Water Resources Research Institute
of The University of North Carolina

Report No. 363

SEDIMENT RESUSPENSION IN THE PAMLICO AND NEUSE RIVER ESTUARIES AN ADDITIONAL SOURCE OF NUTRIENTS AND CONTAMINANTS

By
D. Reide Corbett, Stan Riggs, and Dan Giffin

Department of Geology
Coastal Resources Management
East Carolina University
Greenville, NC 27858

October 2007

UNC-WRRI-363

SEDIMENT RESUSPENSION IN THE PAMLICO AND NEUSE RIVER ESTUARIES AN ADDITIONAL SOURCE OF NUTRIENTS AND CONTAMINANTS

by
D. Reide Corbett, Stan Riggs, and Dan Giffin

Department of Geology
Coastal Resources Management
East Carolina University
Greenville, NC 27858

The research on which this report is based was supported by funds provided by the Water Resources Research Institute of The University of North Carolina (WRRI). Contents of the publication do not necessarily reflect the views and policies of the WRRI, nor does mention of trade names of commercial products constitute their endorsement by the WRRI or the State of North Carolina.

This report fulfills the requirement for a project completion report of the Water Resources Research Institute of The University of North Carolina. The authors are solely responsible for the content and completeness of the report.

WRRI Project 70187

October 2007

ACKNOWLEDGEMENTS

This project could not have been completed without the help of a several individuals. In the field and laboratory, Matt Allen, Chris Foldesi, James Frank, Lorin Gaines, and David Vance all helped in many ways. Without the help of Debbie Daniel in the Central Environmental Laboratory of the Biology Department, ECU, many of these analyses would not have been completed. Rick Leuttich was kind enough to allow us to moor one of his current meters in the Neuse River. Catherine Rigsby provided assistance and equipment for grain size analysis. Much of the interpretation was hinged on weather data provided by JoAnn Burkholder, Howard Glasgow, and Robert Reed of the NCSU Center for Applied Aquatic Ecology.

This research was supported in part by the Department of Geology and a Research/Creativity Grant sponsored by East Carolina University. Major funding was provided through the NC Water Resources Research Institute. We thank the staff at Water Resources Research Institute for seeing the need to fund this research and for their pleasant help and support.

ABSTRACT

The Neuse and Pamlico river estuaries are shallow, dynamic systems that have been plagued with symptoms of eutrophication over the past two decades. Extensive research has been conducted over the last 5-10 years to better understand the complex nutrient dynamics of these systems. However, most of these studies have concentrated on nutrient cycling in the water column. Only recently have studies focused on the benthic environment, and most sediment studies have neglected the dynamic nature of the benthos, focusing instead on diffusion as the dominant transport process delivering nutrients to the water column. Although diffusion of nutrients across the sediment/water interface may be important during quiescent periods of sediment deposition and short-term storage, wind events associated with storms throughout the year will resuspend newly deposited sediments resulting in the advective transport of sediment porewater, rich with nitrogen, phosphorus and carbon, into the water column. Sediment resuspension may increase water column nutrient concentrations, and therefore present estimates of nutrient and carbon inputs from the sediments may be too low.

This project estimated short-term sediment dynamics and flux of nutrients released to the water column from natural resuspension events in these two estuaries. Sediment cores at 9 sites in the estuaries have been collected at least bi-monthly since May 2001. The short-term rate of sediment deposition was evaluated using the naturally occurring radionuclides Be-7and Th-234. Porewater nutrient inventories at all sites have also been determined. This technique has allowed the evaluation of the depth to which sediments have been disturbed and the advective flux of nutrients to the water column. Evaluating this advective flux of nutrients to the water column is crucial to understand estuarine nutrient cycling.

(Key words: sediment, resuspension, nutrients, diagenisis, eutrophication, porewater, water quality, radionuclides)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SUMMARY AND CONCLUSIONS

The overall effectiveness of sediment resuspension and remobilization in introducing diagenetic end-products from porewaters into overlying coastal waters was examined. The study period, May 2001 – May 2002, turned out to be a fairly quite year relative to large weather events, e.g. Hurricanes, Northeasters, etc. A preliminary laboratory study was performed to evaluate whether resuspension of sediments actually contributes to increases in the nutrients nitrogen and phosphorus in overlying waters. Results of this preliminary experiment indicated a 17% increase in dissolved nitrogen and a 12% increase in dissolved phosphorus following the resuspension event. TSS increased an order of magnitude from a mean value of 34 mg/l to ~340 mg/l. This advective transport of porewater constituents can serve to greatly alter the concentration and phase partitioning of contaminants in the overlying waters.

The short-term rate of sedimentation and nitrogen/carbon (N/C) deposition was determined at select locations in the Neuse and Pamlico River Estuaries over this12-month period. Variations in ^{7}Be and ^{234}Th inventories are good indicators of deposition and removal processes in estuarine environments. As previous studies have indicated, the main deposition area for the Neuse River, as indicated by the short-lived tracers, occurs primarily around NR-3 and NR-4. Total inventories at most locations in both estuaries showed large variations between sampling events. The largest variations in the Neuse River were found in the lower estuary between NR-4 and NR-6. The largest sediment removal in the Neuse was observed during August 2001 at the downriver stations NR-4 through 6, while the second greatest episode was observed in February 2002 at Stations NR-2 and once again at Stations NR-5 and NR-6. These are the areas most susceptible to wind driven sediment disturbances. The largest depositional episode was observed in July 2001. Interestingly, the Pamlico didn't show as large a variation in total inventory throughout the estuary as the Neuse, this is probably associated with the size and dominant direction of wind events (northwest/northeast). The only observed removal in the Pamlico occurred in August at PR-1.

It was shown that the amount of sediment resuspended in a removal episode can be calculated using the ^{7}Be inventory lost in dpm cm^{-2} and assuming only the top most sediments are involved to determine the surface activity in dpm $^{-}$g. This calculation gives the amount of sediment resuspended. Using a simple relationship developed by Hjulstrom, one can approximate the depth of a resuspension event. The largest removal in the Neuse in August 2001 at NR-6 involved a ^{7}Be inventory loss of 0.7893 dpm cm^{-2} in the top several centimeters where the ^{7}Be activity measured was 1.79 dpm g^{-}. This means that sediment removal was about 0.44 g cm^{-2}. Bulk density in the upper sediments was determined to be approximately 0.2 g cm^{-3}. Using this bulk density for the amount of sediment removed shows that the removal involved the top 2.2 cm of sediment. It should be noted that this maximum removal occurred in a year of monitoring in which there was very little storm activity and river discharges were at a minimum.

Frequency of sediment resuspension events was measured utilizing meteorological data and in situ sensors. Two turbidity meters and one velocity meter were installed on monitoring platforms currently being used by NCSU. These sensors aided in measuring total suspended sediment, conductivity, and current velocity. The Cherry Point location has been maintained for long term monitoring. These remote devices provided information throughout several weather events when it was impractical to physically sample. Current velocity data for the Neuse River estuary show that currents are predominantly 10-20 cm/sec and rarely obtain values of 30-40 cm/sec with only slight observations in the 50-60 cm/sec range. Turbidity measurements indicated resuspension of sediments primarily during wind events ≥ 8 m s^{-1}. These events occurred mostly as the result of northwesterly and northeasterly winds since these have the greatest fetch. Peak events occurred during the winter months when these wind directions were prevalent. Current data indicated that reversals with higher velocities (≥ 30 cm/sec) appear to be correlated with the larger turbidity events which indicates that these frontal passages are likely the responsible for the majority of the resuspension events. These data could provide useful information for future model development.

Although the ^{7}Be data indicates deposition during the majority of the sampling events, the high total ^{234}Th inventories indicate increased interaction of bottom sediments and the water column on the time scale of days to weeks. It is believed these deviations from a depositional environment can be related to wind events that occurred between the two sampling periods.

Cs-137 and Pb-210 activity indicated deposition rates of 1.4 to greater than 5 mm yr^{-1} which are in close agreement to rates determined more then 10 years ago prior to the passage of several major hurricanes, including Floyd. Interestingly, this points to the apparent lack of any long-term effects on the sediment budget by these major weather events. Areas of sediment accumulation and removal that were indicated by ^{137}Cs activity were also in close agreement to those areas indicated by the short-lived radioisotopes.

The magnitude of diagenetic transformations occurring in estuarine sediments at all sites was determined by characterizing changes in porewater concentrations of selected constituents that occurred due to storm/wind events that disturbed the sediment/water interface. Cores were collected from 9 sites in the estuaries and processed for solid phase and porewater analyses. Water column samples for nutrient analyses were also collected at each site. Solid phase data (C/N) was also collected. With this data, porewater profiles and inventories of biotransformation products (N/P) were correlated with the information on deposition and histories of removal events**.** These bi-monthly comparisons of N/C solid phase profiles and inventories of N/P in porewater serve as a basis to better understand the short term and seasonal history of sediment composition at each site.

Results from the sampling of surface and bottom waters of the Neuse showed the physical parameters, salinity and dissolved oxygen (DO), have been strongly influenced by drought conditions that limited discharge to the Neuse River over the last year. A distinct wedge can be seen in the upper estuary throughout most of the year with high salinities in the bottom water. . DO levels in surface water maintained well above hypoxic conditions (<2 mg/l) throughout the entire sampling period while hypoxic conditions were observed with nearly anoxic levels in bottom waters of the upper estuary. The periods of bottom water hypoxia seem to correspond with contemporaneous increases of bottom water salinity and increased stratification. Ammonium (NH_4^+) concentrations in surface and bottom waters showed decreasing values toward the estuary mouth and were greatest upriver. The highest levels were in summer and December. NH_4^+ levels in bottom water correlate with oxygen depletion as previously stated in Modmon (Luettich et al, 2000). These elevated concentrations also correspond with periods of sediment removal in the system. Nitrate (NO_3^-) and nitrite (NO_2^-) concentrations in surface water while bottom water NO_3^- and NO_2^- concentrations show depletion especially in the upper part of the estuary due to a possible combination of benthic uptake and plankton assimilation (Christian et al, 1991). Oxygen depletion could also account for this observation. PO_4^- surface and bottom water concentrations were highest in summer and December. The August sampling followed a period of increased sediment removal in the estuary. Porewater concentrations were also determined for NH_4^+, NO_3^- and NO_2^-, and PO_4^- in the top 10 cm of river sediments at each station. NH_4^+ concentrations displayed highest levels in late summer and lowest in spring. Levels increased downstream to Station 2, an area of documented fish kills, and then decreased towards Cherry Point. Vertical profiles exhibited the same increasing concentrations with depth to about 20 cm as previously shown in Modmon. Porewater NH_4^+ concentrations were generally higher at times and locations of increased sediment removal. PO_4^- concentrations displayed the same general trends as porewater NH_4^+ concentrations. Nitrate and nitrite exhibited the same spatiotemporal distribution as surface water NO_3^- and NO_2^-.

Overall, nutrient concentrations in the surface and bottom waters of the Pamlico estuary were less elevated than those of the Neuse and displayed the same spatiotemporal trends. NH_4^+ surface water concentrations had the same spatial distribution as the Neuse with highs in February and lows in October. Bottom water concentrations generally decreased towards the mouth except for higher levels at Station 3 in winter. The higher levels at Stations 1 and 2 in August correspond to sediment removal at Station 1 during this timeframe. Porewater NH_4^+ highest concentrations were at the mid-estuary station immediately downriver from PCS. PO_4^{3-} concentrations were slightly lower than porewater ammonium but exhibited the same spatiotemporal distribution.

Concentrations of porewater and bottom water nutrients increased to higher levels during resuspension events indicating increased denitrification and release of NH_4^+ and PO_4^{3-} to overlying waters. Bottom water conditions with elevated NH_4^+ and PO_4^{3-} indicate that nutrients stored in the sediments continue to play an important role in overall water quality in these estuaries. Thus, the necessity of determining the effect of advective flux from porewaters during resuspension events becomes significant. In summary, the use of short-lived radionuclides characterized the short-term sediment dynamics enabling the comparison of nutrient concentrations during resuspension events. Concentrations of NH_4^+ and PO_4^{3-} in advected porewaters were found to be at least 2 to 15 times those reported in previous studies of benthic flux. It should be noted that these results were obtained during a year of monitoring where there was only minor storm activity and low river discharge. Thus it can be seen that, even during only wind-induced resuspension events, advection can have a greater influence on water quality than passive diffusion.

RECOMMENDATIONS

• The results of this study should be incorporated into a sediment and water quality model for these estuaries so that the effects of resuspension events can be accounted for. Current and meteorological data should also be essential parts of any forecasting tool.

• A more in-depth laboratory experiment should be performed to determine a better understanding of water quality changes due to resuspension events.

• Research of the benthic nepheloid layer should be undertaken to determine the properties, i.e. turbidity, nutrient concentration, sediment properties of this region with very high sediment concentrations.

• A more directed spatio-temporal characterization of river current should be undertaken to determine the full extent of density flow and under what conditions it occurs.

•Only with a program that incorporates modeling, long-term monitoring, and experimentation can one predict, track, and understand ecosystem change. Therefore, the MODMON program should be maintained to verify the impacts of nutrient reduction strategies.

• Data should also be collected and analyzed to examine possible ecosystem shifts from change in nutrient dynamics within these systems.

• With the ongoing monitoring and modeling results in hand, elements of the nutrient reduction strategy should be periodically reassessed and evaluated by state environmental agencies to see where they require modification to further enhance improvements to these estuaries and to generate reliable TMDLs.

1.0 Introduction

1.1 Research Need

The Pamlico and Neuse River Estuaries are shallow, dynamic systems that have been plagued with symptoms of eutrophication, including nuisance cyanobaterial and dinoflagellate blooms, bottom water hypoxia/anoxia, and fish kills over the past two decades. Nutrient loading, especially nitrogen, by increased urbanization, industrialization, and coastal development has contributed to the current water quality problems. Extensive research has been conducted over the last 5-10 years to better understand the complex nutrient dynamics of these systems. However, most of these studies have concentrated on nutrient cycling in the water column and have only recently included the benthic environment. The complex sequencing of governing processes that occur in the sediments (deposition, benthic diagenetic, transformation, resuspension/redistribution and burial) play an important role in the overall water quality of the ecosystem. Studies that have included sediment processes in this environment have neglected the dynamic nature of the benthos and state that diffusion is the dominant transport process in delivering nutrients to the water column (Fisher et al., 1982; Alperin, 2000; Alperin et al., 2000). However, the resuspension of bottom sediments results in the <u>advective</u> transport of porewater and diagenetic end-products (Nitrogen/Phosphorus/Carbon) into surface waters and serves to <u>increase water column nutrient concentrations</u>, which potentially exacerbates the poor water quality of both estuarine environments. To this date, there has not been a study that has considered the implication of sediment resuspension on water quality. It is imperative that these sediment dynamics be considered when developing an estuarine water quality model for this and any ecosystem. Therefore, this study has increased the overall understanding of nutrient dynamics in these two systems.

Recommendations from the MODMON (Luettich et al, 2000) project stated several areas of research priority. The priority research area that was addressed during this study is: Bottom sediment – water column coupling, specifically targeting better information on rates of nutrient exchange, carbon processing and the residence time of these materials in the system. This study evaluated this priority research area by using short-lived radioisotopes to understand short-term sediment dynamics and nutrient exchange and deposition.

This study has integrated physical and geochemical measurements to better understand sediment dynamics and the fate of nitrogen, phosphate, and carbon in the shallow estuarine environment of the Pamlico and Neuse Rivers. Current sediment studies do not consider sediment remobilization as a source of nutrients to surface waters, only passive benthic fluxes. Although diffusion of nutrients across the sediment/water interface may be important during quiescent periods of sediment deposition and short-term storage, wind events associated with storms throughout the year resuspend newly deposited sediments, thus <u>advecting</u> porewaters and diagenetic end-products into the overlying waters. This provides significantly more nutrients to surface waters on much shorter time scales than would be expected by diffusion alone. Therefore, present estimates of nutrient and carbon inputs from the sediments may be substantially too low. This study provides an estimate of short-term sediment dynamics and the flux of nutrients that are released to the water column, associated with sediment resuspension events, through advection rather than diffusion alone, thus providing a more realistic flux of nutrients and carbon.

Results from this study increase our current knowledge on the sediment dynamics of these two estuarine systems and other shallow coastal systems. This study fills a void in the ongoing studies of these two estuaries and could easily be integrated to provide a comprehensive understanding of the nutrient dynamics of the ecosystem. In addition, results from this study would directly enhance current efforts to develop a nitrogen model for the Neuse River Estuary.

1.2 Natural Particle-Reactive Tracers

The distinction in time scales between temporary versus permanent storage of particulate material in bottom sediments is important in determining the ultimate fate of pollutants in coastal ecosystems. This difference in time scales can be distinguished quantitatively using radiochemical techniques for establishing geochronologies within bedded sediments, and for examining rates of sedimentary processes. Radioisotopes, such as beryllium–7 (^{7}Be) and thorium–234 (^{234}Th), can be used to determine fluxes and rates of internal processes in sedimentary compartments such as rivers, estuaries and oceans. Beryllium is produced by cosmic ray spallation reactions with nitrogen and oxygen in the atmosphere. These reactions occur primarily in the stratosphere and upper troposphere where charged particles (alpha particles, electrons, and protons) induce nuclear reactions in oxygen and nitrogen atoms. Be-7 is delivered to the surface of the earth through precipitation (wet and dry) where it quickly adsorbs to particle surfaces and subsequently is deposited to bottom sediments in coastal environments (Olsen et al., 1986; Baskaran and Santchi, 1993). In contrast, ^{234}Th is primarily produced in the water column through the decay of its immediate parent ^{238}U. When utilizing radioisotopes for investigating natural processes, it is important to match the time scale of interest with the half-life of a particular radionuclide. For the purpose of this study (i.e. short- term deposition), the half-life of ^{7}Be (53.3 days) and ^{234}Th (24.1 days) enables them to be useful as particle tracers on time scales of days to months.

Some of the most common uses of ^{7}Be and ^{234}Th are to measure sediment inputs, exports, resuspension events, rates of deposition, and sediment mixing (Feng et al, 1998; McKee and Baskaran, 1999, Olsen et al, 1985, McKee et al, 1983). An understanding of these sedimentation processes is important for determining biogeochemical cycles in these environments. Sedimentation goes through three processes: deposition, removal, and accumulation (the end difference between deposition and removal). Deposition is the temporary emplacement of particulate material on a sediment surface and can be measured using ^{234}Th and ^{7}Be because of their short half-lives. Seasonal variations and storm events that impact a system can be quantified in the depositional record with these radioisotopes. The rapid scavenging of these isotopes by sediment particles is used to identify areas of increased deposition by elevated sediment inventories, e.g. down-core integration of tracer activity (Olsen et al, 1986). In addition, in an environment with limited mixing, these tracers will exhibit log-scale reductions in radioactivity with depth that can be used to determine short-term deposition and accumulation process rates (McKee et al, 1983). On a longer-term basis, year to decade range, sediment accumulation can be determined with the use of ^{137}Cs or ^{210}Pb. Cesium–137 is unique and especially helpful in this respect since areas where minimal mixing occurs will retain the fallout signature from 1963 (peak ^{137}Cs deposition) in the sediments, thus providing a distinct activity maximum during that year. By comparing deposition to accumulation rates one can derive the net erosion rate (sediment export). We have employed ^{7}Be, ^{234}Th, ^{210}Pb, and ^{137}Cs in this study to evaluate spatial and temporal trends in sediment deposition in the Neuse and Pamlico estuaries. This study represents the first time these short-lived radionuclides (^{7}Be and ^{234}Th) have been used to evaluate short-term sediment dynamics in these estuaries.

1.3 Research Objectives

This study evaluated whether seasonal and short-term sediment storage, diagenesis, and remobilization affect the cycling of nutrients and carbon in the Pamlico and Neuse River estuaries. The following specific objectives were addressed:

- Determine the short-term rate of sedimentation and nitrogen/carbon (N/C) deposition at select locations in the Neuse and Pamlico River Estuaries over a 12-month period. The distinction in time scales between temporary versus permanent storage of particulate material in bottom sediments is important in determining the ultimate fate of pollutants in coastal ecosystems. The terms used to describe sedimentation on various time scales can be distinguished quantitatively using radiochemical techniques for establishing geochronologies within bedded sediments, and for examining rates of sedimentary processes. Deposition is the temporary emplacement of particulate material on a sediment surface. Burial (accumulation) is the sum of deposition and removal over a longer time scale (McKee et al., 1983). Cores were collected at select sites bi-monthly and on selected event scales (associated with the passage of storm/wind events) to evaluate these processes.

- Measure frequency of sediment resuspension events utilizing meteorological data and sensors. Two turbidity meters and one velocity meter were installed on monitoring platforms currently being used by NCSU. These sensors aided in measuring total suspended sediment, conductivity, and current velocity. The turbidity meters were initially installed at a station near New Bern and a station near Cherry Point for baseline data. The Cherry Point location has been maintained for long term monitoring. These remote devices provided information throughout several weather events when it was impractical to physically sample. These data could provide useful information for future model development.

- Determine the magnitude of diagenetic transformations occurring in estuarine sediments at all sites by characterizing changes in porewater concentrations of selected constituents that occur due to storm/wind events that disturb the sediment/water interface. Cores were collected from 9 sites in the estuaries and processed for solid phase and porewater analyses. Water column samples for nutrient analyses were also collected at each site. Porewater profiles and inventories (i.e., depth integrated sum of an individual interstitial contaminant within the core) of biotransformation products (N/P) were correlated with information on deposition rates and histories of resuspension events. Bi-monthly comparisons of N/C solid phase profiles and inventories and N/P in porewater served as a basis to better understand the short term and seasonal history of sediment composition at each site.

- Examine the overall effectiveness of sediment resuspension and remobilization in introducing diagenetic end-products from porewaters into overlying coastal waters. During the remobilization phase, bed sediments and associated pore fluids are likely to be resuspended and introduced into the overlying water column. This advective transport of porewater constituents can serve to greatly alter the concentration and phase partitioning of contaminants in the overlying waters. This has been observed in many natural environments (see references in Carper and Bachman, 1984). The resultant change in partitioning of contaminants directly affects the transport pathways and bioavailability of these constituents. The study of distribution and fate of diagenetic products in the water column is important because deposition, diagenesis, and subsequent <u>advection</u> of diagenetic products, are additional processes in the nutrient/contaminant pathway, which are often overlooked. Quantification of such processes is essential for the refinement of geochemical mass balances and the prediction of contaminant fate (Turner et al.,1993). The timely prediction of diagenetic advection (on a time frame useful for opportunistic sampling) is not possible, since episodic events such as flood and tidal oscillations cause resuspension of the bottom sediments. Also, measurement of diagenetic products in the water column is extremely difficult due to the dilution effects, especially in a dynamic environment such as the proposed study area.

  A preliminary laboratory study was performed to evaluate whether resuspension of sediments actually contributes to increases in the nutrients nitrogen and phosphorus in overlying waters. The study consisted of the collection of two 40 cm cores in tubular microcosms from the Neuse River for the sediment resuspension experiments. Bottom river water from the same location as the cores was also collected in a sufficient amount to establish at least a 20 cm water column above the microcosm sediments in each core. Baseline samples were collected from each microcosm and analyzed to determine total dissolved nitrogen (TKN), total dissolved phosphorus (TDP), and total suspended sediment (TSS). After several days to allow for the settling of suspended sediments, one microcosm was maintained as the control while the other was agitated by increased stirring to simulate a resuspension event. Both microcosms were then sampled again several times for TKN, TDP, and TSS. A comparison of the results determined the overall impacts of resuspension to the gross impacts of nutrients on water quality.

  In the field, the effectiveness of resuspension in releasing diagenetic end-products from bottom sediments was directly measured by comparing the porewater inventories of nutrients before and after specific resuspension events (e.g., predictable frontal passages). Turbidity meters were deployed to record sediment resuspension. In addition, measurement of the short-lived radionuclides allowed the evaluation of the depth to which sediments had been disturbed. ***Using this information, estimates of the total advective flux of interstitial fluids can then be quantified by accounting for porosity and the interstitial contaminant concentration.***

2.0 Background

The Neuse River is one of the oldest rivers in the United States and has the widest river mouth on the continent. It is also part of the second largest estuarine system, in combination with the Tar-Pamlico River system and Pamlico Sound, with a drainage basin covering 6,192 square miles through 19 counties. One-sixth (~ 1,500,000 people) of North Carolina's population live in this basin. Both the Pamlico and the Neuse are Type A estuaries (Pritchard, 1955), which are dominated by river flow and characterized by internal wave mixing, high stratification and increased sedimentation in their salt wedge areas.

2.1 Study Area

Bottom sediments in both estuaries are related to the bathymetry. Simply, the shoulders of the estuary are typified by medium and fine grained sands, while the deeper regions are predominantly organic-rich muds with little lithologic variability (Alperin et al, 2000).All sample locations were located near the center of the river within the organic-rich muds. Six sites (**Figure 2.1**) were selected in the Neuse River based on proximity to MODMON sediment sampling locations and North Carolina Division of Water Quality (DWQ) Ambient Monitoring System (AMS) locations in order to allow for comparative evaluation of some of the data obtained. The sites covered a salinity range of 0-10 ppt near the Trent tributary up to the mesohaline (15-30 ppt) waters near the mouth. Three stations were chosen in the Pamlico River based on physiographic similarity to stations sampled in the Neuse and to correspond with the low, mid, and higher salinities (one at 0-1 ppt, one at 5-10ppt, and one near the mouth). Distances downstream, from New Bern for the Neuse and Washington for the Pamlico, are shown in **Table 2.1**.

