atmosphere that is required to maintain the observed Be-7 inventory in a core (termed the “actual” Be-7 flux) is determined by multiplying the Be-7 inventory by the Be-7 decay constant (0.01876 per day). A comparison between the atmospheric supply and the “actual Be-7 flux measured in a core is used to determine sediment loss or sediment focusing at a location. This is called the “relative Be-7 flux” and if this number is greater than 1 (actual/atmospheric) then sediment focusing from other parts of the lake system is indicated. This is called convergence. If the relative flux is less than one, then sediment erosion and dispersal from this location to other sites is indicated. This is called divergence. Figure 10 demonstrates that convergence and divergence of sediments are temporally and spatially variable. Note that nearly constant values (within error) of xsPb-210, Cs-137, Ra-228, K-40 and U-238 downcore and between stations and sampling times indicate that the convergence and divergence of sediment is the result of movements within sediments supplied by the Haw River.

Figure 9 Source of Be-7 to Jordan Lake

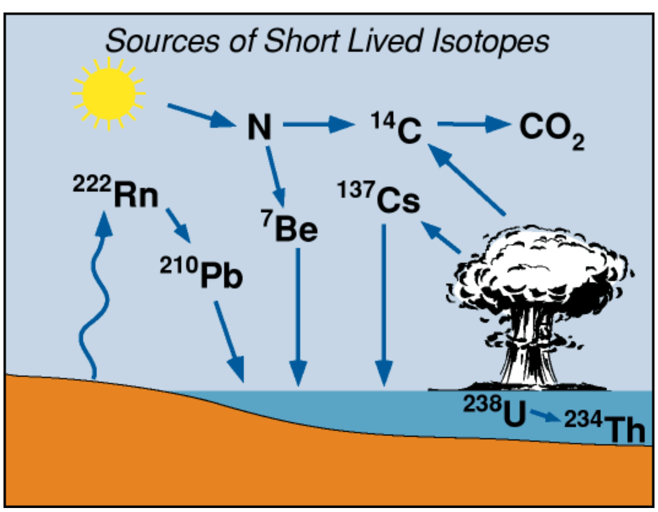
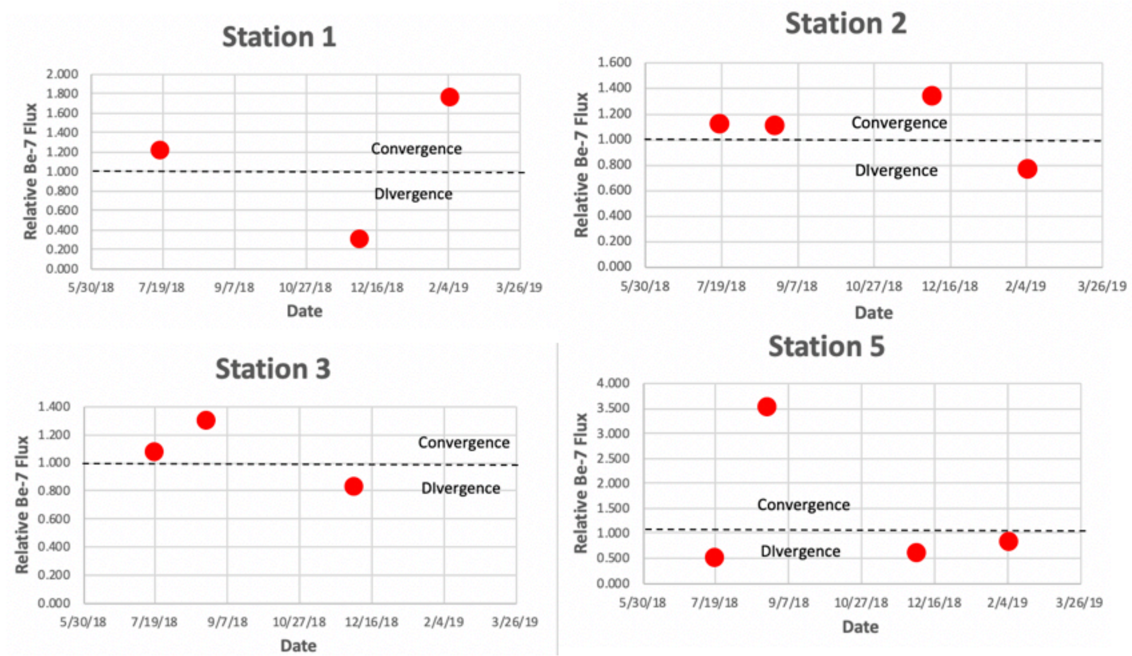