It has been suggested that most of the surface sediments within these estuaries will be deposited and resuspended many times before permanent accumulation on the bottom (Wells and Kim, 1989). This is due to the fine-grained nature of the sediments, the shallow water character of the sediment basin, and the high levels of wind stress on the basin (Riggs et al., 1991).

The complex sequencing of governing processes that occur in the sediments (deposition, benthic diagenetic, transformation, resuspension/redistribution and burial) play an important role in the overall water quality of the ecosystem. Studies that have included sediment processes in this environment have neglected the dynamic nature of the benthos and state that diffusion is the dominant transport process in delivering nutrients to the water column, while studies in other systems that have compared the nutrient flux associated with stable (passive) sediments and those that have been recently resuspended found significantly higher nutrient fluxes associated with resuspended sediments (Fanning et al., 1982; Kristensen et al., 1992; Sondergaard, 1992; de Jonge et al., 1995).

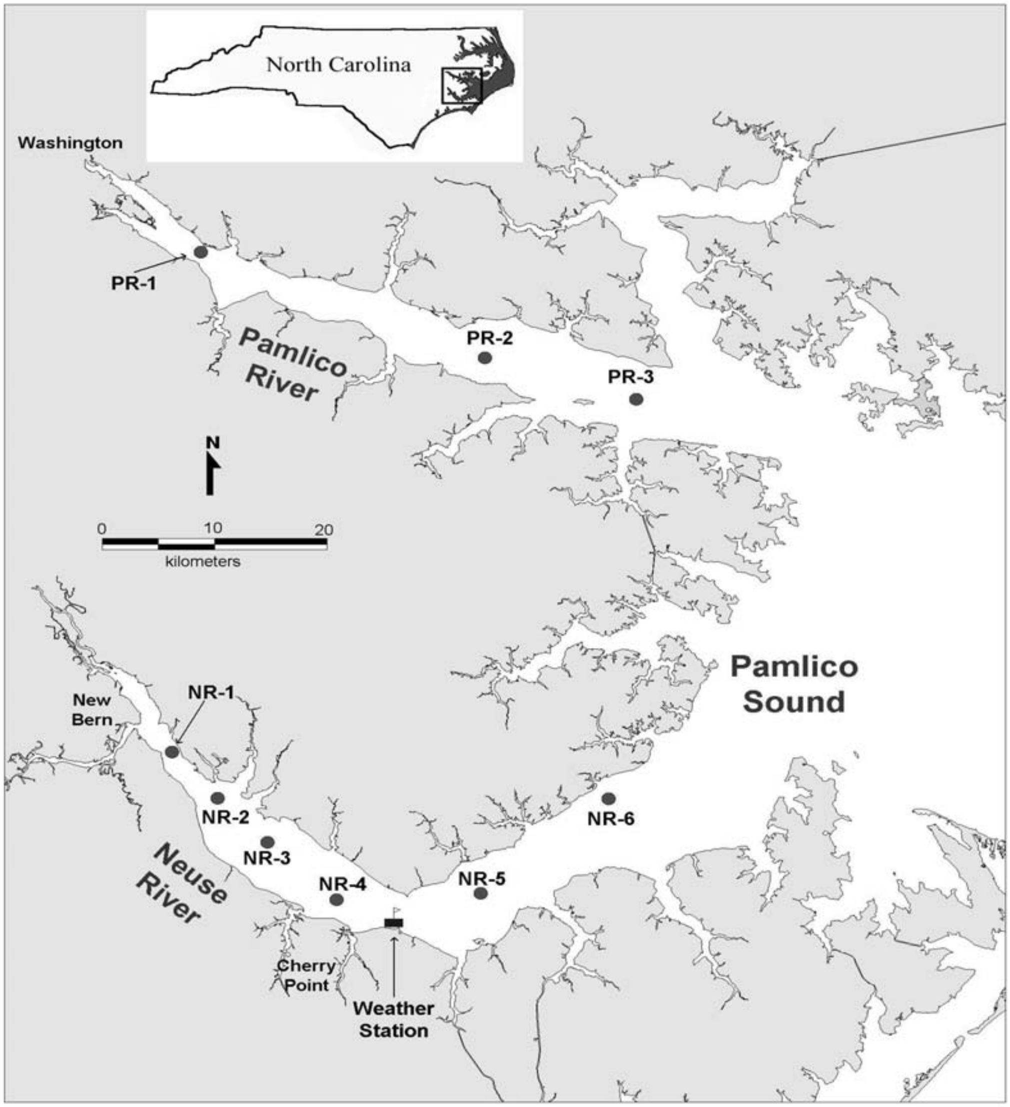


Figure 2.1. Sampling locations in the Neuse and Pamlico estuaries.

Table 3.1. Sampling location downstream distances.

Station Number	Distance downstream from New Bern (km)
NR-1	5
NR-2	13.3
NR-3	21.7
NR-4	32.5
NR-5	49.2
NR-6	69.2

Station Number	Distance downstream from Washington (km)
PR-1	18.3
PR-2	54.2
PR-3	72.5

2.2 Previous Studies

The seasonal storage and remobilization of sediments in rivers is a worldwide phenomenon that has been observed and described for rivers ranging in size from small streams (Emmett et al., 1983; Meade et al., 1990) to the Amazon, the world's largest river (Meade et al., 1985). During the sediment storage phase, rates of sediment deposition to the riverbed may be relatively high and the resulting sediment deposits remain undisturbed for periods of weeks to months. These conditions and time scales are conducive to a number of significant chemical transformations within the riverbed sediments. In particular, the remineralization of organic carbon and the accompanying generation of diagenetic products (nitrogen/phosphorus/carbon) in porewaters. Determining what role sediments play on basin-scale nutrient dynamics and elucidating the factors that control net nutrient exchanges have important implications for understanding nutrient flux and production dynamics in both estuarine and coastal oceanic environments. Increased incidences of coastal eutrophication and anoxia due to anthropogenic influences on the total nutrient input to a variety of systems make the understanding of nutrient dynamics imperative.

In most estuaries, the amount of nutrients supplied by external sources (e.g. rain, river runoff, nitrogen fixation, etc.) have consistently been shown to supply less than that required by primary producers (Dugdale and Goering, 1967; Haines, 1976; Windom et al., 1975; Stanley and Hobbie, 1977; Kuenzler et al., 1979; Nixon, 1981; Stanley and Hobbie, 1981; Fisher et al., 1982; Boyer et al., 1988; Kemp and Boynton, 1992). The remainder of the nutrient supplies must, therefore, come from *in situ* regeneration and recycling. A major component of this internal recycling is sediment-water column exchange. The benthic environment is particularly important due to the large portion of organic matter that reaches the sediment surface. This organic matter is then remineralized, increasing concentrations of inorganic forms of nitrogen, phosphorus, and carbon in the interstitial waters. The newly regenerated nutrients are then transported back to the water column through exchange with overlying waters. In most shallow-water systems, surficial sediments and the overlying water are continually interacting, exchanging and redistributing particles and solutes, making this recycling process extremely important (Wells and Kim, 1991; Rizzo, 1993; Rizzo and Christian, 1996; Alperin et al., 2000). However, this exchange of solutes from the sediments to the overlying water is often quantified assuming the benthos is a passive environment, not considering extremely dynamic events such as resuspension. Therefore, the amount of nutrients that the sediments deliver would be considerably greater when considering exchange during both passive/quiescent and more dynamic stages of the sediment.

Resuspension of bottom sediments, or the act of dispersing settled particles back into the water column caused by either bioturbation, tides, or winds, may have a significant effect on the flux of nutrients in an estuarine system. Studies that have compared the nutrient flux associated with stable (passive) sediments and those that have been recently resuspended found significantly higher fluxes associated with resuspended sediments (Fanning et al., 1982; Kristensen et al., 1992; Sondergaard, 1992; de Jonge et al., 1995). Therefore, resuspension of sediments may play an important role in the overall water quality of any shallow-water ecosystem. The resuspension of bottom sediments will result in the advective transport of porewater and diagenetic end-products (N/P/C) into surface waters and may serve to increase water column nutrient concentrations, thus affecting the overall water quality of the system. The basic processes and driving forces of resuspension and sediment transportation have been described in detail, e.g., by Hakanson and Jansson (1983), Carper and Bachman (1984), Hilton et al. (1986), Bengtsson et al. (1990), Leuttich et al. (1990), Weyhenmeyer et al (1997), and Douglas and Rippey (2000). Lam and Jaquet (1976) suggested that threshold current velocities of 2-3 cm s^{-1} were sufficient to resuspend non-cohesive clay and silt particles. Although other studies have found that current velocities must exceed 10 cm s^{-1} to move unconsolidated fine particles (Postma, 1967; Douglas and Ripley, 2000). Studies conducted in the lower Neuse River have shown near bottom currents as high as 20 cm s^{-1}, with an average current near or below 5 cm s^{-1} (Woods, 1969; Knowles, 1975; Leuttich et al., 2000). In any event, wind-induced waves, inducing orbital movement in the water column, are typically the dominant process causing resuspension of sediments. The resuspension of bottom sediments and the implications on water quality have yet to be studied in the Pamlico and Neuse River Estuaries. However, based on the average current velocity measured in the Neuse River, and assuming the Pamlico River has similar circulation patterns, resuspension may be prevalent throughout the year in both basins.

Massive summer fish kills in 1995 drew public attention to deteriorating water quality in the Neuse River and its estuary. The Pamlico River, although not as publicized as the Neuse, has also had and continues to have similar water quality problems. Extensive research has been conducted over the last several years to understand the complex nutrient dynamics of these systems. Majority of these studies have focused on nutrient cycling in the water column and have only recently included the benthic environment (Matson and Brinson, 1983; Rudek et al., 1991; Rizzo, 1993; Paerl, 1995; Paerl et al., 1995; Rizzo and Christian, 1996; Pinckney et al., 1997; Paerl et al., 1998, Alperin, 2000; Alperin et al., 2000). These studies have shown the importance of sediment-water exchange to the nutrient concentrations in overlying waters. However, these studies have employed benthic flux chambers, typically Plexiglas cylindrical chambers placed over a known area of sediment and equipped with inlet and outlet ports to collect water samples at varying time intervals, or other passive sampling method, including simply applying Fick's law to the concentration gradient across the sediment/water interface, to quantify the nutrient flux from the sediment bed. In order to describe the nutrient flux associated with sediment-water exchange, experiments were specifically designed to prevent any porewater exchange due to the disturbance of the sediment bed, e.g. sediment resuspension. Water is mixed within these chambers by pumps or magnetic stirrers, which move at a rate sufficient to mix the overlying water without disturbing the sediment bed (Fisher et al., 1982; Alperin, 2000; Alperin et al., 2000). Therefore, these estimates are based on a quiescent benthic environment and have not yet accounted for the nutrient contribution associated with any disturbance of the sediments due to winds or waves. It is important to note that Wells (1981) and Wells and Kim (1989) believe that most of the surface sediments within the Neuse River trunk estuary will be deposited and resuspended many times before permanent accumulation on the bottom. This is due to the fine-grained nature of the sediments, the shallow water character of the sediment basin, and the high levels of wind stress on the basin (Riggs et al., 1991). Thus, it seems necessary to understand the dynamics of these resuspension events, including the aerial extent to which they occur and the frequency, and the potential impact they may have on surface water quality.

Conclusions from the MODMON project stated several areas of research priority (Leuttich et al., 2000). Of particular interest was the inference to the importance of the bottom sediment – water column coupling; specifically targeting better information on rates of nutrient exchange, carbon processing and the residence time of these materials in the system. Past and current studies of benthic processes have neglected short-term dynamics such as resuspension events, which will be addressed here.

Research currently being conducted at the University of North Carolina, Chapel Hill seeks to understand the impact of hurricane Floyd on sediment deposition, erosion and benthic nutrient fluxes in Pamlico Sound (Alperin and Benninger, pers. comm.). This work will include measurements of carbon and nitrogen fluxes by means of in situ benthic flux chambers and laboratory flux measurements, again based on a stable/passive benthic environment. Their study will not focus on the short-term sediment dynamics, such as sediment resuspension and remobilization, and the influence on water quality. However, we intend to collaborate closely with this ongoing project, collecting cores and benthic nutrient samples from the same stations. This proposed work would complement and extend the current study of Benninger, Alperin, and Wells.

Research at the University of North Carolina, Chapel Hill is currently being conducted to provide seasonal information regarding rates of nitrogenous nutrient processing in the upper Neuse River, including rates of denitrification and sediment-water nutrient exchange. This study is designed to evaluate the flux of nutrients via benthic chambers in the field and laboratory experiments. Again, short-term sediment dynamics and establishing the history of nutrient and carbon deposition will not be considered (Whalen, pers. comm.).

In addition, a WRRI report entitled *Impact of Sediment Processes on Water Quality in the Neuse River Estuary* (Alperin, 2000) presented results that evaluated nutrient benthic fluxes and oxygen utilization in the Neuse River Estuary. In situ benthic chambers and laboratory-based chambers were utilized throughout the study. An empirical model is currently being developed to describe the porewater nutrient concentrations in the Neuse during the summer months. The model solves several equations to describe the sequence of diagenetic reactions that occur in the sediments (**Figure 2.2**). The model can incorporate changes in water column oxygen concentrations, but does not include disturbances to the sediment/water interface since data on this process is not available.

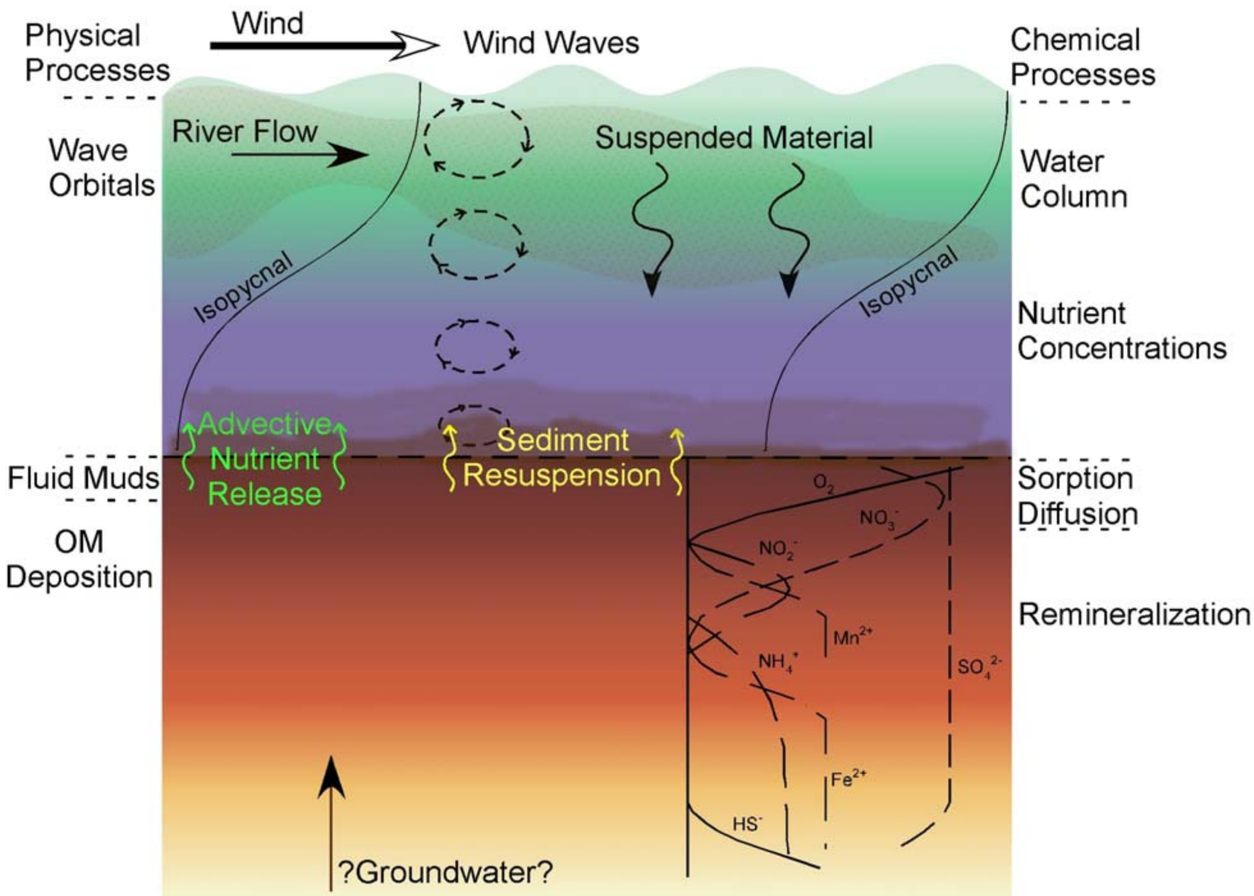


Figure 2.2. Sediment processes in the Neuse and Pamlico estuaries.

Finally, previous studies have evaluated long-term trends in sedimentation in both the Pamlico and Neuse River estuary (Benninger, 1989, 1990; Wells and Kim, 1991). These studies found the highest long-term sedimentation rates near the mid-estuary regions and ranged between 1-6 mm yr^{-1}. More recently, the Duke University Wetland Center has focused on the history of water quality in these two estuaries dating sediment core samples and analyzing water quality indicators (Cooper, 1998). Results of short-term sediment dynamics obtained from this study may help in the further interpretation of historical trends of water quality within the estuaries (Sherri Cooper, pers. comm.).

3.0 Methods

All water column and sediment samples were collected using trace-metal clean techniques. Water samples were collected from just above the bottom and near the surface at each site using a large peristaltic pump. Conductivity, temperature, salinity, and dissolved oxygen (DO) were measured at these same intervals. Particulates were collected by filtration onto Whatman GFF filters (0.7 µm; 47 mm diameter). Dissolved fractions were collected (after in-line filtration) in acid-cleaned polyethylene bottles.

Cores were collected by push core from a small boat with a PVC coring device outfitted with a one-way check valve and a 4" diameter clear acrylic tube (core tube). The sample core tube was gently pushed into the bottom sediments to obtain a vertical column of sediment. For radionuclide analyses, these sediments were immediately extruded and sealed in 50 ml centrifuge tubes. Cores were subsectioned the length of the core (~19 cm). The first two subsections were 2 cm thick and the next subsections were 3 cm each to a depth of 19 cm total. The wet sediments from each interval were dried, ground, transferred into aluminum containers (50 mm x 9 mm) or plastic vials and then analyzed by low-background high-resolution gamma ray spectrometry to measure ^{7}Be, ^{137}Cs, ^{210}Pb and ^{234}Th activity (the energies of these peaks are 477.6, 661.6, 46.5, and 63.2 KeV respectively). A 20-milliliter (ml) sample of each subcore was taken for porosity calculations. For porewater and solid phase analyses, the core samples were also obtained (along with overlying water) using the centrifuge tubes. The tubes were immediately sealed (with no air space) with a tight fitting plastic end cap. Samples were taken back to the East Carolina University laboratory and then centrifuged and syringe filtered to separate the dissolved phase from the solid phase. Dissolved samples were analyzed for total and organic/inorganic nitrogen and phosphate. Solid phase samples were also analyzed for particulate carbon and nitrogen.

Standard methods, shown in the accompanying **Table 3.1**, were used to measure total/organic nitrogen, phosphate, and carbon, as well as total suspended material, DO, and salinity in water column samples (particulate and dissolved) and bottom sediments (solid phase and interstitial waters). Porosity of the bottom sediments for use in determining radiometric inventories was also measured using standard methods. Measurement of these environmental parameters provides the necessary supportive information for the contaminant studies – providing insights about particulate material composition and diagenetic stage.

Sediment deposition rates as well as mixing coefficients were quantified by measuring the naturally occurring radioisotopes ^{7}Be (half life = 53.3 days) and ^{234}Th (half life = 24.1 days) by low-background high-resolution gamma ray (**Table 3.1**). Beryllium is produced by cosmic ray spallation reactions with nitrogen and oxygen in the atmosphere. These reactions occur primarily in the stratosphere and upper troposphere where charged particles (alpha particles, electrons, and protons) induce nuclear reactions in oxygen and nitrogen atoms. Th-234, very particle reactive, is primarily produced in the water column through the decay of its immediate parent ^{238}U. Be-7 is delivered to the surface of the earth through precipitation (wet and dry) where it quickly adsorbs to particle surfaces and subsequently is deposited to bottom sediments in coastal environments (Olsen et al., 1986; Baskaran and Santchi, 1993). When utilizing radioisotopes for investigating natural processes, it is important to match the time scale of interest with the half-life of a particular radionuclide. For the purpose of this study (i.e. short-term deposition), the half-life of ^{7}Be and ^{234}Th enables them to be useful as particle tracers on time scales of days to months (deposition).

Table 3.1. Techniques employed for sample analyses.

Measurements	Methods
^{7}Be, ^{234}Th, ^{137}Cs	Gamma/Beta Spectroscopy
Particulate C and N	Exeter Analytics CHN Analyzer
Total dissolved P	Persulfate Digestion
NH_4^+	Solorzano
DKN	Kjeldahl
Dissolved N, P	Auto Analyzer
Cond., Temp., Salinity, DO	Electrodes
Total Suspended Solids	Gravimetric (0.2 µm filter)
Grain Size	Coulter LS230 Analyzer

Sediment ^{7}Be, ^{137}Cs and ^{234}Th inventories are calculated according to the following equation (after Canuel et al., 1990):

$$I = \sum X_i (1-\phi_i)\rho(xsA_i)$$

where I is the total inventory of the sediment core in disintegrations per minute per square centimeter (dpm cm^{-2}); X_i is the subsection thickness (cm); ϕ_i is the porosity of the subsection (volume/volume); ρ_i is the sediment density (g cm^{-2}); and xsA_i is the activity above the level supported by the radioactive parent (dpm g^{-1}). The individual subsections are then summed to obtain the total inventory, which integrates over the depth scale of interest. Total inventories of ^{7}Be/^{234}Th are separated into two components: residual and new inventory. The residual inventory accounts for the ^{7}Be/^{234}Th inventory of the previous sampling period (since ^{7}Be and ^{234}Th have a half-lives of 53.3 and 24.1 days, respectively), decay corrected to the present sampling period. The new inventory is the difference between the total inventory minus the residual inventory.

The figure below, **Figure 3.1,** demonstrates the utility of the short-lived tracers, ^{7}Be and ^{234}Th. Simply, cores are initially collected at each site (Month A) to evaluate the sediment inventory of both ^{7}Be and ^{234}Th. The two cores show the two possibilities: 1) no new deposition, thus no short-lived tracer present; or 2) new deposition within the mean life of the tracer (^{7}Be – 77 days and ^{234}Th – 35 days). The inventory of the core is calculated by integrating polynomials fit to the activity versus depth.

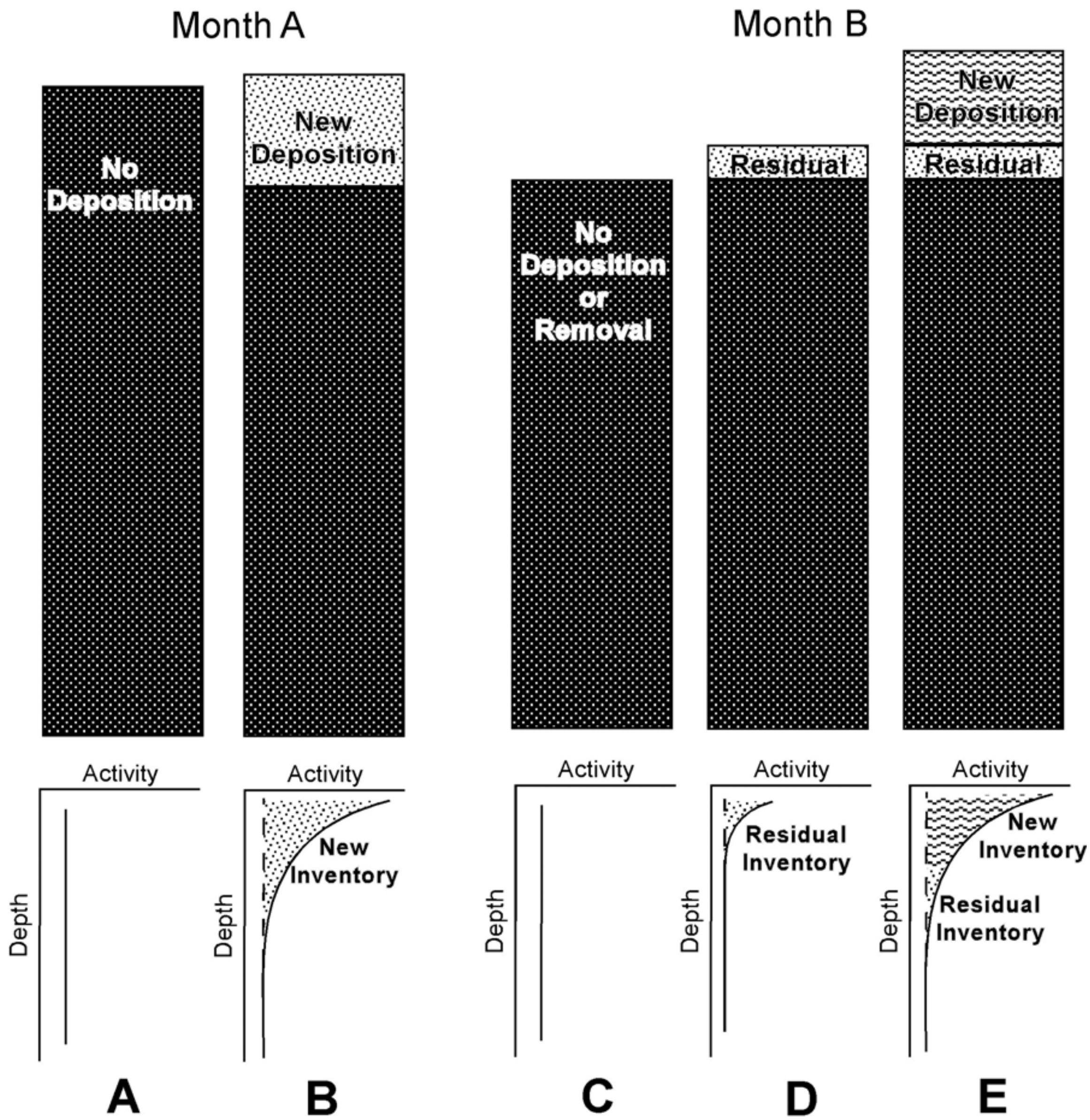


Figure 3.1 Schematic representation of core inventories between sampling events. Month A refers to the first sampling event and Month B is a subsequent sampling event.

Subsequent cores collected approximately every 6 weeks (Month B) are then compared to the original cores (Month A). These cores will show either no change (3 or 4), removal (3), or new deposition (5). The total inventory (Month B) is separated into two components:

Residual Inventory = inventory of previous sampling period decay-corrected to the date of present sampling

New Inventory = total inventory (present sampling) – residual inventory

Therefore, if the total inventory is equal to the residual inventory, then this would indicate no net sediment delivery or loss during the sampling period. However, if the residual inventory is greater than the total inventory, this is an indication of net sediment removal during the sampling period. And finally, if the residual inventory were less than the total inventory, this would indicate net sediment deposition during the sampling period.

4.0 Natural Tracers and Resupension: Results and Discussion

4.1 Short-term sediment dynamics

The spatial variability of the short-lived tracers (^{234}Th and ^{7}Be) is summarized in **Table 4.1**. The coefficient of variation (C.V.) for ^{7}Be was significantly higher than that of ^{234}Th during both experiments. Most notable was the substantial decrease in variability of ^{234}Th during the May experiment when samples were collected down to 4 cm depth, an indication that the surface activity is the most variable. A similar ^{7}Be C.V. and downcore pattern was observed in cores collected from Cape Lookout Bight, NC (Canuel et al., 1990). All inventories in this paper are reported as ±15% and ±33% for ^{234}Th and ^{7}Be, respectively. For most instances, this is an overestimate of the propagated counting error.

Table 4.1. Variability studies conducted in the Neuse River estuary.

	February, 2002	
Core	**^{7}Be dpm cm^{-2}**	**^{234}Th dpm cm^{-2}**
1	0.20	4.46
2	0.30	3.88
3	0.23	3.25
4	0.47	5.01
5	0.41	3.00
Mean	0.32	3.92
s.d.	0.11	0.83
C.V. (%)	34	21
	May, 2002	
1	0.57	2.84
2	0.58	2.80
3	0.30	2.62
Mean	0.48	2.75
s.d.	0.16	0.12
C.V. (%)	33	4.2

Total ^{7}Be inventories at most locations, **Table 4.2,** in both estuaries show large variations between sampling events. The largest variations in the Neuse River are found in the lower estuary between NR-4 and NR-6. This area of the lower estuary is most susceptible to wind driven sediment disturbances because of the large surface area and shallow uniform depth that allow for winds to develop large wind tides (Pilkey et al, 1998). Interestingly, the Pamlico didn't show as large a variation in total inventory throughout the estuary as the Neuse, probably associated with the size and dominant direction of wind events (northwest/northeast).

Table 4.2. Total inventories in dpm cm^{-2} for ^{7}Be and ^{234}Th in the Neuse and Pamlico estuaries. Note that ^{7}Be shows large variations in the lower Neuse (NR-4 to NR-6); and excess ^{234}Th shows largest variation in the middle reaches of the Neuse estuary.

	May '01		**Jul '01**		**Aug '01**		**Oct '01**		**Dec '01**		**Feb '02**	
Station	**^{7}Be**	**^{234}Th**	**^{7}Be**	**^{234}Th**	**^{7}Be**	**^{234}Th**	**^{7}Be**	**^{234}Th**	**^{7}Be**	**^{234}Th**	**^{7}Be**	**^{234}Th**
NR-1	1.3	45.1	0.9	36.3	1.2	27.3	1.3	45.9	0.7	31.2	1.3	20.4
NR-2	1.8	36.2	1.0	42.9	1.3	36.6	1.8	34.3	0.7	25.1	0.3	24.1
NR-3	1.8	-50.3	1.6	84.3	1.6	29.3	0.3	52.6	1.8	42.8	1.2	40.8
NR-4	0.9	22.2	3.5	50.8	1.4	54.0	1.5	77.7	1.2	25.5	0.7	43.2
NR-5	1.0	33.0	2.1	69.0	1.1	41.7	0.9	18.7	1.2	34.9	0.5	23.3
NR-6	2.1	17.6	4.6	26.0	1.9	18.1	2.1	13.7	1.4	4.1	0.3	12.0
PR-1	0.9	51.6	3.3	53.1	1.5	47.2	1.2	108	4.2	62.8	0.9	39.8
PR-2	1.6	24.4	1.8	47.6	2.3	27.9	1.2	44.4	2.1	24.9	0.9	23.5
PR-3	1.6	30.1	2.3	44.0	1.9	32.7	0.9	48.1	1.5	11.7	1.9	24.7

It has been noted that seasonal variation in ^{7}Be in the sediment inventories can result from differences in precipitation throughout the year (Canuel et al, 1990). Precipitation (**Figure 4.1**) was collected at New Bern, North Carolina, adjacent to the Neuse River Estuary. River discharge for the Neuse is also presented to show the relationship with precipitation. The daily precipitation data show a fairly uniform distribution throughout the year of the study with the notable exception of the low precipitation of the October to November timeframe. Comparison of this data to the ^{7}Be total inventory (**Table 4.2**) shows no observable decline in ^{7}Be during the late fall when precipitation was at its' lowest. The reasons that no decline in ^{7}Be was observed were most probably due to the half-life of 53.3 days being longer than this short dry spell and that dry deposition, as small as it may be, continued through this period. Further, sediments delivered through basin wide runoff are a major source of ^{7}Be to the estuary. The area of the basin is relatively large compared to that of the estuary, reducing the effects of short-term rainfall variations.

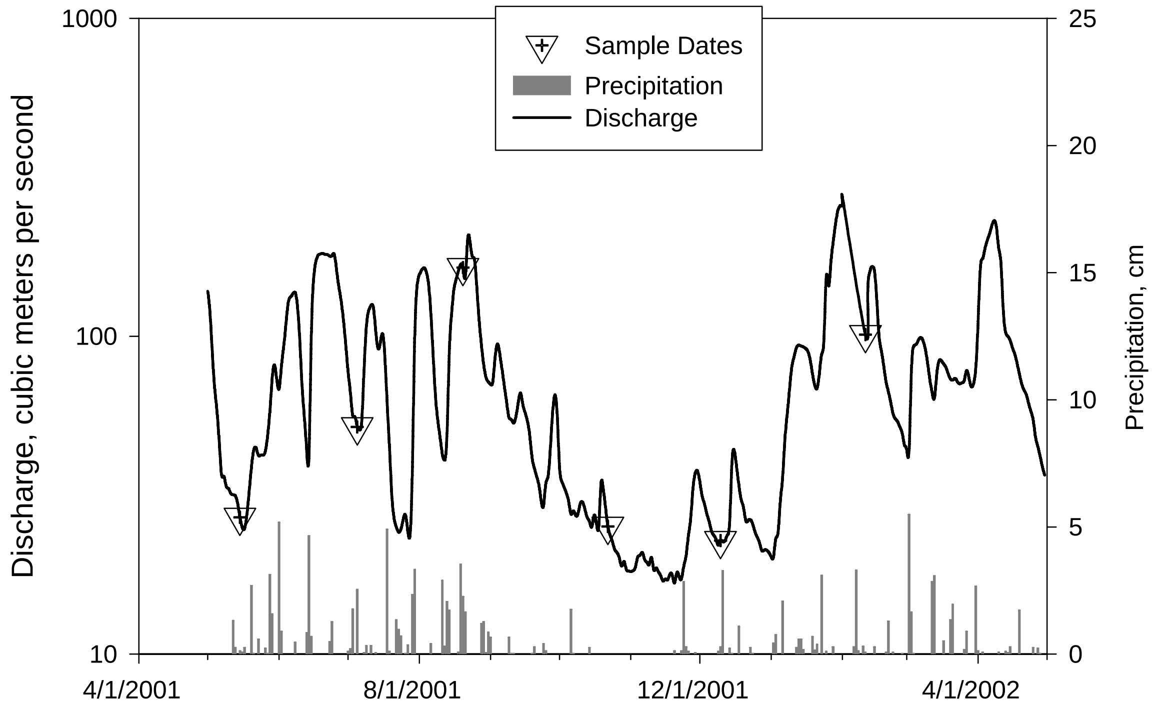


Figure 4.1. Discharge and precipitation for the study year. Precipitation data is from New Bern, NC and discharge data is from the gaging station at Fort Barnwell on the Neuse River.

As with the ^{7}Be inventories, ^{234}Th excess inventories showed the most variability and the greatest magnitudes in the middle reaches of the Neuse River (**Table 4.2**). These increased excess inventories may be attributed to increased resuspension and deposition between the sampling intervals or associated with the uranium geochemistry within the estuary. Based on observed linear relationships between dissolved uranium concentration and salinity, uranium is considered to behave conservatively in many estuarine and coastal environments (Borole et al., 1977; Martin and Maybeck, 1979; Toole et al., 1989). In this scenario, the remaining ^{234}Th activity would appear to have increased due to the desorption of ^{238}U, rather than increased adsorption of ^{234}Th. However, it should be noted that evidence for the removal of dissolved uranium at low salinities (non-conservative behavior) has also been observed (Carroll and Moore, 1993). Comparisons of total ^{234}Th inventory to bottom water salinity in the estuary, especially the upper portion where seasonal variation is greatest, did not demonstrate large variations associated with salinity changes. However, deciphering the uranium geochemistry of this estuary was beyond the scope of this project. Therefore, we believe the ^{234}Th inventory fluctuations are associated with variations in sediment delivery and transport. The ^{234}Th results agree with those of ^{7}Be and demonstrate the active sediment remobilization that occurs in the middle reaches. Further, this region between NR-3 and NR-5 also appears to be an area of lower relative sediment accumulation based on ^{137}Cs dating (see below).

Other factors that could possibly affect the temporal distribution of these radionuclides can be related to the possible differences in their residence times in the water column and seasonal variability in partitioning coefficients, Kd. Baskaran and Santchi (1993) reported a Kd range of 3.0×10^{3} to 8.2×10^{5} g cm^{-3} for ^{234}Th which was seasonally dominated and residence times from 0.7 to 7.8 days. Values for Kd were lowest in winter and spring and highest in summer. Residence times were greatest in spring which could be attributed to current resuspension. Kd values for ^{7}Be have been reported to be 7.0×10^{3} to 2.0×10^{5} g cm^{-3} (Olsen et al, 1986) where residence times ranged from 1 to 3 days and that > 95% of the ^{7}Be inventory was in the sediments. In the Olsen et al (1986) study, seasonal variation for ^{7}Be was only noted for differences in atmospheric supply and not from the water column. For our study residence times of these radionuclides in the water column can be considered irrelevant since they are much shorter than the radionuclides' half-lives and the sampling interval (~6 weeks). Fluctuations in Kd values are mostly due to the concentration effect of suspended particulates (TSS) (Baskaran and Santchi, 1993). TSS in this study had little variability and predominantly low values with average means ranging from 5.5 to 8.6 mg l^{-1} with the exception of one sample period during February 2002. Therefore, it would be expected that Kd values did not vary significantly.

A comparison of the $^{7}Be/^{234}Th$ ratio over distance was also performed to see if there was any correlation. The only changes observed were coincident primarily with removal episodes and therefore showed ^{7}Be to be a better tracer of resuspension events than ^{234}Th. This is probably due to the time scale of sampling being shorter than the mean life of ^{7}Be (77 days) and a supply source function for both radionuclides.

4.2 Sediment Delivery and Remobilization

When the residual activity is calculated and providing for the new inventory (**Figure 4.2**), sediment deposition versus removal can be evaluated. It should be noted that this provides the cumulative (net) result between the sampling events. There may have been removal and/or deposition occurring at some point between the sampling events, but only the overall effect is obtained. In addition, the differences in the mean life (35 vs 77 days for ^{234}Th and ^{7}Be, respectively) of the two tracers may provide additional insight into the sediment dynamics. In most instances, both tracers indicate a net deposition between sampling periods. It should be noted that the year of sampling did not include any major weather events, ie. Nor'easters or hurricanes. However, there are subtle deviations from a depositional system at several sites, indicating net removal, particularly with the ^{7}Be data.

The largest sediment removal in the Neuse was observed during August 2001 at the downriver stations NR-4 through 6 while the second greatest episode was observed in February 2002 at Stations NR-2 and once again at Stations NR-5 and NR-6. A small removal was also observed at NR-2 in December 2001.The largest depositional episode was observed in July 2001.

The only observed removal in the Pamlico occurred in August at PR-1, however this location was primarily depositional throughout the study. The high amount of sediment deposition at PR-1 relative to downstream locations is possibly due to effects from the turbidity maximum being predominantly located in this area (Postma, 1967). This is also an area where the river widens thus current velocities decrease and possibly enhance settling of the suspended sediment load. This effect is not seen in the same area of the Neuse where the turbidity maximum is predominantly located. This could be due to the confluence of the Trent tributary and the Neuse's orientation to dominant wind directions. Both these forces can enhance current velocities and produce more mixing and consequently increase suspended load capacity thus precluding the turbidity maximum zone in the Neuse from being an area of deposition.

The amount of sediment resuspended in a removal episode can be calculated using the ^{7}Be inventory lost in dpm cm^{-2} and assuming only the top 5 cm of the sediments are involved in the disturbance, allowing for an estimate of the surface activity (dpm g^{-1}). This calculation gives the amount of sediment resuspended assuming the sediment can be transported. Using a simple relationship developed by Hjulstrom (Pipkin, 1994), where the grain size and current velocity are known, the critical erosion velocity (CEV) can be evaluated. Grain size analysis showed primarily silts and fine sands at surface with down core median diameters of 23 to 155 µm in the Neuse and 19 to 74 µm in the Pamlico (**Table 4.3**). Other studies have found similar results for grain size (Wells and Kim, 1989). The results of the grain size analysis for the top 10 cm did not reveal any fining sequences either vertically or laterally throughout the estuaries. The largest removal in the Neuse in August 2001 at NR-6 involved a ^{7}Be inventory loss of 0.8 dpm cm^{-2} in the top several centimeters where the ^{7}Be activity measured was 1.8 dpm g^{-1} or approximately 0.4 g cm^{-2}. Grain size analysis at this site (NR-6) determined that sediments primarily consist of unconsolidated silt and very fine sand. Observed current calculations have shown that velocities of 20 cm sec^{-1} are common, which on a Hjulstrom diagram are sufficient to initiate transport of these sediment sizes. Accounting for the bulk density of the sediment removed indicates that the removal involved the top 2.2 cm of sediment.

Table 4.3. Grain size data for cores collected in July, 2001. All values are presented in µm, where fine sand = 125 to 250 µm, very fine sand = 62.5 to 125 µm, and silt = 3.9 to 62.5 µm**.**

Depth (cm)	PR-1	PR-2	PR-3	NR-1	NR-2	NR-3	NR-4	NR-5	NR-6
0-2	71	58	50	83	89	124	116	88	153
2-4	19	74	52	42	153	105	127	77	71
4-7	25	51	33	54	155	87	74	90	53
7-10	19	35	34	43	46	23	26	67	54

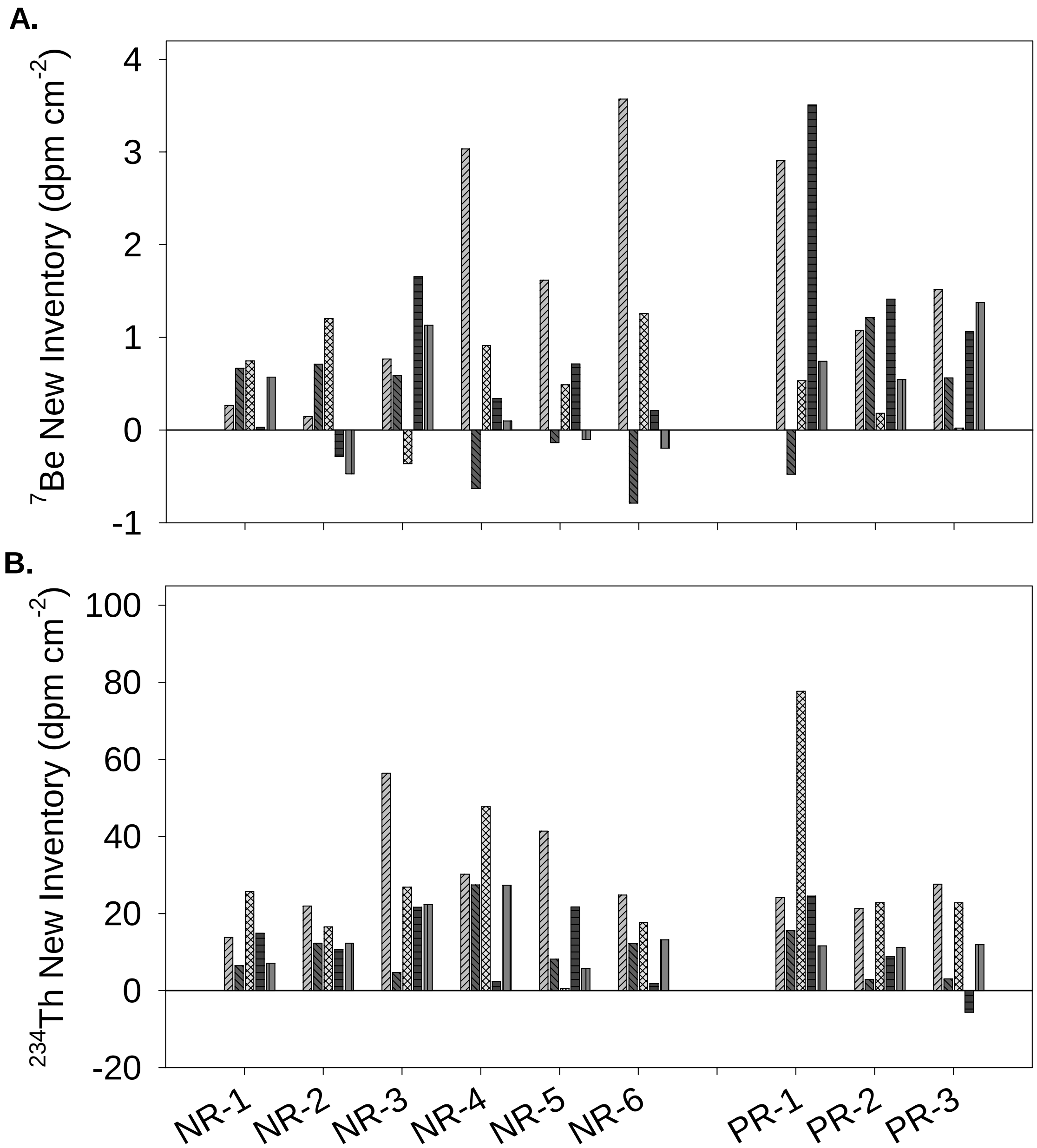


Figure 4.2. Calculated new inventories for the Neuse and Pamlico River estuaries for (A) ^{7}Be; and (B) ^{234}Th. Removals are indicated by negative values.

As described earlier and can be seen in **Figure 2.2**, porewaters elevated in nutrients are delivered to the water column during such a resuspension event. In order to put this removal into perspective, flux calculations for ammonium (NH_4) and phosphate (PO_4) were made using the porewater concentration of previous studies (Luettich, et al, 2000; Fisher et al, 1982) for the near surface sediments in this region of the estuary to determine the possible impacts of this removal on water quality. Calculated advective fluxes of 147 mg m^{-2} d^{-} for NH_4 and 125 mg m^{-2} d^{-} for PO_4^{3-} were determined for the August sediment removal in the vicinity of NR-6. Ammonium flux is at least 3 times the reported average value of 45 mg m^{-2} d^{-1} of NH_4 for a benthic flux from prior studies (Luettich, et al, 2000). Phosphate flux is also about 14 times the reported value of approximately 9 mg m^{-2} d^{-1} of PO_4^{3-}.Thus it can be seen that the advective impacts on water quality during resuspension events can be substantially greater than the effects from passive diffusion. Further, it should be noted that this maximum removal occurred in a year of monitoring in which there was very little storm activity and river discharges were at a minimum.

4.3 Sediment Deposition

Estimates of sediment deposition rates were measured via ^{210}Pb and ^{137}Cs (**Table 4.4**) where the maximum peak downcore depth was distinguishable, indicating the 1963 fallout signature. In some areas coring was not performed deep enough (>19 cm) to determine this peak since activities were still increasing in the bottom of the sample core. It should be noted that no evidence of significant macrobenthic bioturbation was observed. Similar results in this system have been obtained in other studies (Matson and Brinson, 1983; Cooper, 1998). It is believed that intermittent bottom water anoxia interferes with biotic life cycles in the finer grained sediments of both estuarine systems (Tenore, 1972). Profiles of ^{137}Cs (**Figure 4.3**) can be sharp and distinct or broad and blunt dependent on the mixing depth of the sediments (Jeter, 2000). Deposition rates were determined to range from a low of 1.4 to greater than 5 mm yr^{-1} by averaging the depth of the signature by the interval of time from 1963 to 2001. These are very similar to rates previously cited of 1 to 6 mm yr^{-1} for sediment accumulation in the Neuse (Benninger and Wells, 1993). Variations in ^{137}Cs sediment accumulation rates correspond with spatial variation in sediment remobilization. That is, the majority of sediment removal/remobilization occurs in the lower estuary (NR-3 to NR-5 region) and a distinct maximum can be observed. The upper estuary (NR-1 to NR-2) is primarily a depositional area and no ^{137}Cs horizon was noted. The mouth of the Neuse (NR-6) is an exception and also acts as a depositional area. This is probably due to a combination of factors such as a decrease in the influence of river currents and proximity to greater tidal influence from Pamlico Sound. Rates in the Pamlico River Estuary ranged from 0.3 to greater than 5 mm yr^{-1}.

Profiles of ^{210}Pb (**Figures 4.4 and 4.5**) exhibited conservative behavior in the upper portions of both estuaries in the topmost sediments. They also confirmed the ^{137}Cs findings showing that mixing is occurring with depth at most locations. Deposition rates were determined at sites showing decreasing trends with depth using the constant initial concentration (CIC) method since the trends are not linear due to mixing (Appleby and Oldfield, 1992) and the absence of ^{210}Pb was not reached in lower sediments (Anderson et al, 2000):

$$t_i = 1/\lambda \ln (A_o / A_i), \qquad 2$$

where t_i is the difference in ages of surface sediment and depth i sediment in years, λ is 0.03108 yr^{-1}, the decay constant for ^{210}Pb, A_o the excess ^{210}Pb activity at the sediment surface and A_i excess activity at depth. Deposition rates averaged 1.9 mm yr^{-1} in the Neuse and 1.6 in the Pamlico.

Table 4.4. Average sediment deposition and peak ^{137}Cs activity.