Figure 10 Relative Be-7 fluxes and sediment focusing



Station 1 (most adjacent to the Haw River input) results (Figure 10) indicates a net focusing at this site with the exception of the December 2018 sampling, which integrated over a period of two event scale sediment inputs from the Haw. This net sediment dispersal from this site for this time frame indicated that originally deposited sediment delivered by Florence and Michael were resuspended and redistributed away from Station 1. Station 2 results indicate that this site within the southern part of the Narrows is a depocenter during most of the study period. Only the period prior to core collection in February 2019 displays a minor net removal of sediments. Station 3 further north within the Narrows also appears to be net depositional (similar to Site 2), with the December 2018 sampling date indicating a minor deficit of sediments. Station 5 results demonstrate that this site is net erosional (except for the period prior to the August 2018 sampling, which is highly depositional). This site is the most distal from the Haw River input and was selected to observe the amount of sediments that make it through the Narrow and is deposited in the middle lake. Based on the data displayed in Figure 10, the net deposition of Haw River sediments into the middle lake is usually minimal but pulses of sediments occasionally (represented by the July-August 2018 period) during periods when lake levels are stable and very little water is being passed through the dam.

For each core collected, the calculated "New" inventory is the observed Be-7 inventory in the sediments that is decay corrected to remove the Be-7 from the previous core sample that remains at the site. The "New" inventory divided by the mean concentration of Be-7 in the core yield a sediment deposition rate ($g/cm^2/day$). To make this number more applicable to use in the field, we have converted this to $g/m^2/day$ and it is plotted in Figures 11 and 12.

Figure 11. Deposition rates ordered by sampling times

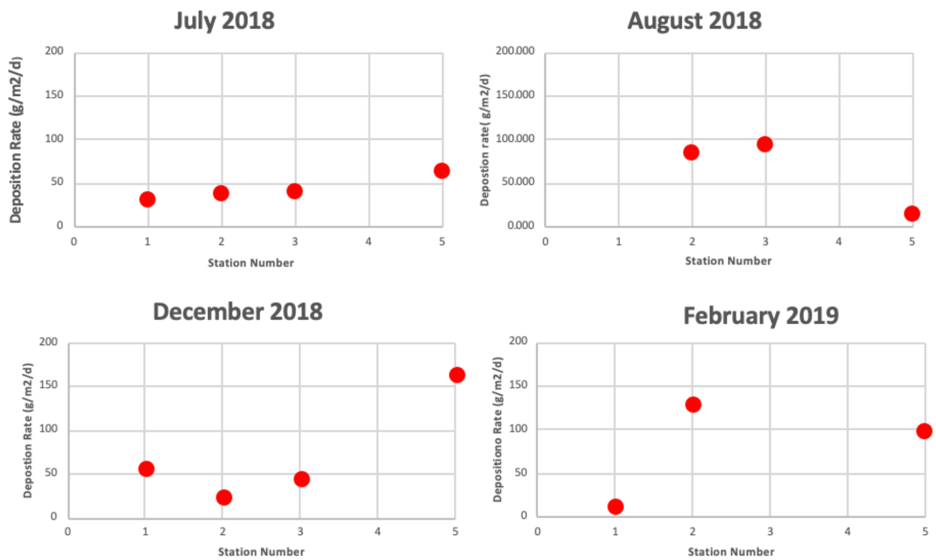
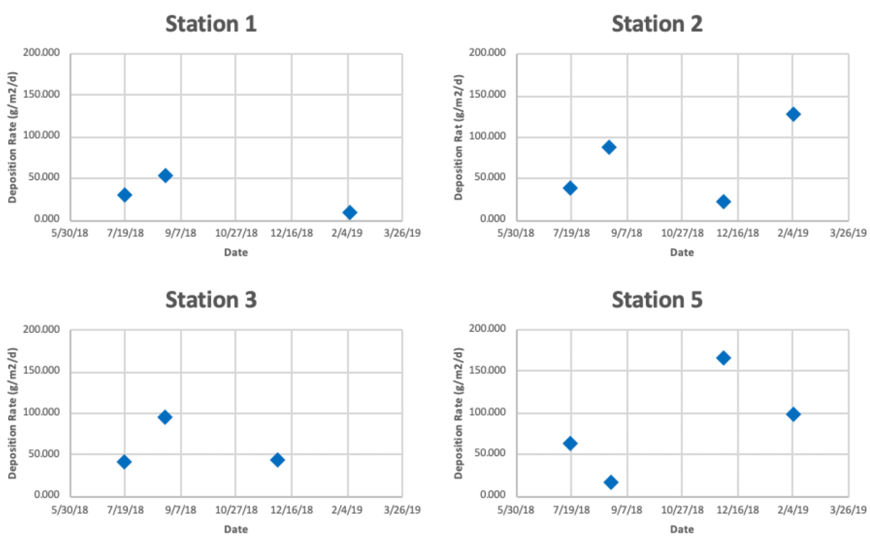


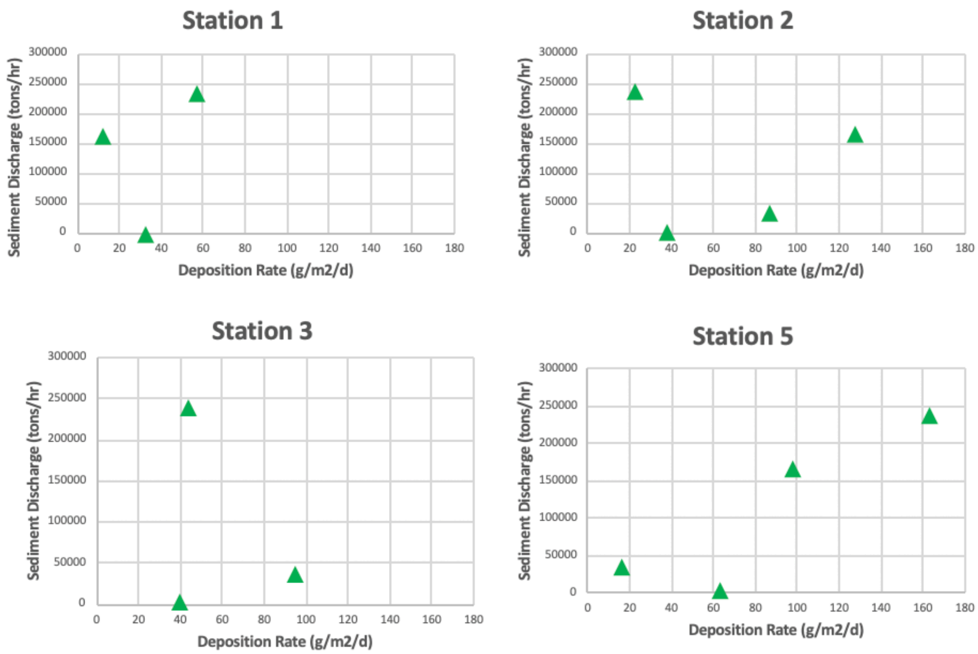
Figure 12. Deposition rates ordered by sampling stations



Consistent with the Figure 10 results, the highest deposition rate observed was at Station 5 during the period prior to December 2018 (over 150 g/m^2/d). Although these deposition rates are high, this site experiences net loss during other sampling periods (Figure 10). Deposition rates at all sites are temporally variable, indicating a complex relationship between sediment supply from the Haw and sediment deposition at sites 1-5.

Combining the information given in Figures 5 and 12, a comparison can be made between the sediment supply from the Haw River at each station and each sampling date and the observed deposition rates for each core. This provides insight as to where and when the pulses in Haw River sediment discharge influence the rate of sediment deposition (Figure 13). If the relationship between sediment discharge and deposition rate is positively linear at a site, this suggests that sediment discharge from the Haw is the governing factor controlling sediment deposition at a location and date. When sediment discharge and sediment deposition rates are poorly correlated, this suggests that post depositional resuspension and redistribution is the governing process (displayed in Figure 13).

Figure 13. Comparison of cumulative sediment discharge and net deposition rates



With the possible exception of Station 5, there is a poor correlation at sampling locations with the net sediment supply from the Haw during the period represented by the core data. In other word, the Haw River sediment discharge appears not to be the primary factor controlling sediment deposition in the lower area of Jordan Lake represented by Stations 1-5 in this study.

Data Analysis and Interpretation

Sediment discharge to Jordan Lake from the Haw River was dominated by Hurricane Florence and Tropical Strom Michael during the study period (Figure 5). Be-7 profiles were analyzed to determine sediment deposition rates at each of the core sites (Station 1-5; Figure 6) and during four sampling periods prior to July 2018, August 2018, December 2018, and February 2019 (Figure 8). Be-7 concentrations and total inventories varied temporally (sampling dates) and spatially (stations 1 to 5). The other sediment parameters that were measured in each core indicate that the Haw River is the dominant source of sediments to the study area and that no significant additional sources of sediments (organic inputs from land, organic debris from surface water productivity) are evident in the lake bottom sediments examined. Inorganic sediments from land (suspended river sediments) have a characteristic signature of uranium decay series radioisotopes (U-238, Ra-226, Pb-210) that did not change over the course of the study. Cs-137 is a man-made impulse tracer that entered the atmosphere via above-ground nuclear bomb testing (Figure 9). Its atmospheric concentration and flux from the atmosphere to land/water peaked in 1963. Cs-137 concentrations in the cores collected were very low and without any indication of sub-surface peaks, making Cs-137 unusable as a sediment tracer in this study. K-40 is another isotope whose signal come exclusively from land. Its uniform distribution within all cores further indicate that the sediments examined in this study entered Jordan Lake from the Haw River.