Sample Area	Average Depth (cm)	Average Sediment Deposition Rate (mm/yr)	Average Activity (dpm/g)
NR-1	>19	> 5	-
NR-2	>19	> 5	-
NR-3	5.5	1.4	0.95
NR-4	7.5	2	1.90
NR-5	7	2	1.62
NR-6	>19	> 5	-
PR-1	11	3	2.59
PR-2	>19	>5	-
PR-3	10.7	3	1.43

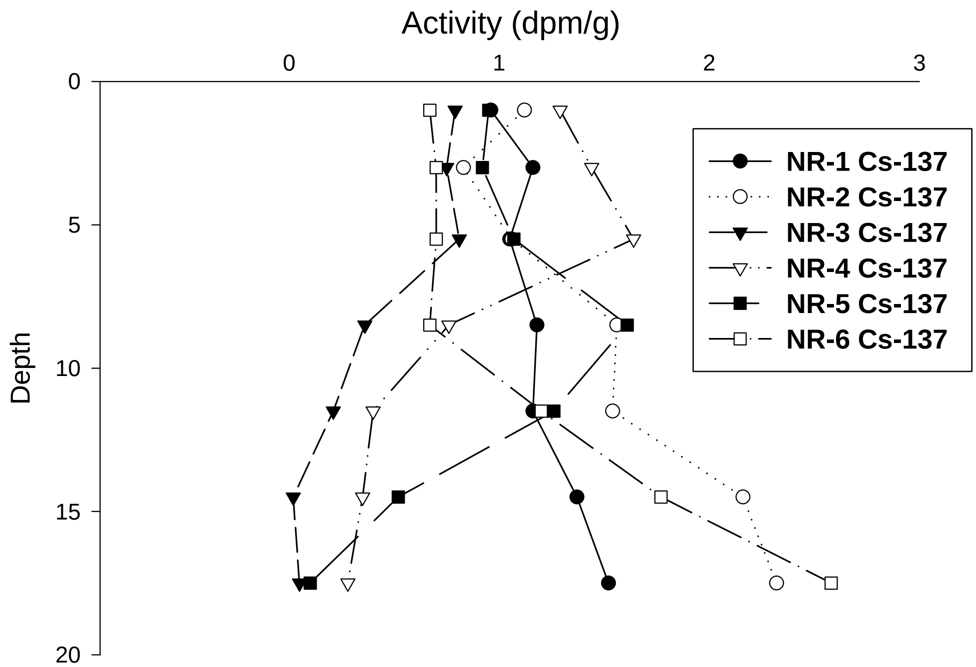


Figure 4.3. Cs-137 activity for August 2001 on the Neuse River. Stations NR-1, NR-2, and NR-3 show increasing levels at depth; while NR-3 through 5 show distinct maximums.

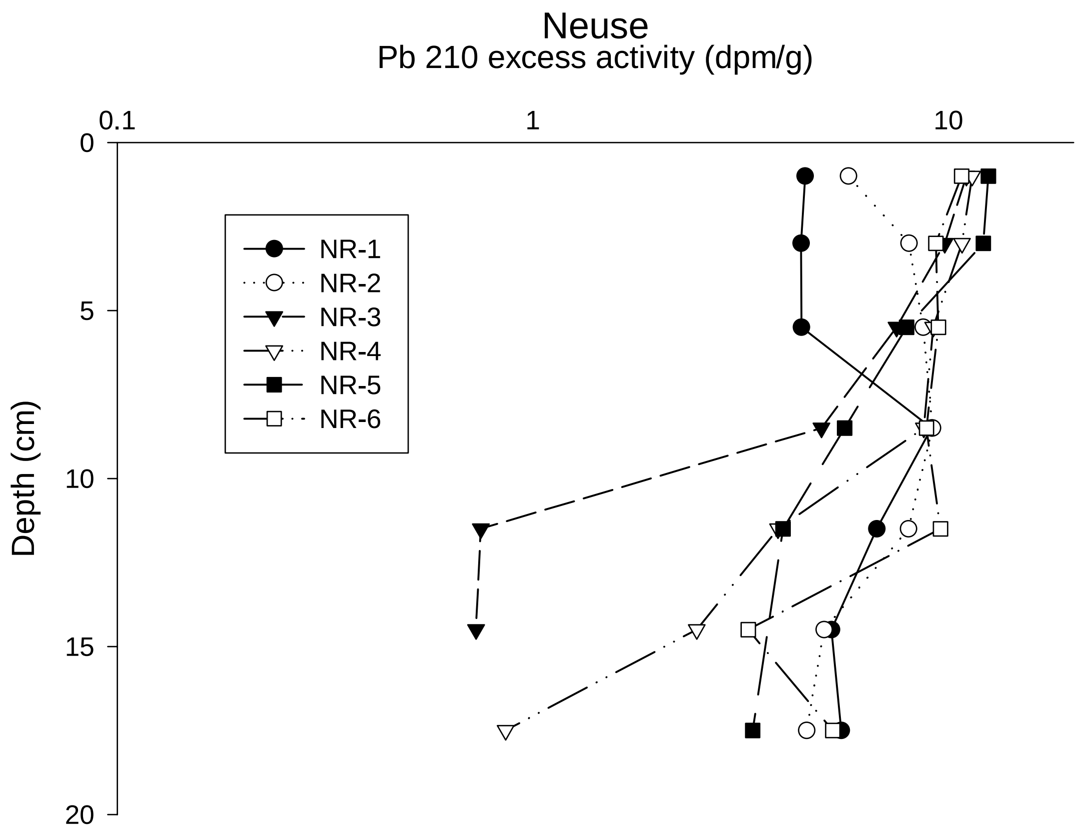


Figure 4.4. Excess ^{210}Pb profiles for the Neuse River. Stations NR-3 and NR-4 show decreasing levels at depth, while remainder of sites show mixing with depth.

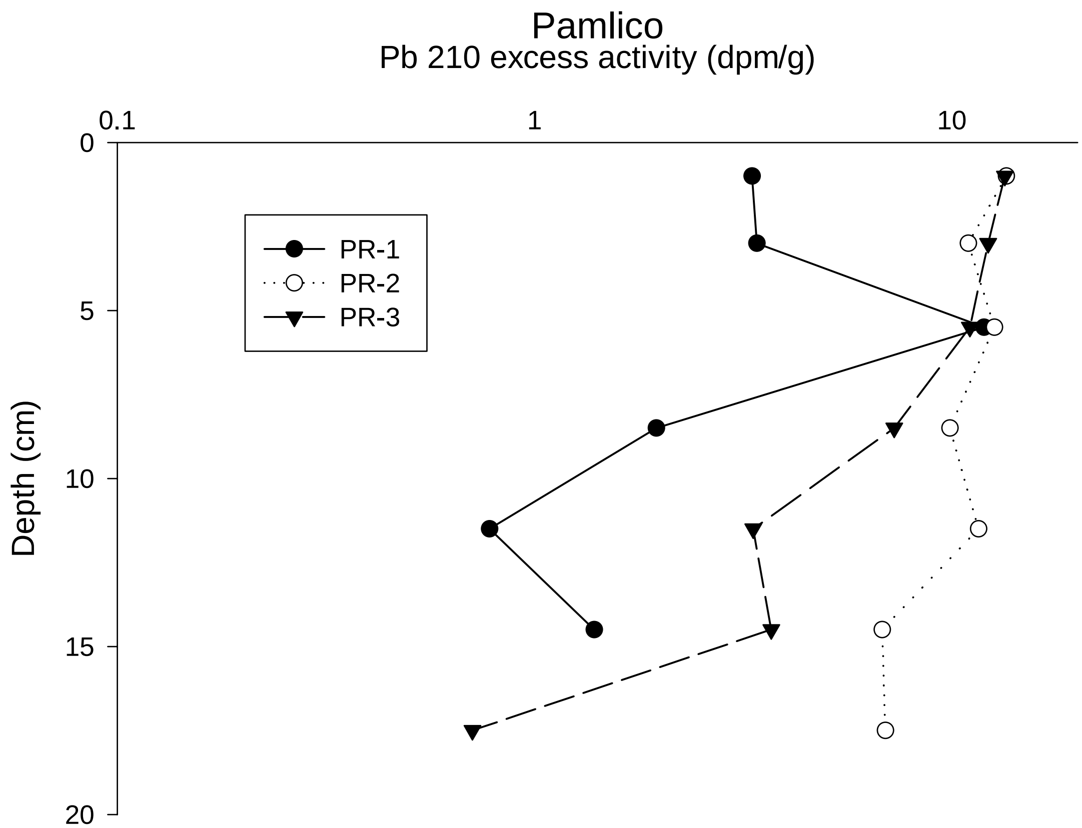


Figure 4.5. Excess ^{210}Pb profiles for the Pamlico River. Stations PR-1 and PR-3 show decreasing levels at depth, while PR-2 shows mixing with depth.

4.4 *In Situ* Monitoring of the Neuse River

Meteorological data were collected for the monitoring period May 2001 to May 2002 for wind speed and wind direction from a monitoring platform in the Neuse River in the area of Cherry Point, North Carolina. Wind data was obtained through the Neuse River Monitoring Program, Center for Applied Aquatic Ecology, North Carolina State University. The data indicated the passage of several cold fronts followed by high pressure systems that generated winds of 5 to 17 m s^{-1}. Peak events occurred during the winter months. Depending on the wind direction and its available fetch, resuspension of sediments due to wave action occurred which elevated turbidity to as much as several hundred nephelometric turbidity units (NTUs). These turbidity events primarily occurred during fronts with wind speeds $\geq$ 8 m s^{-1}. Northeasterly and northwesterly wind directions have the greatest fetch and seemed to have the greatest influence. A typical monitoring period from September through October 2001 is shown (**Figure 4.6)**. The most noteworthy frontal systems causing increased turbidity during this period occurred on October 9 (A), October 14 and 15 (B) and Oct 17 (C). It is evident that even these frontal systems are by no means large weather events. However, it appears during each event that a combination of wind speed approaching 8 m s^{-1} and rapid shifts in wind direction produce rapid increases in turbidity. This is due to developing sufficient wave energy to generate orbital velocities capable of resuspending bottom sediments. A lag is noticed between the termination of a front and the decrease in turbidity accounting for slow settling velocities of these fine-grained sediments.

Current data was obtained from February through May 2002 using a Falmouth Scientific, Inc. 2D-ACM current meter. Unfortunately, data from our in situ turbidity meter was lost during this period due to a faulty internal battery. However, we were able to obtain information from an in situ meter monitored by the Center for Applied Aquatic Ecology, North Carolina State University. The data show that current velocity is predominantly 10-20 cm/sec and rarely obtains values of 30-40 cm/sec with only slight observations in the 50-60 cm/sec range. Reversals of current from downriver, easterly flow to upriver, northwesterly flow were periodically observed. These reversals appear to be produced by prolonged northeast winds. The mechanism for these reversals was previously observed as being the result of seaward surface water entrainment which produces upriver estuarine flow of the deeper, denser, more saline water (Luettich, et al, 2000). Reversals with higher velocities ($\geq$ 30cm/sec) appear to be correlated with the larger turbidity events, which indicates that these frontal passages are likely responsible for the majority of the resuspension events.

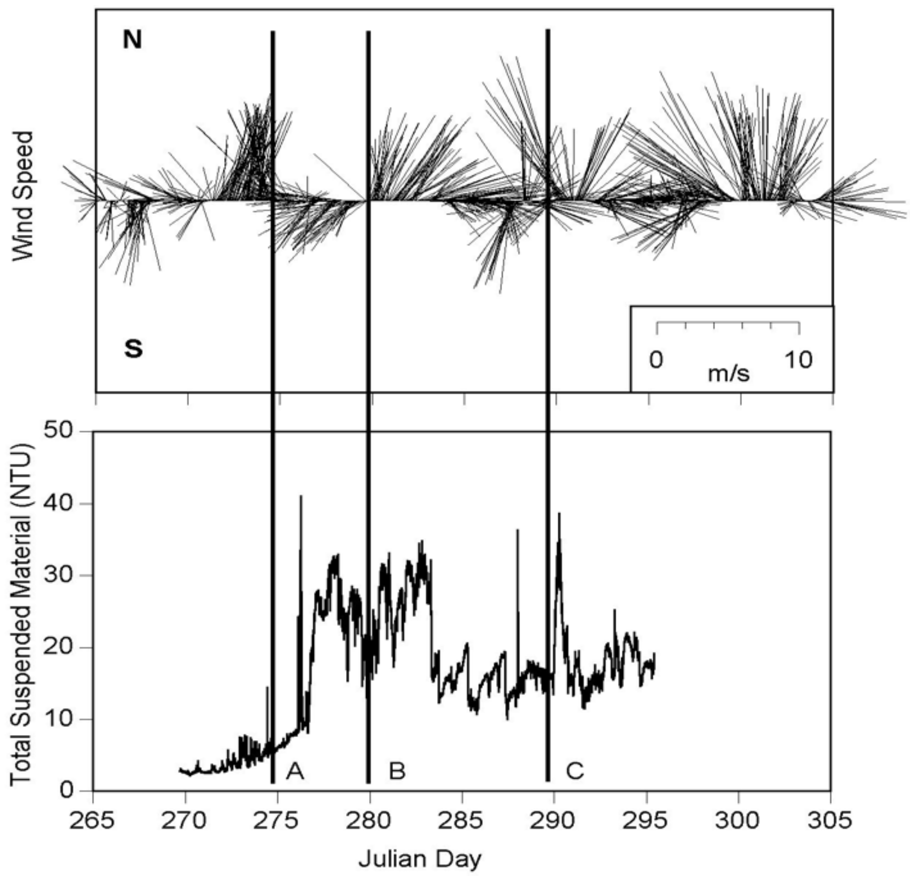


Figure 4.6. Typical in-situ monitoring period for meteorological events (September through October 2001). Three frontal systems (A,B, and C) are noted.

5.0 Nutrients: Results

5.1 Resuspension Experiment

A preliminary laboratory study was performed to evaluate whether resuspension of sediments actually contributes to increases in nitrogen and phosphorus in overlying waters of the Neuse River estuary. The preliminary laboratory study consisted of the collection of two 40 cm cores in tubular microcosms from the Neuse River for the sediment resuspension experiments. Bottom water from the same location was also collected in a sufficient amount to establish approximately a meter water column above the microcosm sediments in each core. A 12-V motor was placed in each core to stir the water gently in order to maintain a well-mixed column (Corbett et al. 1998). After several days to allow for the settling of suspended sediments, baseline samples for TKN, TDP, and TSS were collected from each microcosm prior to agitation. One microcosm was then maintained as the control while the other was agitated by increased stirring to simulate a resuspension event. Both microcosms were then sampled again several times for TKN, TDP, and TSS. Results of this preliminary experiment indicated a 17% increase in dissolved nitrogen and a 12% increase in dissolved phosphorus in the agitated water column following the resuspension event. TSS increased an order of magnitude from a mean value of 34 mg l^{-1} to ~340 mg l^{-1}. The control did not exhibit any increase for any of the sampled parameters. These results were obtained after the disturbance of only ~0.3 cm, the maximum removal that could be obtained with this experimental design.

5.2 Water Column Nutrients

The physical parameters, salinity, DO, and TSS were strongly influenced by low flow conditions that limited discharge through portions of the last year (**Figure 4.1**). For the Neuse River estuary, a distinct saltwater wedge could be seen in the upper region of both estuaries throughout most of the year with high salinities in the bottom water up to ~15, and relatively lower salinities in the surface water ranging from several to more than 10. The lower estuary showed little difference in surface and bottom salinities, typically ranging from 10 to 20, indicating well mixed conditions. Temporally, the wedge showed a steady increase in salinity upriver until fall and early winter where it exhibited a slight decrease. DO levels in surface water maintained well above hypoxic conditions (<2 mg l^{-1}) with levels above 5 mg l^{-1} throughout the entire sampling period. Hypoxic conditions were observed with nearly anoxic levels in bottom waters of the upper estuary (Stations 1-3) and in portions of the lower estuary (Stations 4 and 5). For much of the year the lowest levels were observed at Station 2 with concentrations < 1 mg l^{-1} for 5 of the 6 sample periods. This area is close to the locations of documented fish kills that occurred during the sampling timeframe. TSS in both estuaries ranged from a median of 5.5 to 7.2 mg l^{-1} for 5 of the 6 sample periods. During the high flow period in February 2002 (**Figure 4.1**) the median reached 33.3 mg l^{-1}, thus showing that TSS is strongly influenced by river discharge. Temperature measurements showed a consistent temporal distribution in both surface and bottom waters, ranging from a high of 28º C in the summer to a low of 9º C in the winter. There was only slight variation of a few degrees Celsius in the water column between surface and bottom waters occurring primarily in the summer months when bottom waters were slightly cooler. Spatial distributions were fairly uniform throughout the estuary.

In the Pamlico River, salinity concentrations were very similar both temporally and spatially to those in the Neuse, with the exception of the most downriver site (PR-3). This location did not quite reach the elevated levels observed near the mouth of the Neuse. Stratification was present during the spring and summer in the upper estuary. DO and temperature also displayed similar ranges and distribution to those in the Neuse. Bottom water hypoxia was observed with nearly anoxic levels throughout much of the year in the upper estuary (PR-1) and during the summer months in the mid-estuary (PR-2).

Ammonium (NH_4^+) concentrations in the Neuse River surface water, which ranged from 2 to 166 ug l^{-1}, were typically greater upriver decreasing toward the estuary mouth. The highest levels were in August and December and lowest in October. Ammonium exhibited the same distribution in bottom waters (**Figure 5.1**), ranging from 3 to 418 ug l^{-1}, as it did in surface waters however concentrations were more elevated in the summer months. Nitrate concentrations in surface water were highest in August and lowest in October, ranging from 1 to 467 ug l^{-1}, with a generally decreasing trend downriver towards the estuary mouth. Bottom water NO_3^- concentrations (**Figure 5.1**) ranging from 0.1 to 72 ug l^{-1}, were highest in February and showed the same spatial pattern as surface water concentrations. Phosphate surface water concentrations in the Neuse River were highest in the summer months and lowest in winter and spring, ranging from 0.1 to 246 ug l^{-1}, with a spatial distribution that exhibited a mid-estuary high. The same temporal trend (**Figure 5.1**), ranging from 2 to 616 ug l^{-1}, was observed in the bottom waters however concentrations were highest in the upper reach of the estuary and gradually declined towards the mouth of the estuary.

Pamlico surface water NH_4^+ concentrations ranged from 3 to 94 ug l^{-1} with greatest levels in the upper estuary. Bottom water levels (**Figure 5.2**) ranged from 3 to 233 ug l^{-1}. Surface water NO_3^- in the Pamlico ranged from 1 to 319 ug l^{-1} with greatest concentrations in the upper estuary during periods of increased runoff. Bottom water NO_3^- (**Figure 5.2**) only ranged from 1 to 55 ug l^{-1} exhibiting the same spatial distribution as surface water. Surface water PO_4^{3-} levels, ranging from 4 to 95 ug l^{-1}, were highest during the summer and in mid-estuary. The mid-estuary high is probably the result of effluent from ongoing phosphate mine operations as has been documented in the past (Matson et al. 1983). Bottom water (**Figure 5.2**) displayed a similar pattern going from a low of 3 to a high of 353 ug l^{-1}.

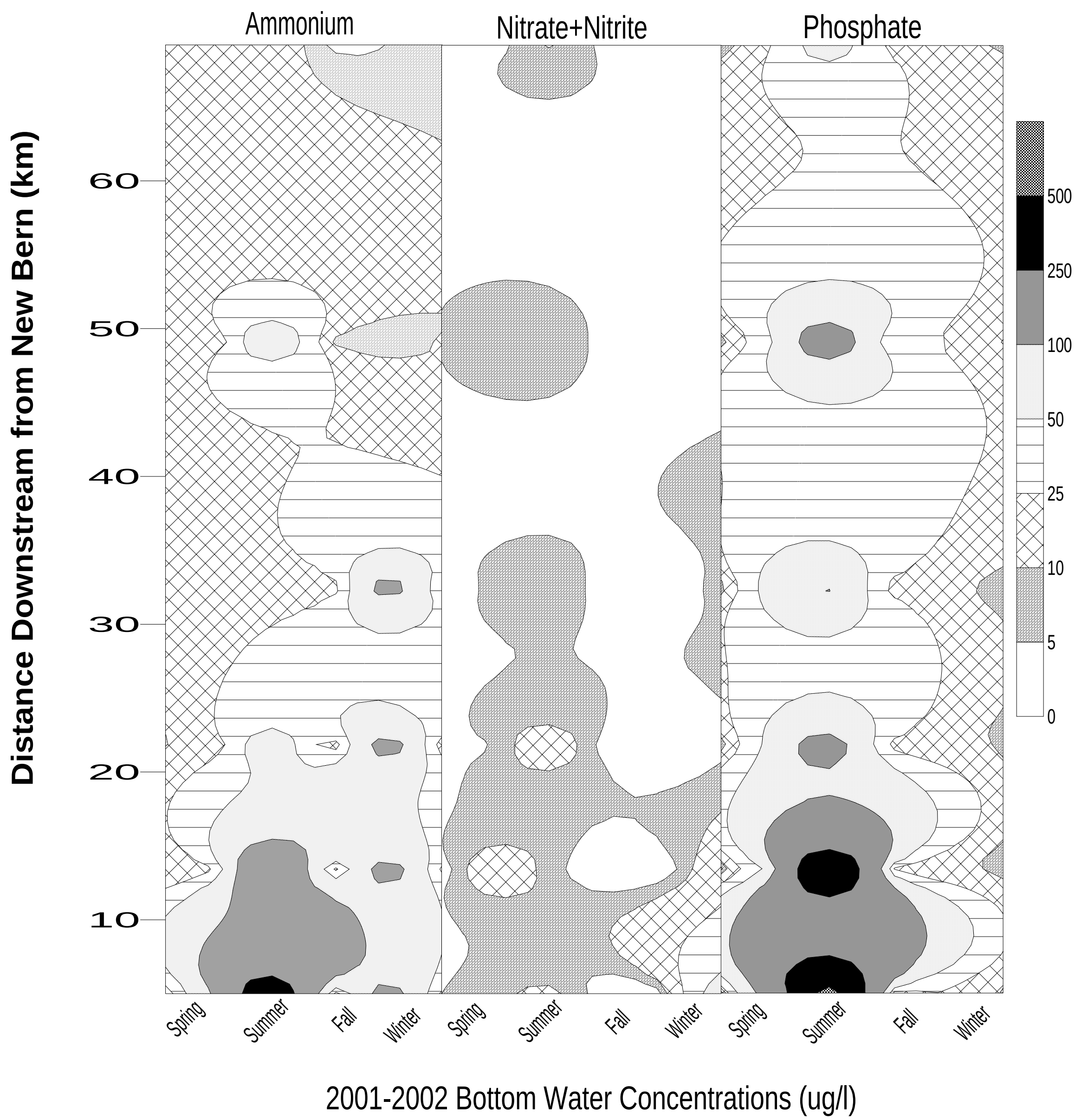


Figure 5.1. Concentrations in ug/l for NH_4^+, NO_3^-, and PO_4^{3-} in bottom waters of the Neuse River estuary for May 2001 through early spring 2002.

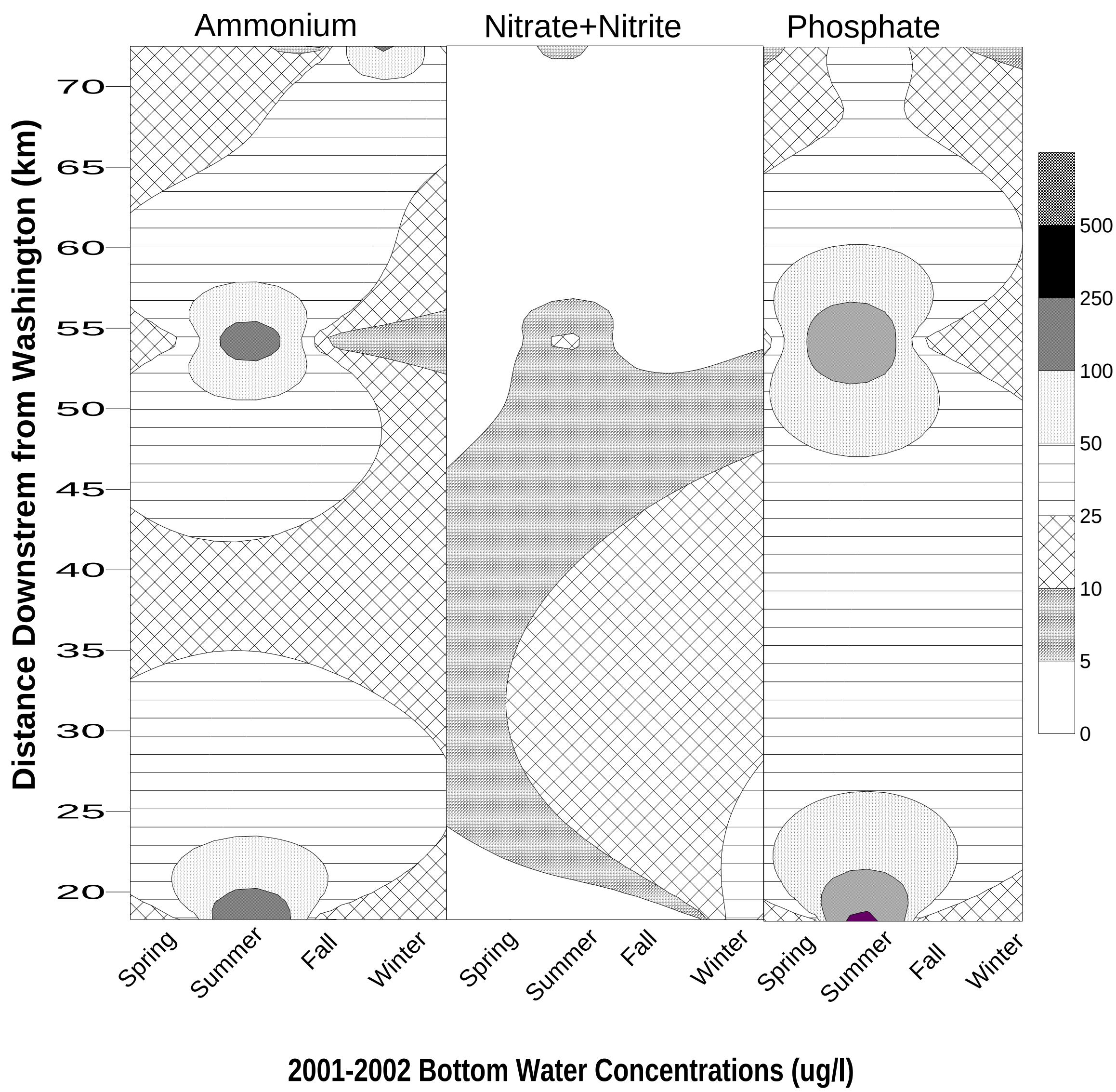


Figure 5.2. Concentrations in ug/l for NH_4^+, NO_3^-, and PO_4^{3-} in bottom waters of the Pamlico River estuary for May 2001 through early spring 2002.

5.3 Porewater Nutrients and Flux

Vertical profiles of porewater NH_4^+ concentrations for the top 10 cm exhibited increasing concentrations with depth for all stations in both estuaries with only a few exceptions. The NH_4^+ concentrations ranging from 0.5 at the mid-estuary locations to 15.7 mg l^{-1} at NR-6 in the Neuse (**Figure 5.3**) generally displayed a temporal distribution with highest levels in late summer and lowest in spring. The lowest NH_4^+ level was in the surficial sediment at NR-4 in May while the highest was at depth (7-10 cm) at NR-6 in August. Levels generally increased downstream to Station 2, an area of documented fish kills, and then decreased towards Cherry Point where they once again gradually increased to their highest levels near the river mouth. The distribution of PO_4^{3-} concentrations, ranging from 0.2 to 13.1 mg l^{-1} in the Neuse (**Figure 5.4**), displayed the same general trends as porewater NH_4^+ concentrations.

In the Pamlico, NH_4^+ levels continually increased downriver and ranged up to 16.4 mg l^{-1} (**Figure 5.5**). PO_4^{3-} concentrations for the Pamlico ranged up to 7.8 mg l^{-1} (**Figure 5.5**) with the highest levels observed in the mid-estuary. This could be the result of this sample location being immediately downriver of PCS Phosphate Company, a phosphate mine and fertilizer producer. The lowest PO_4^{3-} level was in May in the surficial sample at NR-3 while the highest was also at depth (7-10 cm) at NR-6 in August.

Nitrate and nitrite (not shown) ranging from 0.002 to 0.06 mg l^{-1} in the Neuse and 0.001 to 0.09 mg l^{-1}in the Pamlico, exhibited the same spatio-temporal distribution as surface water NO_3^- and NO_2^-. It can readily be seen that nitrate-nitrite concentrations, as intermediates in sediment N redox reactions, compose a very small amount of the total porewater nitrogen in comparison to ammonium, generally representing <1% of the total N.

The flux across a sediment interface has traditionally been assumed to be controlled by molecular diffusion and can be calculated using the following widely used variation of Fick's first law of diffusion (Berner 1980):

$$J = -\phi_0 D_s(\delta C/\delta Z)_{z=0}$$

where ϕ_0 is the porosity, D_s is the bulk diffusion coefficient and $(\delta C/\ \delta Z)_{z=0}$ is the porewater nutrient concentration gradient in the uppermost sediments. Porosity values were typically ~0.9 in the uppermost sediments of both estuaries. Using this relationship, diffusive flux (**Table 5.1**) was determined at all stations for the high, low and mean passive flux for both the Neuse and Pamlico River estuaries. NH_4^+ flux was predominantly highest during the summer months and lowest in spring with an overall mean of 13.5 mg m^{-2} d^{-1} for the Neuse and 10.9 mg m^{-2} d^{-1} for the Pamlico. PO_4^{3-} flux in the Neuse followed the same temporal distribution as NH_4^+ flux, however the overall mean was an order of magnitude less at 3.0 mg m^{-2} d^{-1}. In the Pamlico, PO_4^{3-} flux had an overall mean of 2.4 mg m^{-2} d^{-1} and did not follow a discernible temporal distribution pattern. In both estuaries, highest fluxes for NH_4^+ and PO_4^{3-} were typically found in the mid-estuary locations, e.g. NR-3 and PR-2.

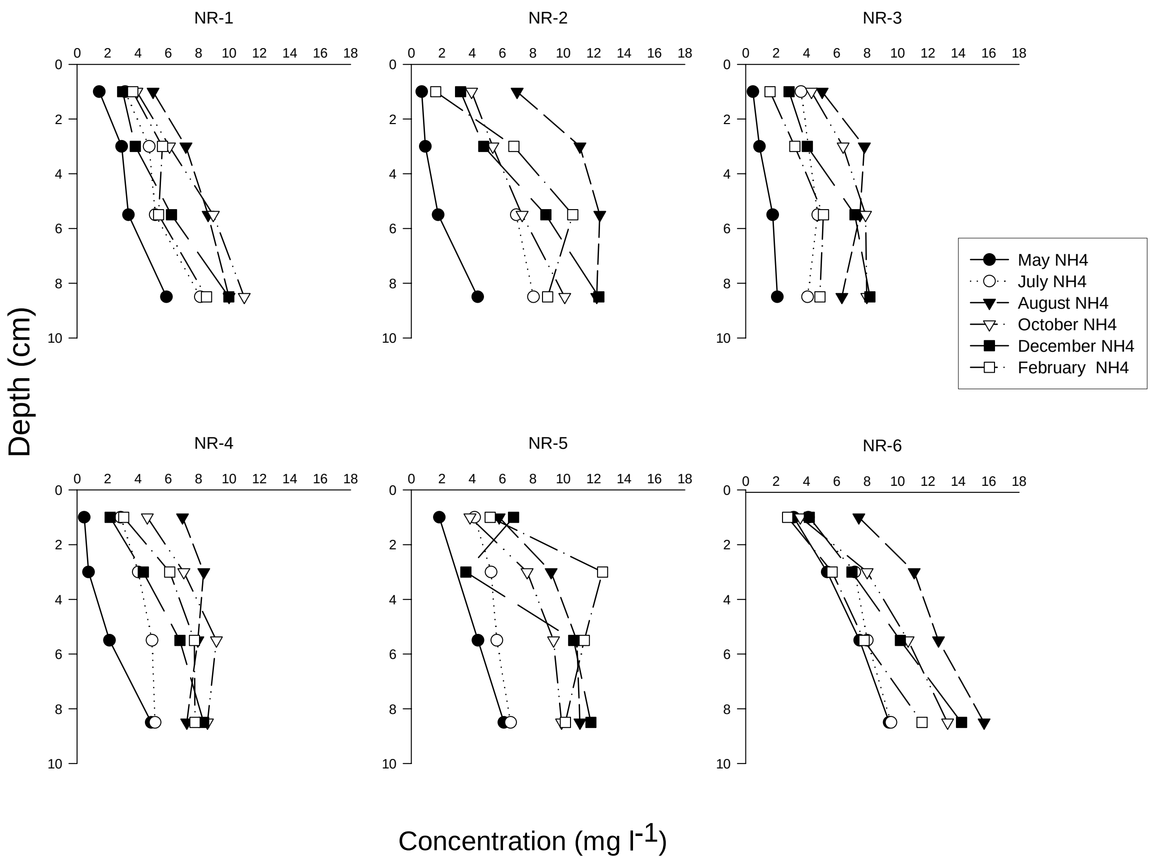


Figure 5.3. Porewater concentrations in mg/l for NH_4^+ in the Neuse River estuary for May 2001 through early spring 2002.

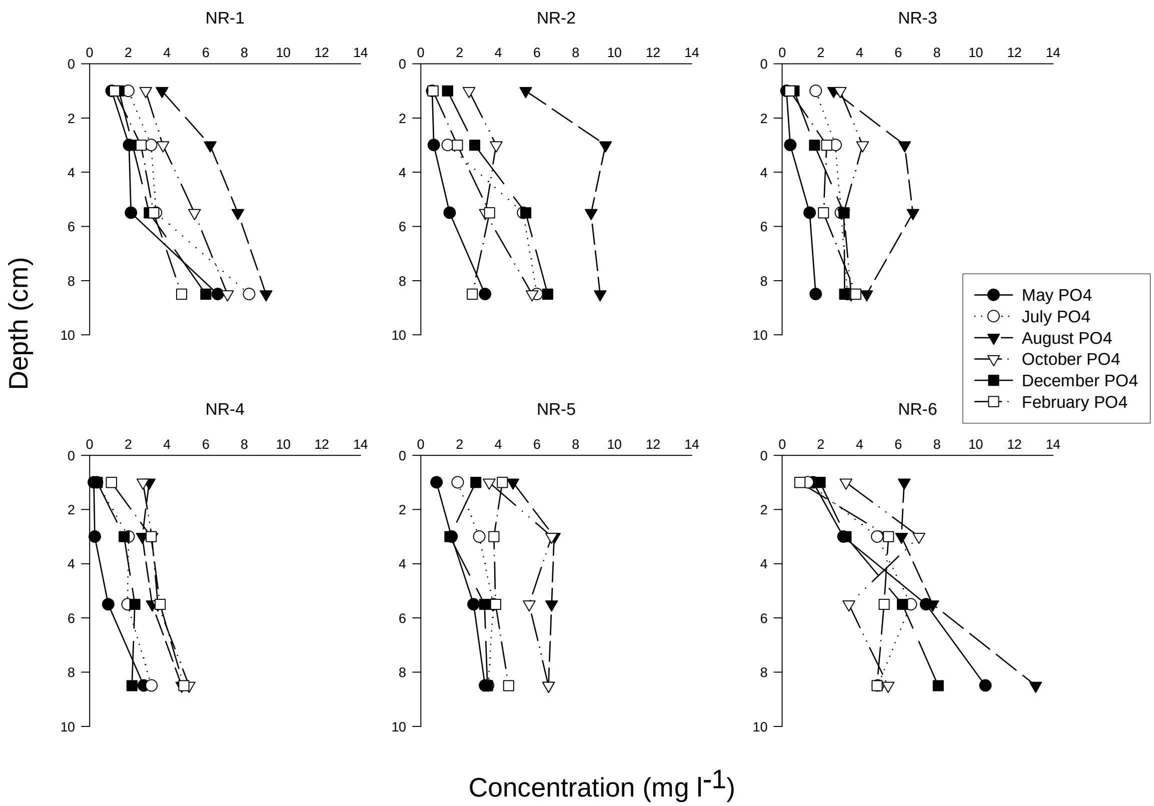


Figure 5.4. Porewater concentrations in mg/l for PO_4^{3-} in the Neuse River estuary for May 2001 through early spring 2002.

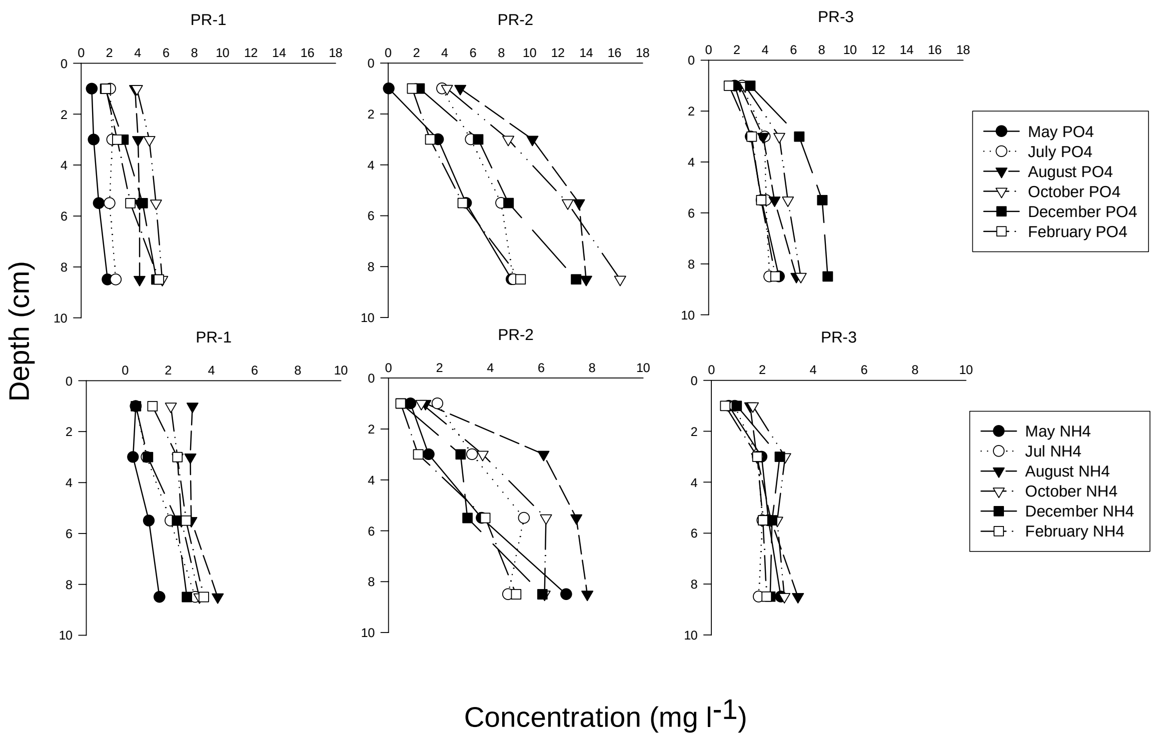


Figure 5.5. Porewater concentrations in mg/l for PO_4^{3-} and NH_4^+ in the Pamlico River estuary for May 2001 through early spring 2002.

Table 5.1. Diffusive flux calculations in mg m^{-2} d^{-1} for all stations in both the Neuse and Pamlico estuaries.

	NH_4^+			PO_4^{3-}		
Site	**High**	**Low**	**Mean**	**High**	**Low**	**Mean**
NR-1	12.4	3.8	8.8	5.6	1.8	2.6
NR-2	25.2	1.3	13.3	9.7	0.1	3.5
NR-3	64.6	2.1	17.8	8.2	0.4	3.0
NR-4	13.2	1.5	8.9	3.9	0.1	1.9
NR-5	31	6.1	16.6	6.8	0.7	3.2
NR-6	22	10.4	15.6	7.3	0.3	4.0
PR-1	12.3	0.7	4.5	1.6	0.1	0.8
PR-2	30.3	5.3	18.1	10.7	1.1	4.3
PR-3	16.7	6.1	10.2	3.1	0.6	2.2

5.4 C/N Ratios

Average C/N ratios in the Neuse River (**Figure 5.6**) ranged from about 14 at the upriver sample location (NR-1) to 10 near the mouth (NR-6) showing intermediate values between terrestrial and marine OC. Excursions from this trend occurred at depth at station NR-3 with a higher average value, C/N ratio of 16, than the upriver site. Values generally showed slight increases with depth in the middle portion of the estuary. Average C/N ratios in the Pamlico River (**Figure 5.7**) ranged from greater than 16 at depth at the upriver sample location (PR-1) to about 9 adjacent to the mouth (PR-3). Values showed increases with depth primarily at PR-1. Both estuaries generally exhibited decreasing downstream gradients implying conservative mixing behavior. Standard error is shown on both figures with the primary areas of variability at sites NR-2, NR-3, and PR-1. The source for this variability is the result of larger changes in %C at these locations respective to other areas of the estuaries. Looking at changes in %C and changes in %N (**Figure 5.6**), a decrease in %C and %N is seen in the middle reaches of the Neuse. This trend is not observed in the Pamlico (**Figure 5.7**). Instead one sees a general increase in nitrogen in the middle estuary and then a decline at the river mouth. Decreasing trends are seen with depth for both %C and %N in the middle to lower (NR-3 to NR-5 region) Neuse estuary. This is also observed in the Pamlico estuary (PR-3).

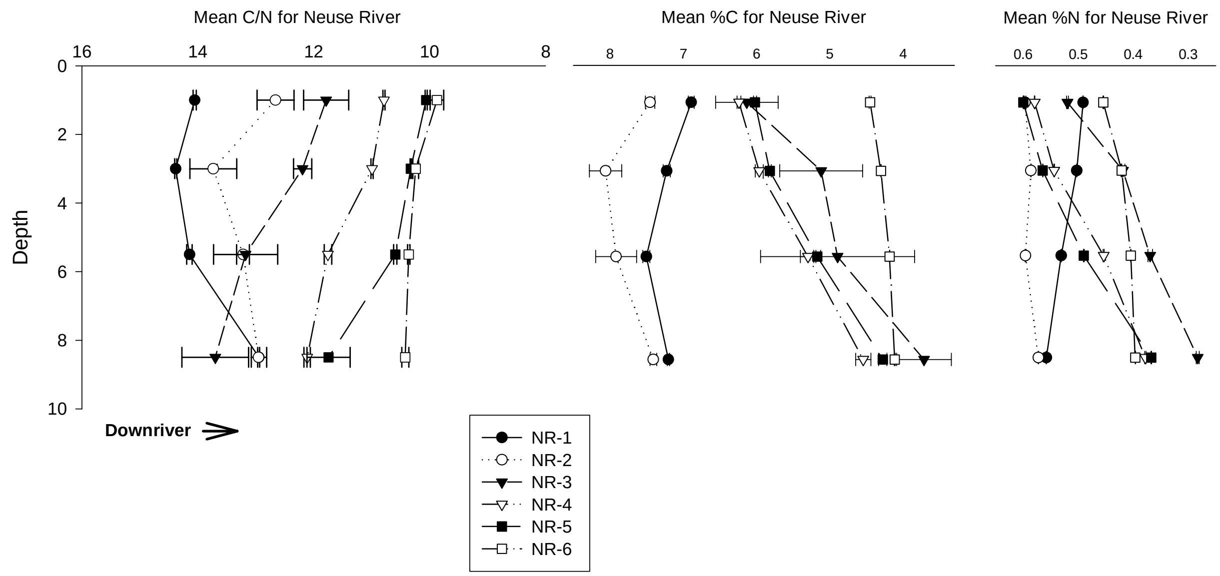


Figure 5.6. Average C/N ratios in the Neuse River ranging from about 14 at the upriver sample location (NR-1) to 10 near the mouth (NR-6).

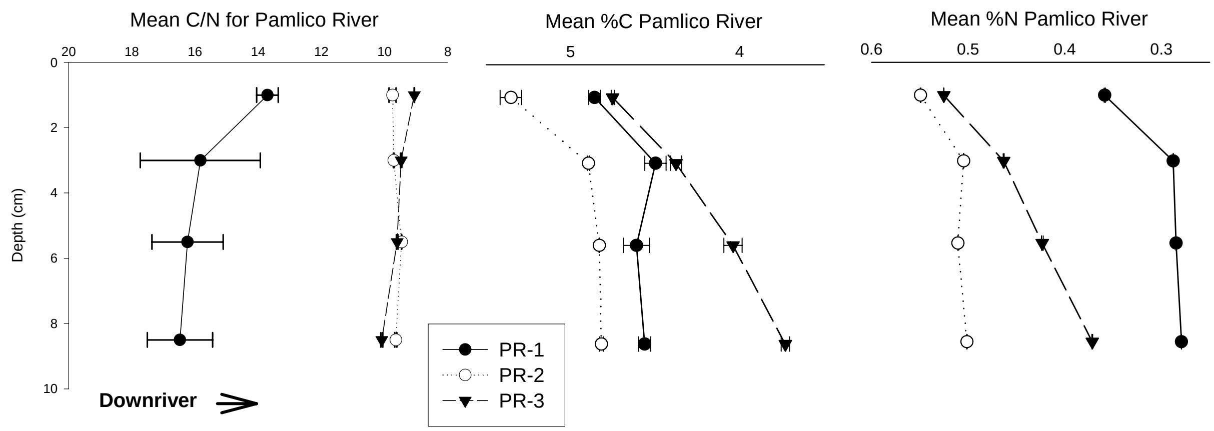


Figure 5.7. Average C/N ratios in the Pamlico River ranging from about 16 at the upriver sample location (PR-1) to 9 near the mouth (PR-).

6.0 Nutrients: Discussion

6.1 Laboratory Study

The results of the resuspension experiment indicated that increases in bottom water nutrient concentrations can actually occur advectively during a resuspension event. In addition, these nutrient concentration increases indicate that advective processes could enable fluxes substantially higher than those derived by considering only passive diffusion. Since the experimental removal only involved ~0.3 cm, these reactions probably occurred mostly in the oxic-suboxic transition zone and could therefore be less representative of actual field results that would occur much deeper in the in situ removals. The largest actual resuspension event calculated in the Neuse involved about 2.2 cm of sediment removal. This is significantly deeper than the removal depth obtained in the experiment and it is therefore likely that an in situ removal initiates the advection of porewaters with much higher concentrations than those witnessed in the experiment. The deeper portion of the core (below several mm) probably consisted of a more anaerobic environment with much higher ammonium and phosphate concentrations as will be shown in the in situ porewater profiles. These results therefore show that increases in bottom water nutrient concentrations actually occur advectively during a resuspension event and are substantially higher than those derived by considering only passive diffusion.

6.2 Water Column

The physical parameters DO, salinity, and temperature appear to strongly influence biotic and water quality conditions in these estuarine systems and are essential in determining influences on bottom water nutrient concentration changes that might result from resuspension events. Low DO conditions throughout most of the year indicated that periods of bottom water hypoxia seem to correspond with contemporaneous increases of bottom water salinity and increased stratification in the upper estuary. Temperature changes, ranging from 9°C in the winter to 28°C in the summer, influenced seasonal changes in porewater nutrient distributions in these estuaries by increasing the available nutrient flux during the summer months. This is primarily due to increased microbial activity during the warmer months (Val Klump and Martens, 1981; Fisher et al., 1982; Hopkinson et al., 1999). Physical and chemical processes such as sediment resuspension, river discharge, and enhanced oxic conditions can influence nutrient concentrations in the water column of both estuaries, especially in the bottom water. Elevated NH_4^+ levels in the Neuse bottom water correlated with oxygen depletion as previously stated in another study (Luettich et al., 2000). These elevated concentrations also corresponded with periods of sediment removal in the system. Bottom water of the Pamlico also showed elevated NH_4^+ and PO_4^{3-} concentrations corresponding to locations and occurrence of sediment resuspension events (PR-1 in August). However, this is also a period of highest remineralization and diffusive flux.

Surface water showed elevated levels of NO_3^- that could be the result of increased basin runoff since most of the NO_3^- input to these estuaries has been documented to occur during periods of high discharge (Christian et al., 1989; Boyer et al., 1994; Luettich et al., 2000). Similar results have been reported in other estuaries (Holmes et al., 2000). Additionally, increased nitrification during periods of sediment resuspension can contribute to these elevated NO_3^- levels. Nitrate levels in the bottom water showed depletion during summer months, especially in the upper part of the estuary, due to a possible combination of benthic uptake and plankton assimilation (Christian et al., 1991). Oxygen depletion, as indicated by the low DO concentrations in this area, could also account for this observation. The greater concentrations of NH_4^+ and PO_4^{3-} with depletion of NO_3^- in the bottom waters of both these estuaries could also partially be the result of heterotrophic consumption of organic matter sinking from surficial waters and denitrification (Cruzado et al., 2002). Pamlico bottom water NO_3^- exhibited depletion similar to the Neuse. Nitrate concentrations typically constituted less than 20% of the total nitrogen budget available in the bottom waters during this study.

Several studies over the last two decades have sampled for these nutrients on a regular basis in the Neuse (Christian et al., 1991; Luettich et al., 2000), however only one of these includes results from the Pamlico (Spruill et al., 1998). In general, results showed NO_3^- ranging from 20 to 350 ug l^{-1} in the latter half of the 1980's in the Neuse. Ammonium concentrations ranged from 10 to 73.4 ug l^{-1} and PO_4^{3-} from 9 to 147 ug PO_4^{3-}. In the 1990's, NO_3^- concentrations in surface water were typically >600 ug l^{-1} in the upper estuary during the summer with occasional occurrences exceeding 1000 ug l^{-1}. These larger excursions can usually be related to periods of increased river discharge as previously discussed. Ammonium was typically at levels between 50 to 150 ug l^{-1} with some concentrations exceeding 200 ug l^{-1} in the summer of 1996, while PO_4^{3-} primarily was at 40 to 80 ug l^{-1} with some higher levels also during the summer months. Their results from the mid-1990's indicated that total nitrogen and PO_4^{3-} median summer concentrations were >100 ug l^{-1} in both estuaries. It was stated in all these studies that nutrient levels were excessive in both estuaries. A comparison of our results to these findings, with the possible exception of the USGS study, shows NH_4^+ and PO_4^{3-} at much higher levels, up to three times previous results, and lower NO_3^-. However, several reasons for these variations are possible. Some of these studies primarily sampled from surface waters while our results also include bottom water sampling where sediment porewater fluxes of dissolved nutrients, especially NH_4^+ and PO_4^{3-}, to overlying waters are less diluted. This could account for our higher concentrations of these constituents. The lower nitrate levels could possibly result from prolonged periods of decreased discharge during the year and/or the effect of ongoing nutrient management practices. However, when comparing total nitrogen (TN) values across these studies there has been little change, if any. Differences in NO_3^- versus NH_4^+ between sampling events may just be a function of interannual variability due to differences in physical conditions such as DO availability and stratification. These nutrient concentrations are still at levels that can exacerbate water quality. Eutrophication can be prolonged by nutrient recycling from sediments even after external nutrient reductions have occurred (Rizzo and Christian, 1996).