Be-7 is naturally supplied to surface land and water from the atmosphere. Previous work has documented the average Be-7 flux from the atmosphere to land and water surfaces in North Carolina is 0.05 $dpm/cm^2/day$. Be-7 is rapidly associated with particulate material via adsorption and subsequently follows the pathways of the associated particles. The atmospheric supply of Be-7 can be compared to the Be-7 flux required to sustain the total amount of Be-7 in each core location (Be-7 inventory). The ratio of atmospheric flux to the actual flux measured in sediment cores provides insights regarding the net accumulation of Be-7 at a site and whether sediments are preferentially focused in one place or if the sediments initially deposited have been eroded and redistributed elsewhere. This is called sediment convergence (focused) and divergence (eroded), respectively. Relative Be-7 fluxes are used to better understand how sediments from the Haw River are distributed after entering Jordan Lake. The Narrows Experiment outlined in this report tracked where Haw River sediments were dispersed from the lower Haw River arm of the lake through the restricted channel ("The Narrows") and into the middle lake where municipal freshwater intakes are located.

Figure 10 suggests that sediments are constantly deposited and redistributed at every station. Depending on the time of sampling, every station demonstrates sediment convergence and divergence. This is consistent with a surface sediment layer on the lake bottom whose thickness increases and decreases (is deposited and subsequently eroded and redistributed) throughout the year. If sediment discharge from the Haw River dominated sediment distribution within the lower lake and through the narrows, then one would expect that deposition rates would correspond closely to the cumulative sediment discharge during the period prior to core collection. The December 2018 sampling should therefore exhibit the highest rates of deposition since this period included the large sediment inputs resulting from Hurricane Florence and Tropical Storm Michael. This is not the case, with the exception of Station 5 in December 2018. It is possible that more sediment is transported through the Narrows and is deposited within the middle river during very high discharge events. However, the relative flux of Be-7 at Station 5 in December 2018 does not indicate a net sediment focusing there. In fact, the observed distribution of sediment deposition rates (in space and time) argue that sediment supply from the Haw River is not the dominant factor determining sediment deposition at any one place or time but rather post-depositional movement of sediments resulting from physical processes (resuspension and redistribution by currents) appear to be very important. This is consistent with observations of Drs. Luettich and Seim, whose team measured surface to bottom current velocities. They found that strong currents enter and exit The Narrows periodically and that current directions vary from north-to-south to south-to-north over relatively short time periods (hours to days). Current velocities (direction and magnitude) that redistribute lake bottom sediments may be controlled by the lake water balance whereby when lake levels are high and water is released through the dam into the Cape Fear River the net water balance (and current directions) are north-to-south. When lake levels are rising due to increased water inputs from the Haw River, then net current directions are from south-to-north. The shear strength of these bottom currents is likely to be strong enough to resuspend and transport fine bottom sediments.

In essence, physical water circulation (not Haw River discharge) is more likely to govern the distribution of bottom sediment in the lower lake, and through The Narrows into the middle lake.

Summary and Conclusions

The Haw River delivers 89% of the suspended sediments entering Jordan Lake each year. The suspended sediment load delivered to Jordan Lake increases with the Haw River water discharge. The Haw is a "flashy" river, a hydrologic term indicating that water discharge and river levels change rapidly in response to precipitation events. Figure 14 shows a cross section of the Haw River at Bynum taken on consecutive days. This illustrates how rapidly water discharge and suspended sediment concentrations change in the Haw. During the study period, two strong events occurred (Hurricane Florence and Tropical Storm Michael) that increased the Haw River water and sediment discharge.

Figure 14

Water Discharge: 2.4 m^3s^{-1}
Total Suspended Sediment Concentration = 7 mg l^{-1}

Water Discharge: 1213.5 m^3s^{-1}
Total Suspended Sediment Concentration = 335 mg l^{-1}

Prior to this study, it was widely believed that strong storm events like Florence and Michael controlled sediment dispersal and redistribution in the lower and middle regions of Jordan Lake. The restricted passage known as "The Narrows" has been hypothesized as one possible control on sediment transport from the Haw River to the middle lake. This line of reasoning hypothesized that slow currents within "The Narrows" would result in trapping of sediments in the lower (Haw River) arm of the lake or possibly with the Narrows. Our findings lead us to the conclusion that sediment inputs from the Haw are a secondary factor in determining sediment distributions in Jordan Lake and that physical processes (erosion, resuspension and redistribution by currents) are probably the driving force for sediment transport in Jordan Lake.

This conclusion points to a need for better understanding of the coupling between physical circulation and sediment dispersal, especially on event scales. The role of water removal from the lake via the dam is poorly understood as is the physical factors that lead to more sediment being shunted to the lower Cape Fear River.