6.3 Porewater Gradients

There are several mechanisms that can alter porewater concentrations, and thus create non-steady state conditions. Among some of the more common are large temperature and/or salinity changes, bioturbation, and sediment resuspension. Porewater chemical reactions can be indicated by changes in the concentration gradient of a respective constituent. The shape of the majority of the top portion of the nutrient porewater profiles indicated an upward diffusion to the overlying water column. Strong temporal variation, as displayed during late summer, can indicate shifts in remineralization of organics and exchange of nutrients with the overlying water column (Hopkinson et al., 1999). Rapid shifts of this nature can cause important changes to equilibrium conditions. Due to the anaerobic nature of these sediments there are much greater NH_4^+ concentrations than would be present under aerobic conditions, therefore these changes to non-steady state could be significant.

Increased flux of nutrients from sediments can also occur through bioturbation (Tuominen et al., 1999), and during resuspension episodes, by increasing oxidized conditions. However, no evidence of macrobenthic bioturbation was observed during this study. Other studies in these systems have shown similar results (Matson et al., 1983; Cooper, 1998). It is thought that periodic bottom water anoxia can cause the disappearance of benthic animals and decreased nitrification and denitrification (Tuominen et al., 1999). Bottom water hypoxia in the Pamlico has been attributed with interfering in the biotic life cycles of the benthos (Tenore, 1972) and, as noted, was present during a good portion of this study in both estuaries. Therefore, increased periods of flux are thought to be primarily the result of sediment remobilization.

Resuspension will introduce nutrients and organic matter into the more oxic water column, thus promoting further remineralization (Nichols, 1986). In addition, the benthos is also reoxidized. Generally, the occasional exceptions to the diffusive porewater gradient conditions indicated bottom water uptake and corresponded to areas and timeframes of increased resuspension activity. The NH_4^+ and PO_4^{3-} profiles for NR-4, NR-6, and PR-1 during August, when the largest removal occurred, are indicative of this, as shown by their decreased gradients in the uppermost sediments. Porewater NH_4^+ and PO_4^{3-} levels were also generally higher at all other times and locations of increased sediment removal. Porewater NO_3^- increased an order of magnitude in August at all stations in both estuaries, indicating increased nitrification, but then declined back to low levels by fall. It should be noted that this occurred during a period when the lowest DO concentrations were observed. This increase in NO_3^- was also coincident to the largest resuspension event in both systems, which could have increased vertical mixing (Kemp et al., 1990). Therefore, frequent sediment remobilization during this timeframe could have produced non-steady state conditions thereby enhancing nitrification-denitrification in the surface sediments and bottom waters as is known to occur in other systems (Aller, 1998).

6.4 Porewater Flux

There are several hydrodynamic forces that control the transport of porewater nutrients to the overlying water column. These are convection, molecular diffusion, and advection. Convection commonly refers to flow induced by fluid density differences. In an estuary this process can occur when the sediment porewaters are lower in salinity and density than those in the water column (Webster et al., 1996). This type of transport can take place at times when the salt wedge moves up the estuary.

Many studies have shown a disagreement between measured and calculated flux using Fick's first law. In general laboratory results have indicated lower calculated fluxes than in situ findings (Knox et al., 1993). While molecular diffusion flux calculations may be appropriate during quiescent periods, non-Fickian approaches could be considered more valid during times of greater mixing. During these more active sedimentary processes, gradient changes in the upper portions of the sediments indicate larger fluxes than can be justified using a diffusive approach. Advective flow is usually the result of a disturbance such as sediment resuspension, bioturbation, or gas ebullition (Val Klump and Martens, 1981) and is usually several orders of magnitude greater than diffusive flow. Therefore, a more realistic approach to determining actual fluxes of nutrients to the overlying water column during disturbance events would be the use of in situ concentration comparisons. By comparing nutrient inventories in bottom water and porewater before and after resuspension events, a determination of the effectiveness of advective release of nutrients can be made. Comparisons of Neuse River bottom water NH_4^+ concentrations at 0.418 mg l^{-1} to porewater concentration, with a maximum of 15.7 mg l^{-1}, were 38 times that of the bottom water. Porewater PO_4^{3-} of 13.1 mg l^{-1} was 21 times bottom water PO_4^{3-} at 0.616 mg l^{-1}. This shows the importance of the role pore waters play in supplying nutrients to the overlying water column. It also indicates there should be considerable transport across the interface, especially when sediments are advected in removal episodes. Seasonal comparisons have shown the largest values of porewater and bottom water correspond to each other (August 2001) and, as previously stated, are in unison with the locations of the maximum removals through resuspension during this study. This illustrates the possible effectiveness of resuspension in releasing diagenetic end-products from bottom sediments. This is also important because of the shift it will cause in increased denitrification and the eventual availability of nutrients for primary productivity.

Using the porewater concentration for the uppermost sediments for the removal at NR-6 in August, calculated advective fluxes of 147 and 125 mg m^{-2} d^{-1} for NH_4^+ and PO_4^{3-} were obtained. **Table 6.1** presents a comparison of the diffusive and advective flux calculations from this study to the findings for NH_4^+ and PO_4^{3-} flux from previous studies. NH_4^+ flux is typically 2 to 6 times greater using the advection approach than those with diffusion. Phosphate fluxes were determined to be 15 times greater than the benthic flux obtained in a prior study (Matson et al., 1983). It should be noted that NH_4^+ diffusive flux during this study was at least half that determined in prior studies. This may be a result of averaging in fluxes from less dynamic periods of the study year. Calculations of flux at individual sites (**Table 5.1**) during the summer months and during periods of resuspension show values more representative of prior results.

Table 6.1. A comparison of the diffusive and advective fluxes in mg m^{-2} d^{-1} from this and previous studies.

	PO_4^{3-} flux	NH_4^+ flux	Method and Flow Assumption
This study	125	147	Porewater gradient, advective
	3	13	Mean of porewater gradients, diffusion
Luettich et al, 2000	-	38	Laboratory chamber, diffusion
Rizzo and Christian, 1996	-	34	Unstirred cores, diffusion
Matson et al, 1983	8	25	Porewater gradient, diffusion
Fisher et al, 1982	-	76	In situ chamber, diffusion

6.5 C/N

Ratios of organic carbon to nitrogen (C/N) are frequently used to indicate the source and fate of particulate organic matter (POM) in sedimentary environments since the ratio depends upon the composition of the original organics (Andrews et al, 1998). There are several biological and hydrological mechanisms that can cause variations in the amount of sediment N and C (Herczeg et al, 2001): the amount of algal growth in the water column, source changes with differing N and C composition, fractionation by benthic bacteria, and estuarine circulation. Marine phytoplankton organic carbon (OC) characteristically exhibits lower C/N ratios than OC of terrestrial origin (Fry and Sherr, 1984). Typical values for marine C/N are near 6 to 7 while those for terrestrial OC can be >20 (Redfield, 1958; Graham et al, 2001). If the assumption is made that C/N ratios act conservatively, they can be especially useful in estuaries to determine anthropogenic inputs such as pulp waste (C/N around 200), oil (C/N as high as 80) and sewage (C/N typically 11 to 13) (Andrews et al, 1998). However, it should be noted that variation of these ratios in estuarine environments can also occur due to biological processing and mineralization within the sediments (Thornton and McManus, 1994). Therefore it is advisable to combine the use of C/N with other tracers such as $\delta^{13}C$.

Average C/N values for the Neuse and Pamlico (**Figures 5.6 and 5.7**) suggest that ratios for the middle and lower estuary are indicative of aquatic plant remains (Herczeg et al, 2001). The largest amount of variability occurred in %C, especially at sites NR-2 and NR-3, which are historically an area of frequent fish kills and could be the result of in-situ production from algal blooms (Matson and Brinson, 1990). Terrestrial input is much greater in the upper portion of the Pamlico than that of the Neuse as also indicated in a previous study (Matson and Brinson, 1990) and could account for the large variability in %C at PR-1. Decreasing trends were seen with depth for both %C and %N in the middle to lower (NR-3 to NR-5 and PR-3 region) Neuse and Pamlico estuaries indicating diagenesis. Interestingly, these areas correspond to areas with the lowest sediment deposition rates as previously discussed in the porewater section. These areas also are located where sediment removal episodes are more frequent. Whereas, those areas where C/N, %C, and %N exhibit vertical profiles with little change with depth are located in areas where radioisotopes characterized them as depositional environments.

7.0 References

Allan, R.J. 1986. The role of particulate matter in the fate of contaminants in aquatic ecosystems NWRI Report, NO. 142, Canada Centre for Inland Waters, Burlington, Ontario, Canada.

Aller, R.C. 1998. Mobile deltaic and continental shelf muds as suboxic, fluidized bed reactors, Marine Chemistry, 61, 143-155.

Alongi, D.M., S.G. Boyle, F. Tirendi, and C. Paya, 1996. Composition and behavior of trace metals in post-oxic sediments of the Gulf of Papua, Papua New Guinea. Estuar. Coast. Shelf Sci. 42: 197-211.

Alperin, M.A., 2000. Impact of sediment processes on water quality in the Neuse River Estuary. WRRI, April Seminar Abstract, Raleigh, NC.

Alperin, M.A., E.J. Clesceri, J.T. Wells, D.B. Albert, J.E. McNinch and C.S. Martens, 2000. Sedimentary Processes and Benthic-Pelagic Coupling. In: Neuse River Estuary MODeling and MONitoring Project: Final Report, 325-B. Water Resources Research Institute. Raleigh, NC.

Andrews, J.E., A.M. Greenaway, and P.F. Dennis, 1998. Combined Carbon Isotope and C/N Ratios as Indicators of Source and Fate of Organic Matter in a Poorly Flushed, Tropical Estuary: Hunts Bay, Kingston Harbor, Jamaica, Estuarine, Coastal and Shelf Science, 46, 743-756.

Baskaran, M. and P.H. Santchi, 1993. The role of particles and colloids in the transport of radionuclides in the coastal environments of Texas. Mar. Chem. 43: 95-114.

Bengtsson, L, Th. Hellstrom, L. Rakoczi, 1990. Redistribution of sediments in three Swedish lakes. Hydrobiologia 192: 167-181.

Benninger, L.K., 1989. Ra Isotopes and 137-Cs in sediments of the Neuse River Estuary, North Carolina. EOS, Trans. American Geophysical Union, 70:361.

Benninger, L.K., 1990. Pb-210 in sediments of the Neuse River Estuary, North Carolina. EOS, Trans. American Geophysical Union, 71:531.

Benninger, L.K. and Wells, J.T., 1993. Sources of Sediment to the Neuse River Estuary, North Carolina, Mar. Chem. 43:137-156.

Berner, R., 1980. Early Diagenesis: A Theoretical Approach. Princeton University press. 241 pp.

Booth, J.G., R.L. Miller and B.A. McKee, 1995. Integrating remote sensing and geochemical techniques to analyze sediment dynamics in shallow estuaries. Symposium Volume: Third Thematic Conference on Remote Sensing for Marine and Coastal Environments, Seattle,WA.

Borole, D.V., S. Krishnaswami and B.L.K. Somayajulu, 1977. Investigations of dissolved uranium, silicon, and particulate trace elements in estuaries. Etuar. Coast. Mar. Sci. 5: 743-754.

Boyer, J.N., D.W. Stanley, R.R. Christian, W.M. Rizzo, 1988. Modulation of nitrogen loading impacts within an estuary. In W.L. Lyke and T.J. Hoban (eds) Proceedings N.C. Amer. Water Resoures Assoc., Syposium on Coastal Water Resources. AWRA Technical Publ. Series TPS-88-1. AWRA, Bethesda, MD, p. 165-176.

Boyer, J.N., D.W. Stanley, and R.R. Christian, 1994. Dynamics of NH_4^+ and NO_3^- Uptake in the Water Column of the Neuse River Estuary, North Carolina, Estuaries, Vol. 17, No. 2, 361-371.

Canuel, E., C. Martens and L. Benninger, 1990. Seasonal variations in Be-7 activity in the sediments of Cape Lookout Bight, North Carolina. Geochim. Cosmochim. Acta. 54:237-245.

Carper, G.L. and R.W. Bachman, 1984. Wind resuspension of sediments in a Prairie Lake. Can. J. Fish. Aquat. Sci. 41:1763-1767.

Cheevaporn, V., G.S. Jacinto and M.L. San Diego-McGlone, 1995. Heavy metal fluxes in Bang Pakong River estuary, Thailand: Sedimentary vs. Diffusive fluxes. Mar. Poll. Bull.

Christian, R.R., W.M. Rizzo, and D.W. Stanley, 1989. Influence of nutrient loading on the Neuse River estuary, North Carolina, NOAA, National Underseas Research Program, Research Report 89-2, 19-40.

Christian, R.R., J.N. Boyer, and D.W. Stanley, 1991. Multi-year distribution patterns of nutrients within the Neuse River Estuary, North Carolina, Marine Ecology Progress Series, Vol. 71, 259-274.

Cooper, S.R. 1998. The history of water quality in NorthCarolina Estuarine Waters as documented in the stratigraphic record. NC WRRI Report No. .

Corbett, D.R., W.C. Burnett, P.H. Cable, and S.B. Clark, 1998. A multiple approach to the determination of radon fluxes from sediments, Journal of Radioanalytical and Nuclear Chemistry, Vol. 236, Nos 1-2, 247-252.

Cruzado, A., Z. Velásquez, M. del Carmen Pérez, N. Bahamón, N.S. Grimaldo, and F. Ridolfi, 2002. Nutrient fluxes from the Ebro River and subsequent across-shelf dispersion, Continental Shelf Research 22, 349-360.

de Jonge, V. N., and J.E.E. van Beusekom 1995. Wind- and tide-induced resuspension of sediment and microphytobenthos from tidal flats in the Ems estuary. Limnology and Oceanography **40**(4): 766-
778.

Douglas, R.W. and B. Rippey, 2000. The random redistribution of sediment by wind in a lake. Limnol. Oceanog. 45: 686-694.

Dugdale, R.C. and J.J. Goering, 1967. Uptake of new and regenerated forms of nitrogen in primary productivity. Limnol. Oceanog. 12: 196-206.

Emmett, W., L. Leopold, R. Myrick, 1983. Some characteristics of fluvial processes in rivers. In: International Symposium on River Sedimentation. Water Resources and Electric Power Press, Beijing.

Fanning, K. A., Carder, L.C., and P.R. Betzer. 1982. Sediment resuspension by coastal waters: a potential mechanism for nutrient re-cycling on the ocean's margin. Deep-Sea Research **29**(8A): 953-965.

Feng, H., J.K. Cochran, D.J. Hirschberg, and R.E. Wilson, 1998. Small-Scale Variations of Natural Radionuclide and Trace Metal Distributions in Sediments From the Hudson River Estuary, Estuaries, Vol.21, No. 2, 263-280.

Fisher, T.R., P.R. Carlson, R.T. Barber, 1982. Sediment nutrient regeneration in three North Carolina Estuaries. Estuar. Coast. Shelf Sci. 14:101-116.

Froelich, P., G. Klinkhammer, M. Bender, N. Luedtke, G. Heath, D. Cullen, P. Dauphin, D. Hammond, B. Hartmann, V. Maynard, 1979. Early oxidation of organic matter in pelagic sediments of the eastern equatorial Atlantic: suboxic diagenesis. Geochim. Cosmochim. Acta. 43:1075-1091.

Fry, B., and E.B. Sherr, 1984. $\delta^{13}C$ measurements as indicators of carbon flow in marine and freshwater ecosystems. Contributions in Marine Science, 27:13-47.

Graham, M.C., M.A. Eaves, J.G. Farmer, J. Dobson and A.E. Fallick, 2001. A Study of Carbon and Nitrogen Stable Isotope and Elemental Ratios as Potential Indicators of Source and Fate of Organic Matter in Sediments of the Forth Estuary, Scotland, Estuarine, Coastal and Shelf Science, 52, 375-380.

Haines, E.B., 1976. Nitrogen content and acidity of rain on the Georgia coast. Water Resour. Bull. 12: 1223-1231.

Hakanson, L. and M. Jansson 1983. Principles of lake sedimentology. Springer.

Harrison, W.G. and J.E. Hobbie, 1974. Nitrogen budget of a North Carolina Estuary. NC WRRI Report No. 86.

Herczeg, A.L., A.K. Smith, and J.C. Dighton, 2001. A 120 year record of changes in nitrogen and carbon cycling in Lake Alexandrina, South Australia: C:N, $\delta^{15}N$, and $\delta^{13}C$ in sediments, Applied Geochemistry, 16, 73-84.

Hilton, J. 1986. A conceptual framework for predicting the occurrence of sediment focusing and sediment redistribution in small lakes. Limnol. Oceanog. 30: 1131-1143.

Hobbie, J. E. and N. W. Smith, 1975. Nutrients in the Neuse River Estuary, University of North Carolina Sea Grant Program Publication UNC-SG-75-21.

Holmes, R.M., B.J. Peterson, L.A. Deegan, J.E. Hughes, and B.Fry, 2000. Nitrogen Biochemistry in the Oligohaline Fone of a New England Estuary, Ecology, 81, 416-432.

Hopkinson, C.S. Jr., A.E. Giblin, J. Tucker, and R.H. Garritt, 1999. Benthic Metabolism and Nutrient Cycling Along an Estuarine Salinity Gradient, Estuaries, Vol. 22, No.4, 863-881.

Jeter, H.W., 2000. Determining the ages of recent sediments using measurements of trace radioactivity. Terra et Aqua 78, 21-28.

Kemp, W.M., P. Sampou, J. Caffrey, and M. Mayer, 1990. Ammonium recycling versus denitrification in Chesapeake Bay sediments. Limnology and Oceanography 35: 1545-1563.

Kemp,W.M. and W.R. Boynton, 1992. Benthic-pelagic interactions: nutrient and oxygen dynamics. In: Oxygen dynamics in the Chesapeake Bay: A Synthesis of Recent Research, D.E. Smith, M. Leffler, and G. Mackiernan (eds), Maryland Sea Grant, p. 149-221.

Kirkham, D. and W.L. Powers, 1972. Advanced Soil Physics. Wiley-Interscience, John Wiley and Sons Inc., NewYork.

Knowles, C.E., 1975. Flow dynamics of the Neuse River, North Carolina, Sea Grant Publication UNC-SG-75-16, Sea Grant Program, Raliegh, NC.

Knox, R.C., D.A. Sabatini, and L.W. Canter, 1993. Subsurface Transport and Fate Processes, Lewis Publishers, Boca Raton, FL.

Kristensen, P., Sondergaard, M., and E. Jeppesen 1992. Resuspension in a shallow eutrophic lake. Hydrobiologia **228**: 101-109.

Kuenzler, E.J., D.W. Stanley, J.P. Koenings, 1979. Nutrient kinetics of phytoplankton in the Pamlico River, NC, NC WRRI Report No. 139.

Lam, D.C. and J.-L. Jaquet, 1976. Computations of physical transport and regeneration of phosphorus in Lake Erie, fall 1970. J. Fish. Res. Bd Can. 33: 550-563.

Loffler, H. 1974. Der Neusiedlersee. Naturgeschichte eines Steppensees. Molden, Wien, 175pp.

Luettich, R.A., D.R.F. Harleman, L. Somlyody, 1990. Dynamic behavior of suspended sediment concentrations in a shallow lake perturbed by episodic wind events. Limnol Oceanog. 35: 1050-1067.

Luettich, R.A., C.S. Martens, J.E. McNinch, H. Pearl, , J. Pinckney, C.H. Peterson, J.T. Wells, and M.A. Alperin, 2000. Sedimentary Processes and Benthic-Pelagic Coupling. In: Neuse River Estuary Modeling and Monitoring Project Stage 1: Hydrography and Circulation, Water Column Nutrients and Productivity, Sedimentary Processes and Benthic-Pelagic Coupling, and Benthic Ecology, Report No. 325-B. Water Resources Research Institute. Raleigh, NC.

Luettich, R.A., J.V. Reynolds-Fleming, J.E. McNinch, C.P. Buzelli, 2000. Circulation characteristics of the Neuse River Estuary, North Carolina. Submitted to Estuaries.

Martin, J.M. and M. Meybeck, 1979. Elemental mass balance of material carried by major world rivers. Mar. Chem. 7: 173-206.

Matson, E.A., M.M. Brinson, D.D. Cahoon, G.J. Davis, 1983. Biogeochemistry of the Sediments of the Pamlico and Neuse River Estuaries, North Carolina. Water Resources Research Institute Report No. 191.

Matson, E.A. and M.M. Brinson, 1990. Stable carbon isotopes and the C:N ratio in the estuaries of the Pamlico and Neuse Rivers, North Carolina, Limnology and Oceanography 35: 1290-1300.

McKee, B.A., C.A. Nittrouer and D.J. DeMaster, 1983. The concepts of sediment deposition and accumalation applied to the continental shelf near the mouth of the Yangtze River. Geology, 11: 631-633.

McKee, B.A. W. Wiseman and M. Inoue, 1994. Saltwater intrusion and sediment dynamics in a bar-built estuary: Terrebonne Bay, LA. In: Changes in Fluxes in Estuaries: Implications from Science to Management. (ed.) K. Dyer. Proceeding, ECSA22/ERF Symposium. International Symposium Series. Olsen and Olsen. Fredensborg, Denmark. Pp. 13-16.

McKee, B.A. and Baskaran, M., 1999. Sedimentary Processes of Gulf of Mexico Estuaries, p. 63-85. *In*: T.S. Bianchi, J.R. Pennock, and R.R. Twilley [eds], Biogeochemistry of Gulf of Mexico Estuaries, John Wiley and Sons, Inc.

Meade R., T. Dunne, J. Richey, J. Santos, U. de M. Santos, E. Salati, 1985. Storage and remobilization of suspended sediment in the lower Amazon River, Brazil. Science. 228: 488-490.

Meade, R. T. Yazyk, T. Day, 1990. Movement and storage of sediment in rivers of the United States and Canada. In: The Geology of North America. Woman H. Riggs (eds) v. 0-1.

Nichols, M.M. 1986. Effects of fine sediment resuspension in estuaries, *in* Estuarine Cohesive Sediment Dynamics Vol. 14 , by Mehta, A.J., (ed), Springer-Verlag.

Nishri, A. 1993. Suspended sediments as a source of P to summer biota of Lake Kinnert. Hydrobiologia 253/Dev. Hydrobiol. 84:217.

Nittrouer, C.A., R.W. Sternberg, R. Carpenter and J.T. Nennett, 1979. The use of Pb-210 geochronology as a sedimentalogical tool: Application to the Washington coastal shelf. Mar. Geol. 31: 291-316.

Nixon, S.W. 1981. Remineralization and nutrient cycling in the coastal marine ecosystem. In: Impact of Nutrient Enrichment in Estuaries (Neilson, B. ed.) Humana Press, p.111-138.

Olsen, C.R., Larsen, I.L., Lowry, P.D., Cutshall, N.H., Todd, J.F., Wong, G.T.F., and Casey, W.H., 1985. Atmospheric Fluxes and Marsh-Soil Inventories of ^{7}Be and ^{210}Pb, J. Geophys. Res. 90: 10,487-10,495.

Olsen, C.R., I.L. Larsen, P.D. Lowry, N.H. Cutshall and M.M. Nichols, 1986. Geochemistry and deposition of Be-7 in river-estuarine and coastal waters. J. Geophys. Res. 91: 896-908.

Paerl, H.W., 1995. Coastal eutrophication in relation to atmospheric nitrogen deposition: Current perspectives. Ophelia 41: 237-259.

Paerl, H.W., M.A. Mallin, C.A. Donahue, M. Go and B.L. Peierls, 1995. Nitrogen loading sources and eutrophication pf the Neuse River estuary, NC: Direct and indirect roles of atmospheric deposition. Report No. 291. UNC . Water Resources Research Institute, NC State Univ.

Paerl, H.W., J.L. Pinckney, J.M. Fear and B.L. Peierls, 1998. Ecosystem responses to internal and watershed organic matter loading: consequences for hypoxia in the eutrophying Neuse River Estuary, North Carolina, USA. Mar. Ecol. Prog. Ser. 166: 17-25.

Pilkey, O.H., Neal, W.J., Riggs, S.R., Webb, C.A., Bush, D.M., Pilkey, D.F., Bullock, J., and Cowan, B.A., 1998, The North Carolina Shore and its Barrier Island, Duke University Press, Durham.

Pinckney,J.L., D.F. Millie, B.T. Vinyard and H.W. Paerl, 1997. Environmental controls of phytoplankton bloom dynamics in the Neuse River Estuary, North Carolina, USA. Can. J. Fish. Aquat. Sci. 54:2491-2501.

Pipkin, B., 1994. Geology and the Environment, Minneapolis, West Publishing Co.

Postma, H., 1967, In: Lauff, G.H. (ed.), Estuaries, Publication No. 83, American Association for the Advancement of Science, Washington, D.C., p. 158-179.

Pritchard, D.W., 1955, Estuarine circulation patterns. Proc. Am. Soc. Civil Eng. 81, Separate No. 717.

Redfield, A.C. 1958. The biological control of chemical factors in the environment, American Science., 46:205-222.

Riggs, S.R., J.T. Bray, E.R. Powers, J.C. Hamilton, D.V. Ames, K.L. Owens, D.D. Yeates, S. L. Lucas, J. R. Watson, and H.M. Williamson, 1991. Heavy metals in organic-rich muds of the Neuse River estuarine system. Albemarle-Pamlico Estuarine Study, Report No. 90-07.

Riggs, S.R., 1996, Sediment evolution and habitat function of organic-rich muds within the Albemarle estuarine system, North Carolina: Estuaries, v. 19, no. 2A, p. 169-185.

Riggs, S.R., Bray, J.T., and others, 1993, Heavy Metals in Organic-Rich Muds of the Albemarle Sound Estuarine System: Albemarle-Pamlico Estuarine Study, US EPA and NC DEHNR, Rept. No. 93-02, 173 p.

Rizzo, W.M. 1993. Sediment-water phosphate exchange in the Neuse River, North Carolina. NC WRRI Repot No. 275. 64 p.

Rizzo, W.M. and R.B. Christian, 1996. Significance of Subtidal Sediments to Heterotrophically-Mediated Oxygen and Nutrient Dynamics in a Temperate Estuary. Estuaries, v.19, no. 2B, p.475-487.

Rosa, F., J.O. Nriagu, H.K.T. Wong and N.M. Burns, 1983. Particulate flux at the bottom of Lake Ontario. Chemosphere 12: 1345-1354.

Rudek, J., H.W. Paerl, M.A. Mallin and P.W. Bates, 1991. Seasonal and hydrological control of phytoplankton nutrient limitation in the lower Neuse River Estuary, North Carolina. Mar. Ecol. Prog. Ser. 75: 133-142.

Sondergaard, M., Kristensen, P., and E. Jeppesen 1992. Phosphorus release from resuspended sediment in the shallow and wind-exposed Lake Arreso, Denmark. Hydrobiologia **228**: 91-99.

Spruill, T.B., D.A. Harned, P.M. Ruhl, J.L. Eimers, G.McMahon, K.E. Smith, D.R. Galeone, and M.D. Woodside, 1998. Water Quality in th Albemarle-Pamlico Drainage Basin, North Carolina and Virginia, 1992-95, U.S. Geological Survey Circular 1157.

Stanley, D.W. and J.E.Hobbie, 1977. Nitrogen cycling in the Chowan River. NC WRRI Report No. 121.

Stanley, D.W. and J.E. Hobbie, 1981. Nitrogen cycling in a North Carolina coastal river. Limnol. Oceanog. 26: 30-42.

Tenore, K.R. 1972. Macrobenthos of the Pamlico River Estuary, North Carolina. Ecological Monographs, Vol. 42, No. 1, p. 51-69.

Thornton, S.F. and J. McManus, 1994. Application of Organic Carbon and Nitrogen Stable Isotopes and C/N Rations as Source Indicators of Organic Matter Provenance in Estuarine Systems: Evidence from the Tay Estuary, Scotland, Estuarine, Coastal and Shelf Science, 38, 219-233.

Toole, J., M.S. Baxter and J. Thomson, 1987. The behavior of uranium isotopes with salinity change in three UK estuaries. Est. Coast. Shelf Sci. 25: 283-297.

Tuominen, L., K. Mäkela, K.K. Lehtonen, H. Haahti, S. Hietanen, and J. Kuparinen, 1999. Nutrient Fluxes, Porewater Profiles and Denitrification in Sediment Influenced by Algal Sedimentation and Bioturbation by *Monoporeia affinis*. Estuarine, Coastal and Shelf Science, 49, 83-97.

Turner, A., G.E. Millward, A.j. Bale and A.W. Morris, 1993. Application of K_D concept to the study of metal removal and desorption during estuarine mixing. Estuar. Coast. Shelf Sci. 36: 1-13.

Val Klump, J. and C.S. Martens, 1981. Biogeochemical cycling in an organic rich coastal marine basin –II. Nutrient sediment-water exchange processes. Geochimica et Cosmochimca Acta, Vol. 45, 101-121.

Wan, G.J., P.H. Santchi, M. Sturm, K. Farrenkothen, A. Luech, E. Werth and C. Schuler, 1987. Natural and fallout radionuclides as geochemical tracers of sedimentation in Greifense, Switzerland. Chem. Geol. 63: 181-196.

Water Resources Research Institute (WRRI), 1995. Neuse news articles http://www2.ncsu.edu:8010/ncsu/cil/wrri/

Webster, I.T., S.J. Norquay, F.C. Ross, and R.A. Wooding, 1996. Solute Exchange by Convection Within Estuarine Sediments, Estuarine, Coastal and Shelf Science, 42, 171-183.

Wells, J.T. and S.Y. Kim, 1991. Trapping and escape of fine-grained sediments: Neuse River Estuary North Carolina, in Krause, N.C., et al. eds., Coastal Sediments '91, Seattle WA, Am. Soc. Of Civ. Eng., p. 775-778.

Wells, J.T. and S.Y. Kim, 1989. Sedimentation in the Albemarle-Pamlico Lagoonal System: Synthesis and Hypotheses. Marine Geology, 88, p. 263-284.

Weyhenmeyer, G.A., L. Hakanson, M. Meili, 1997. A validated model for daily variations in the flux, orgin, and distribution of settling particles within lakes. Limnol. Oceanog. 42:1517-1529.

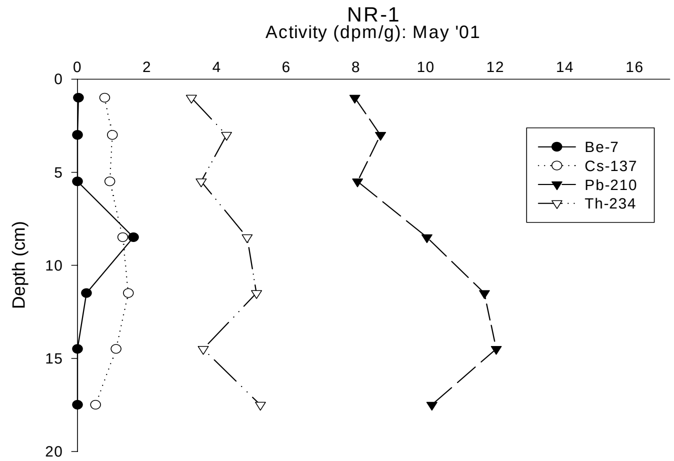
Windom, H.L., W.M. Dunstan, W.S. Gardner, 1975. River input of inorganic phosphorus and nitrogen to the southeastern salt marsh estuarine environment. Recent Advances in Estuarine Research 1, 309-313.

Wisniewski, R. 1993. The release of phosphorus during sediment resuspension. Hydrobiologia 253/ Dev. Hydrobiol. 84:321-322.

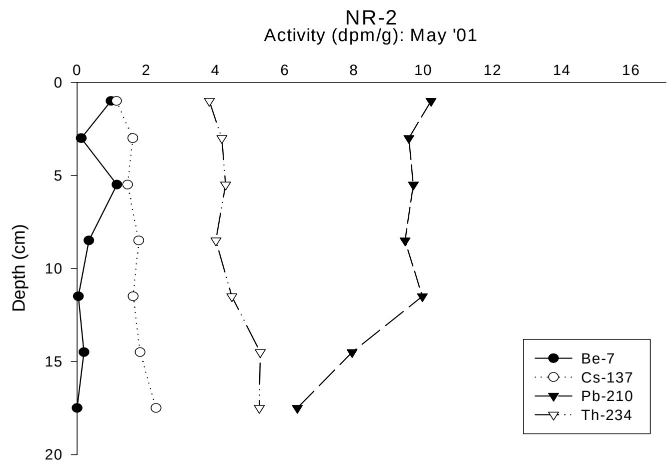
Woods, W.J. 1969. Current study in the Neuse River and estuary of North Carolina. NC WRRI Report No. UNC-WRRI-69-13.

APPENDIX A

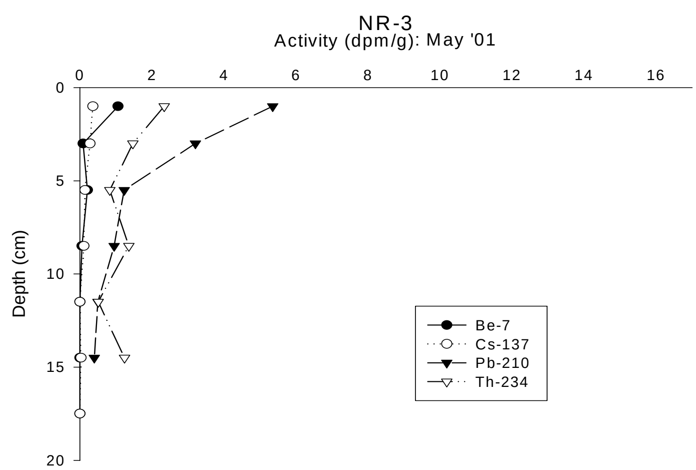
Activity Profiles



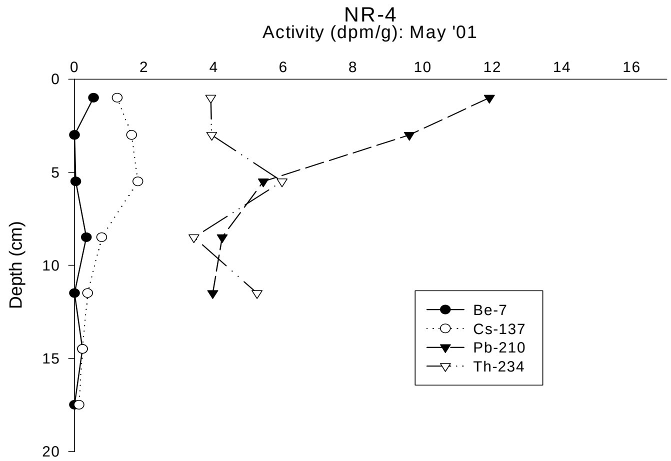
NR-1
Activity (dpm/g): May '01
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234

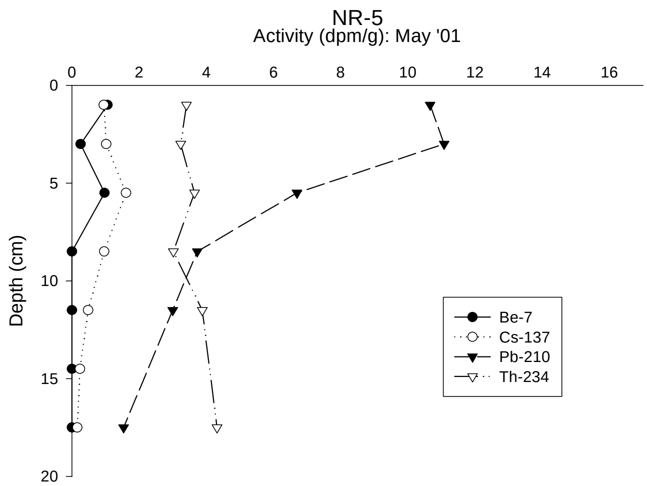


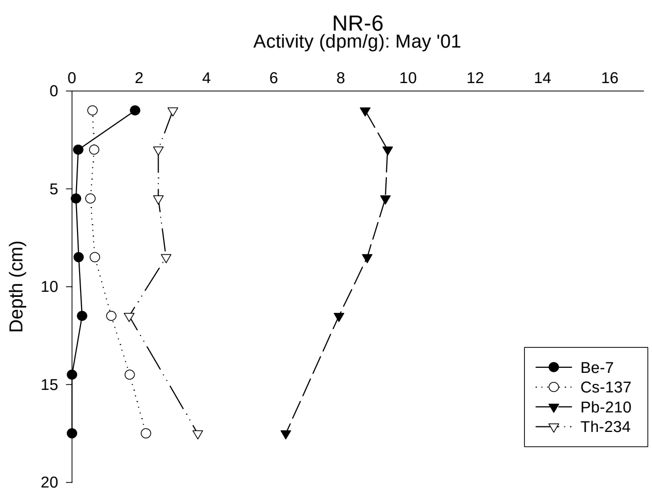
NR-2
Activity (dpm/g): May '01
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234

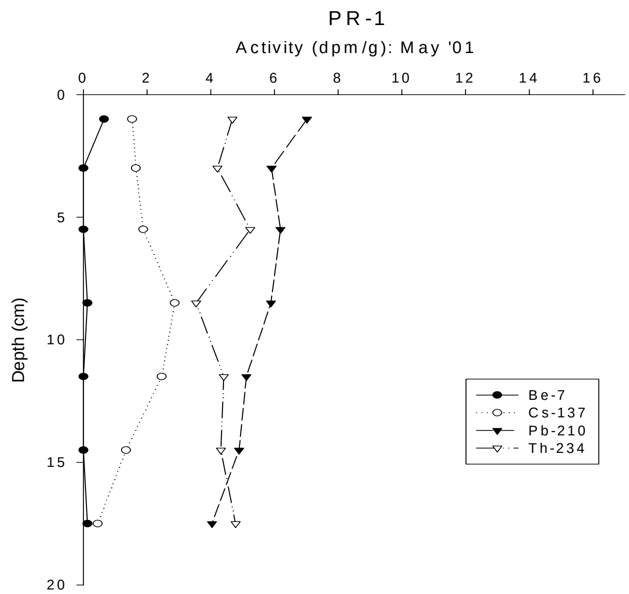


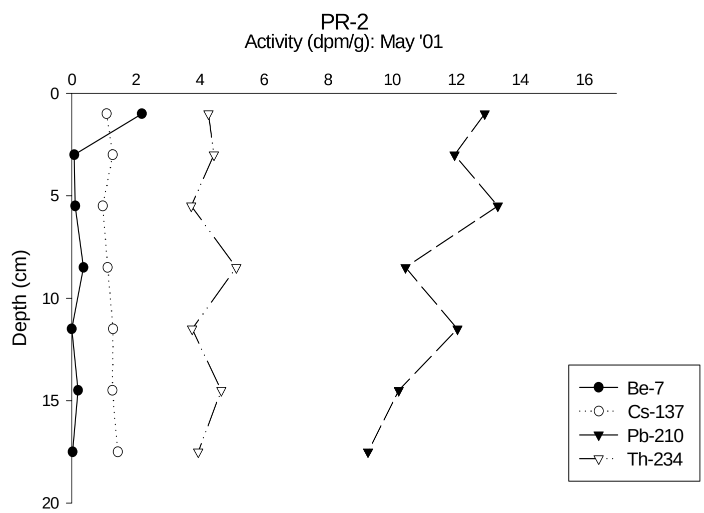
NR-3
Activity (dpm/g): May '01
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234

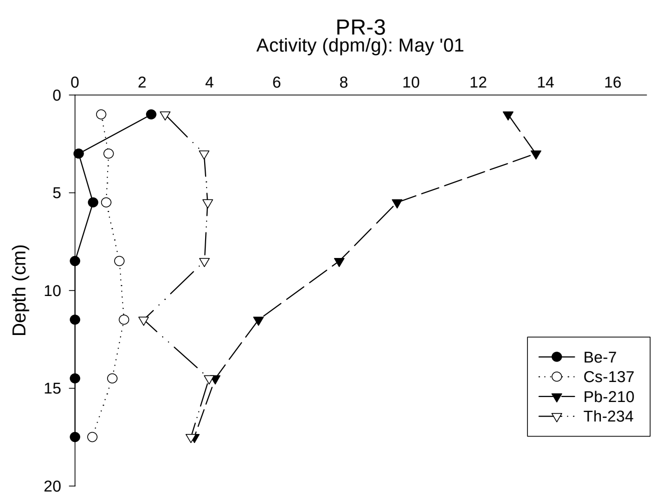

NR-4
Activity (dpm/g): May '01
0
2
4
6
8
10
12
14
16
Depth (cm)
0
5
10
15
20
Be-7
Cs-137
Pb-210
Th-234

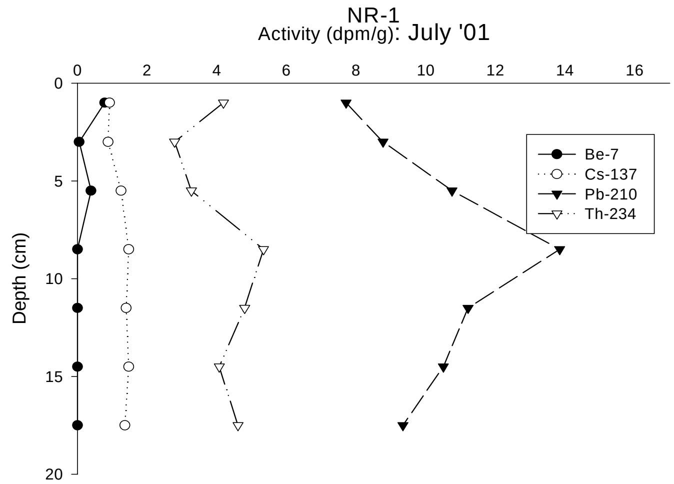

NR-5
Activity (dpm/g): May '01
0
2
4
6
8
10
12
14
16
Depth (cm)
0
5
10
15
20
Be-7
Cs-137
Pb-210
Th-234

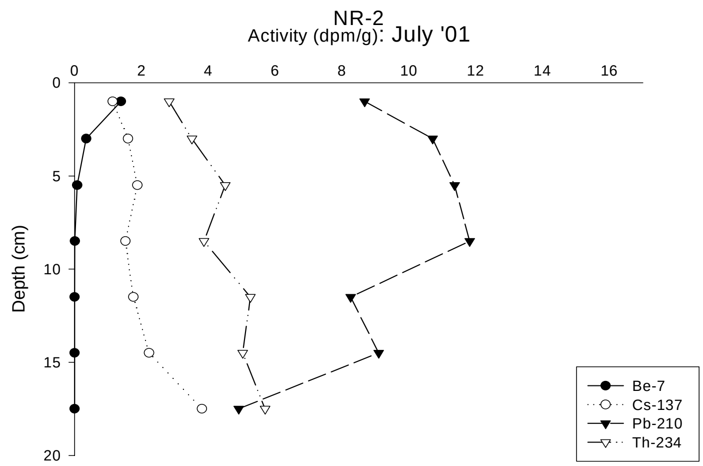

NR-6
Activity (dpm/g): May '01
0
2
4
6
8
10
12
14
16
Depth (cm)
0
5
10
15
20
Be-7
Cs-137
Pb-210
Th-234

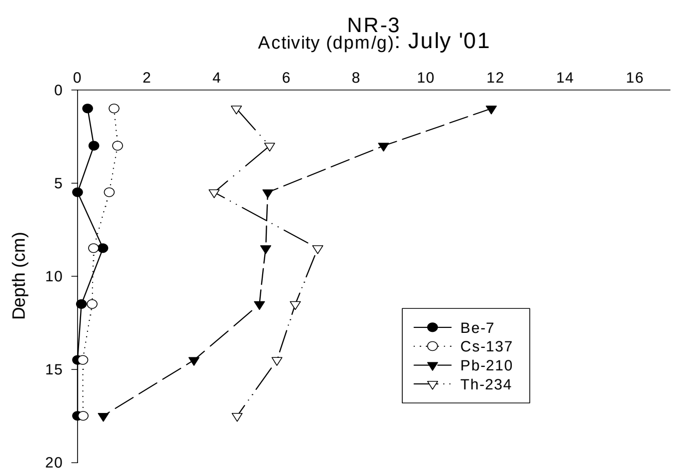

PR-1
Activity (dpm/g): May '01
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234

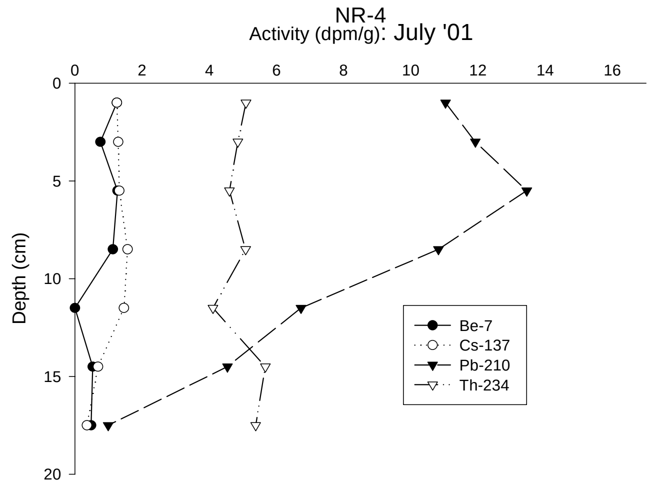

PR-2
Activity (dpm/g): May '01
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234

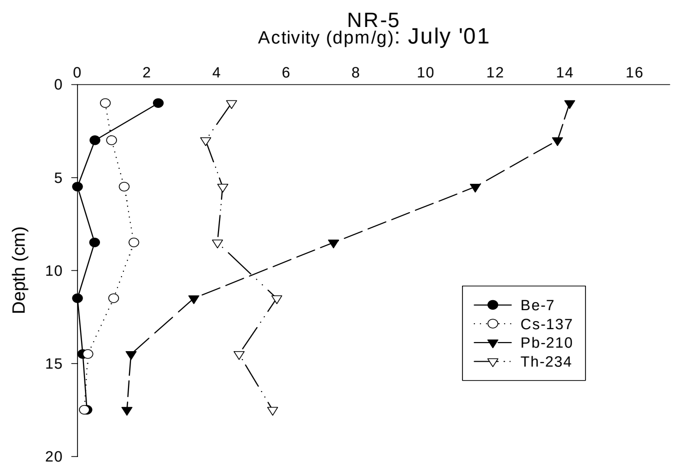

PR-3
Activity (dpm/g): May '01
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234

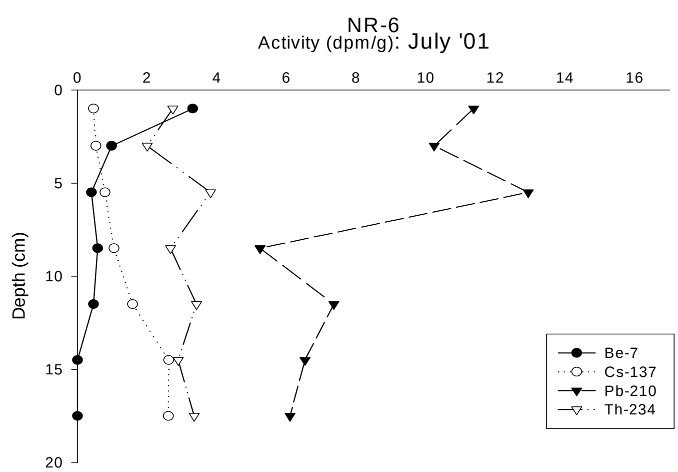

NR-1
Activity (dpm/g): July '01
0
2
4
6
8
10
12
14
16
Depth (cm)
0
5
10
15
20
Be-7
Cs-137
Pb-210
Th-234

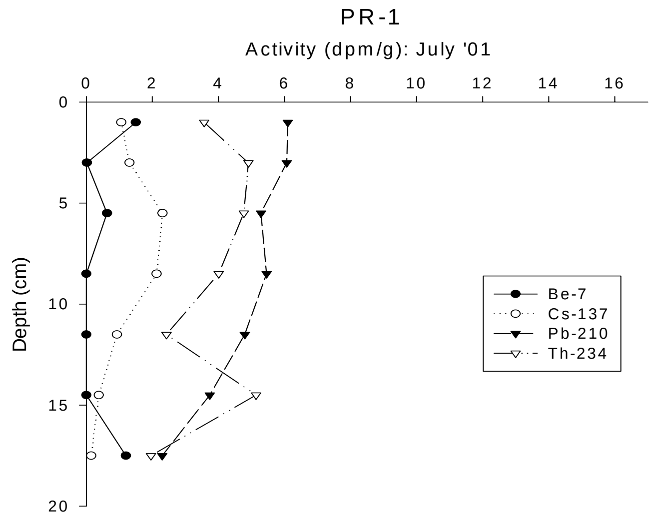

NR-2
Activity (dpm/g): July '01
0
2
4
6
8
10
12
14
16
Depth (cm)
0
5
10
15
20
Be-7
Cs-137
Pb-210
Th-234

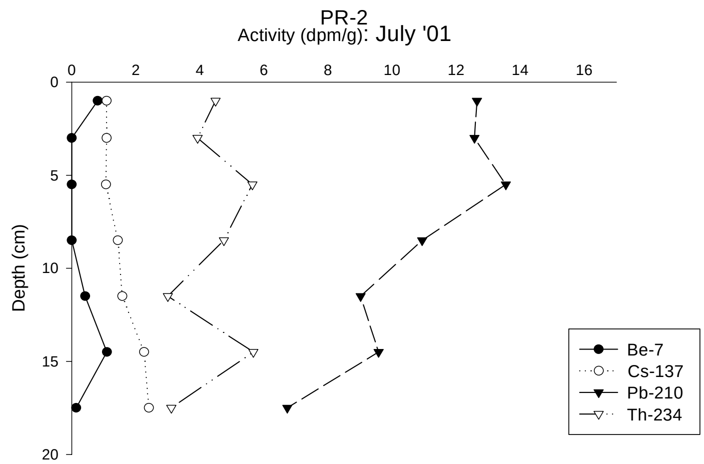

NR-3
Activity (dpm/g): July '01
0
2
4
6
8
10
12
14
16
Depth (cm)
0
5
10
15
20
Be-7
Cs-137
Pb-210
Th-234

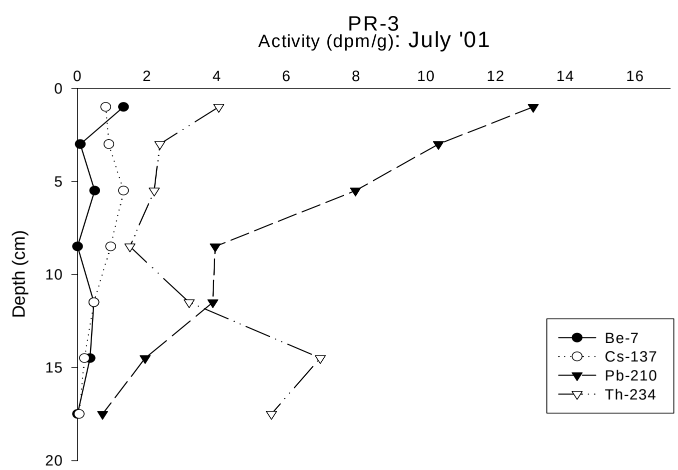

NR-4
Activity (dpm/g): July '01
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234

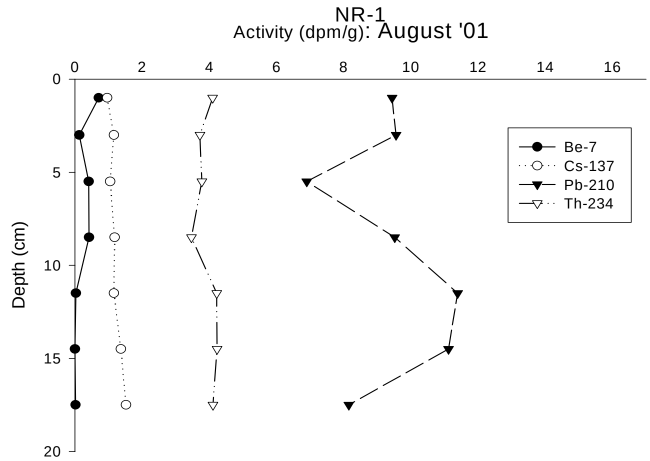

NR-5
Activity (dpm/g): July '01
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234

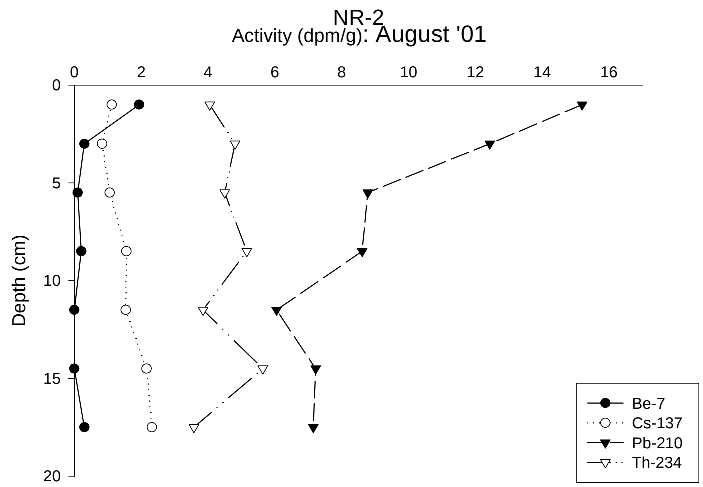

NR-6
Activity (dpm/g): July '01
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234

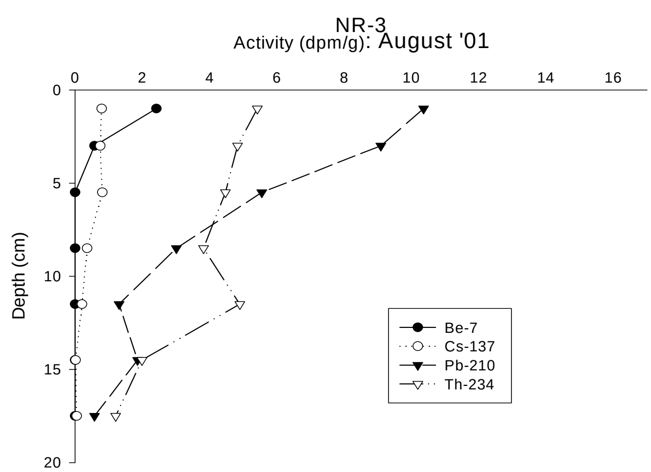

PR-1
Activity (dpm/g): July '01
0
2
4
6
8
10
12
14
16
0
5
10
15
20
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234

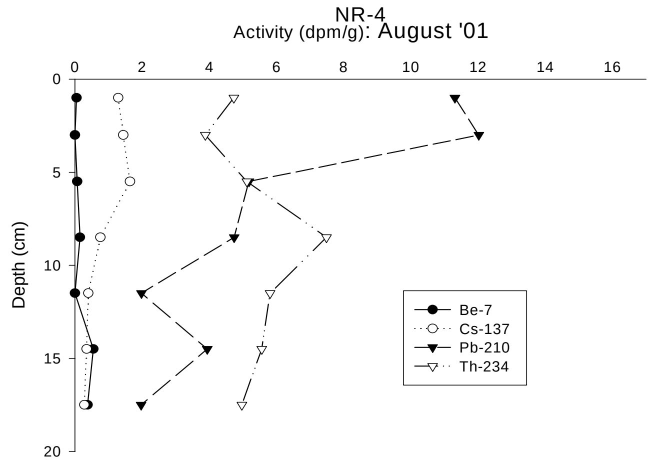

PR-2
Activity (dpm/g): July '01
0
2
4
6
8
10
12
14
16
0
5
10
15
20
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234

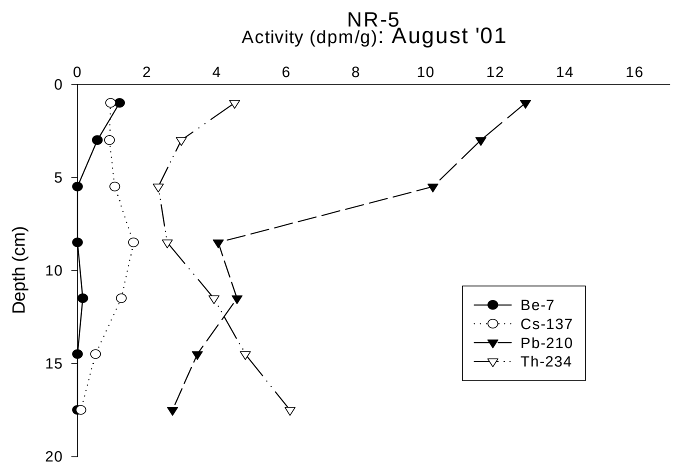

PR-3
Activity (dpm/g): July '01
0
2
4
6
8
10
12
14
16
0
5
10
15
20
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234

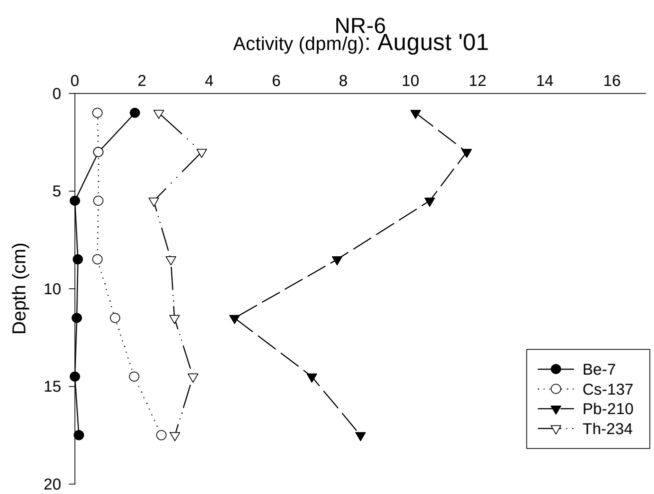

NR-1
Activity (dpm/g): August '01
0
2
4
6
8
10
12
14
16
Depth (cm)
0
5
10
15
20
Be-7
Cs-137
Pb-210
Th-234

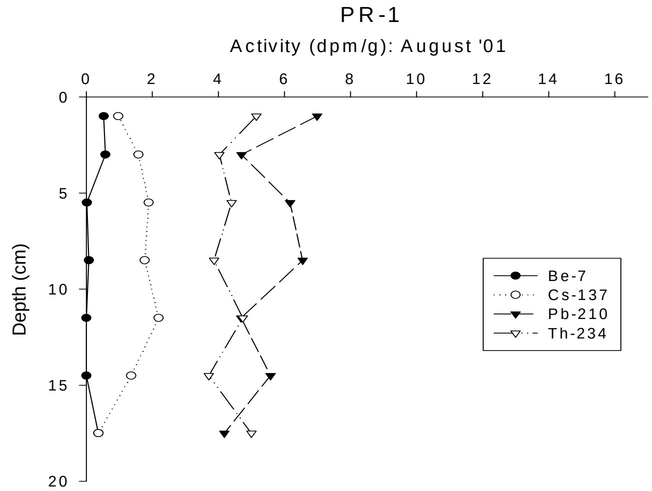

NR-2
Activity (dpm/g): August '01
0
2
4
6
8
10
12
14
16
Depth (cm)
0
5
10
15
20
Be-7
Cs-137
Pb-210
Th-234

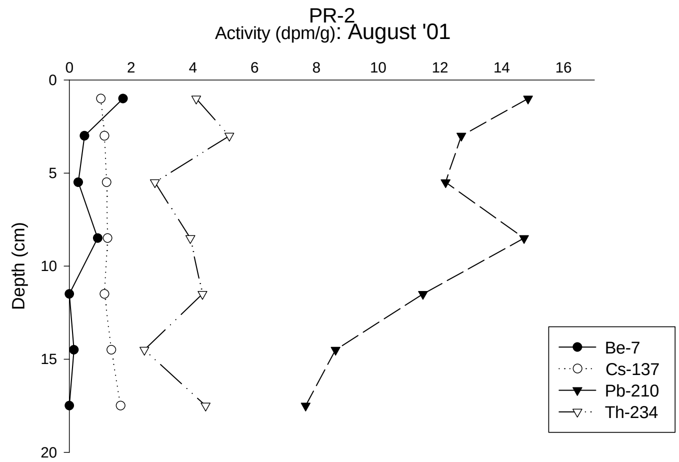

NR-3
Activity (dpm/g): August '01
0
2
4
6
8
10
12
14
16
Depth (cm)
0
5
10
15
20
Be-7
Cs-137
Pb-210
Th-234

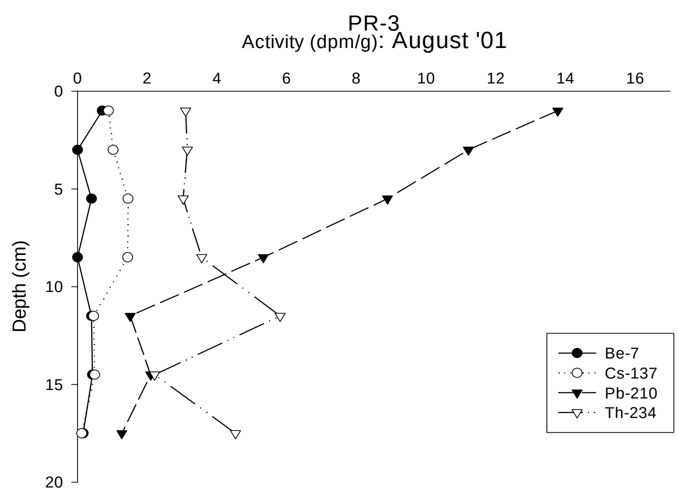

NR-4
Activity (dpm/g): August '01
0 2 4 6 8 10 12 14 16
Depth (cm)
0 5 10 15 20
Be-7
Cs-137
Pb-210
Th-234

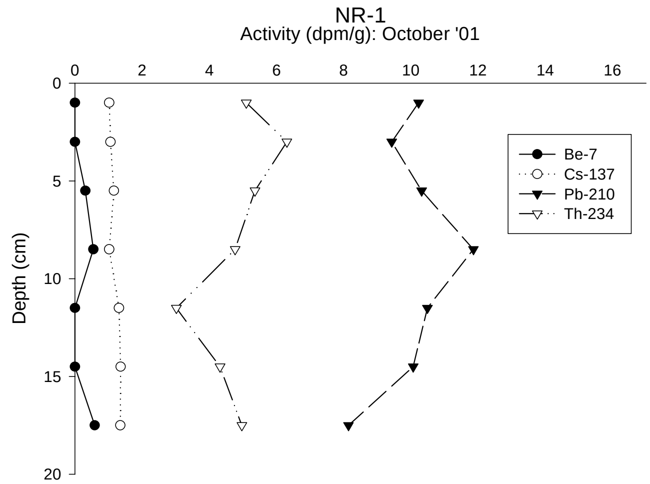

NR-5
Activity (dpm/g): August '01
0 2 4 6 8 10 12 14 16
Depth (cm)
0 5 10 15 20
Be-7
Cs-137
Pb-210
Th-234

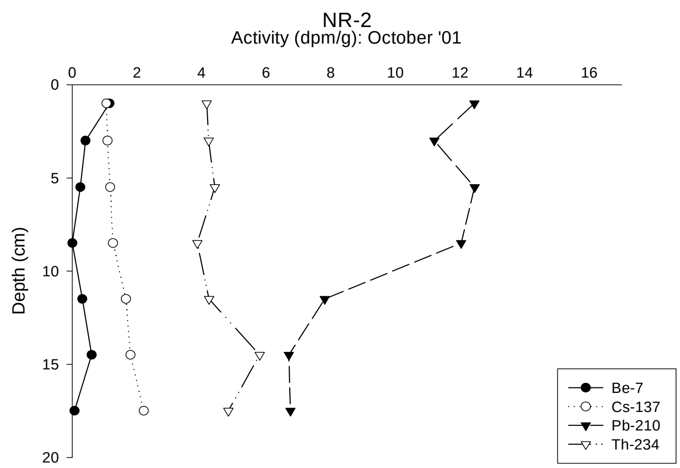

NR-6
Activity (dpm/g): August '01
0 2 4 6 8 10 12 14 16
Depth (cm)
0 5 10 15 20
Be-7
Cs-137
Pb-210
Th-234

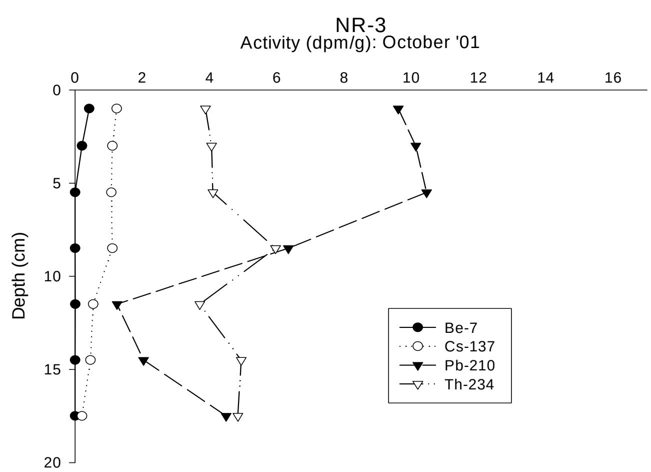

PR-1
Activity (dpm/g): August '01
0
2
4
6
8
10
12
14
16
0
5
10
15
20
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234

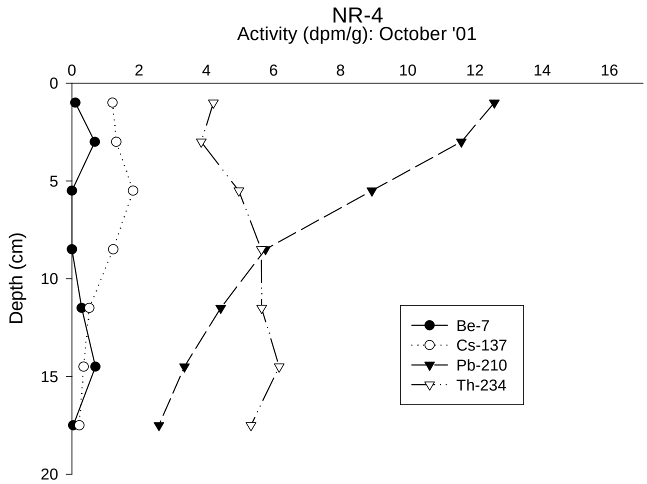

PR-2
Activity (dpm/g): August '01
0
2
4
6
8
10
12
14
16
0
5
10
15
20
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234

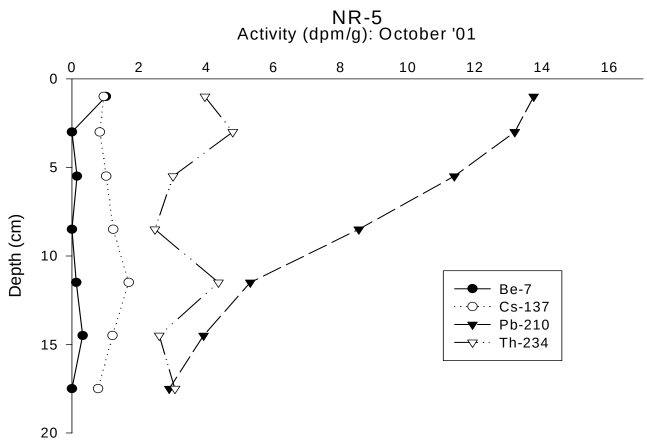

PR-3
Activity (dpm/g): August '01
0
2
4
6
8
10
12
14
16
0
5
10
15
20
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234

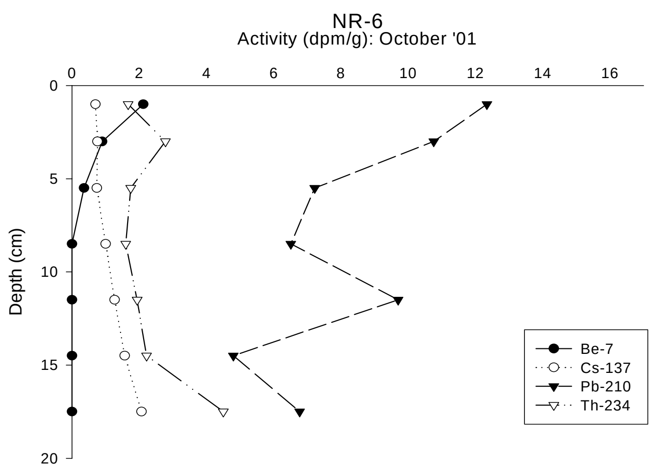

NR-1
Activity (dpm/g): October '01
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234

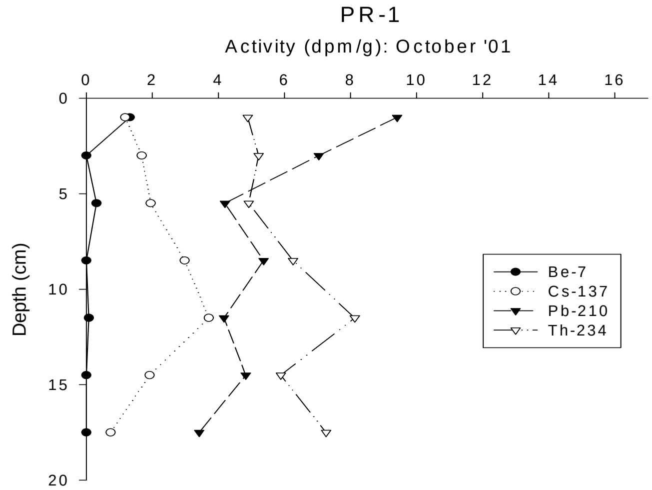

NR-2
Activity (dpm/g): October '01
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234

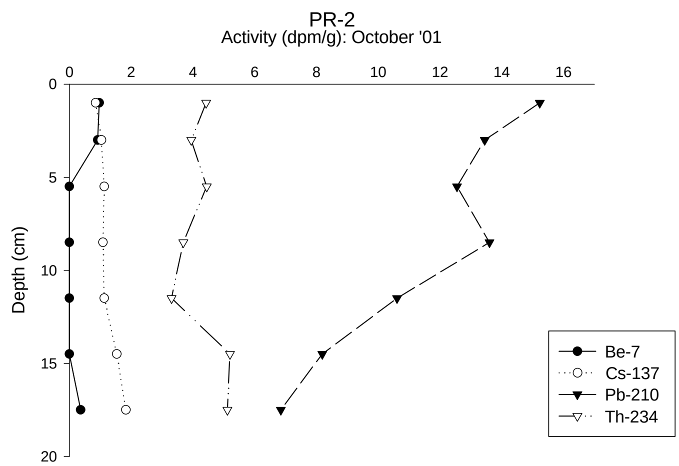

NR-3
Activity (dpm/g): October '01
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234

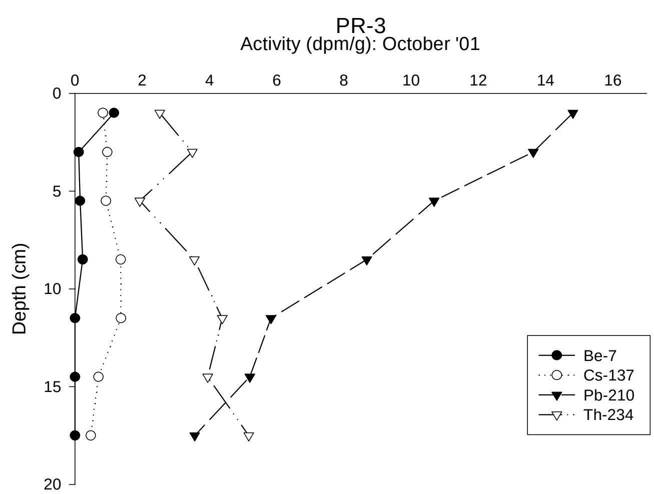

NR-4
Activity (dpm/g): October '01
0
2
4
6
8
10
12
14
16
0
5
10
15
20
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234

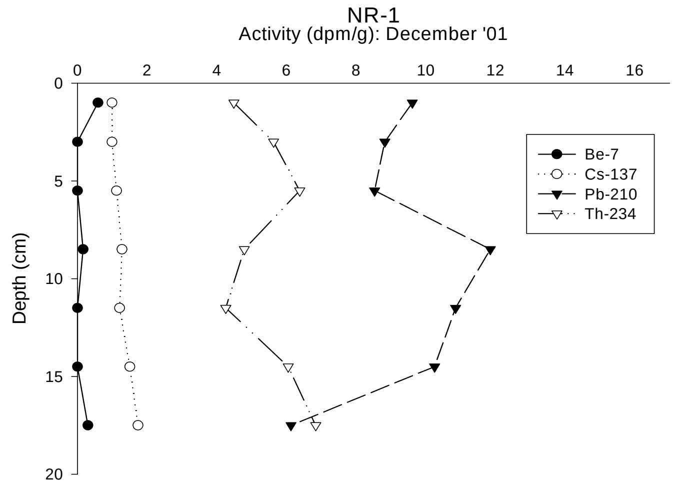

NR-5
Activity (dpm/g): October '01
0
2
4
6
8
10
12
14
16
0
5
10
15
20
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234

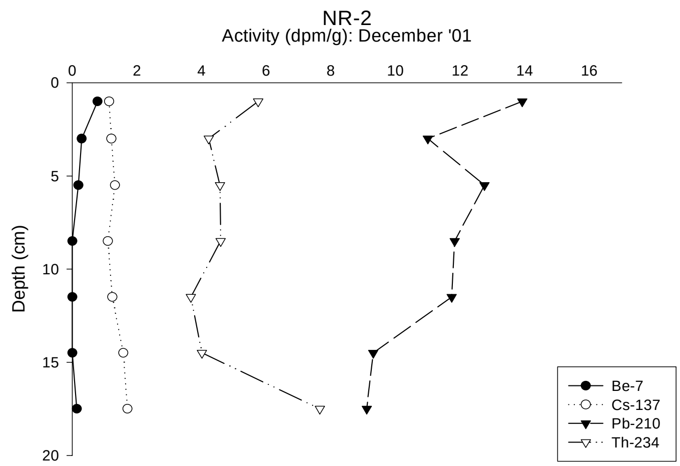

NR-6
Activity (dpm/g): October '01
0
2
4
6
8
10
12
14
16
0
5
10
15
20
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234

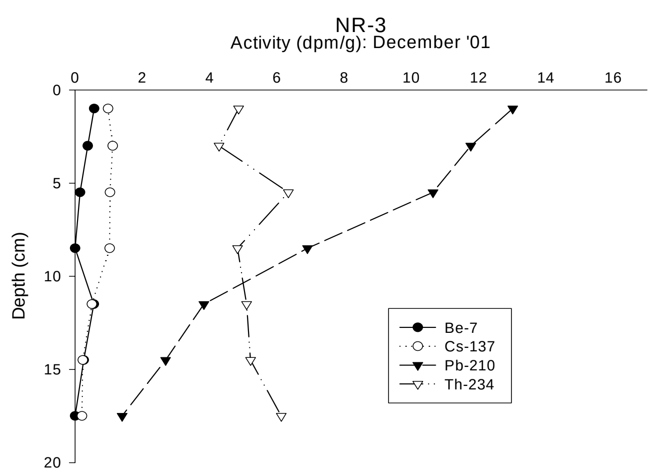

PR-1
Activity (dpm/g): October '01
0 2 4 6 8 10 12 14 16
Depth (cm)
0 5 10 15 20
Be-7
Cs-137
Pb-210
Th-234

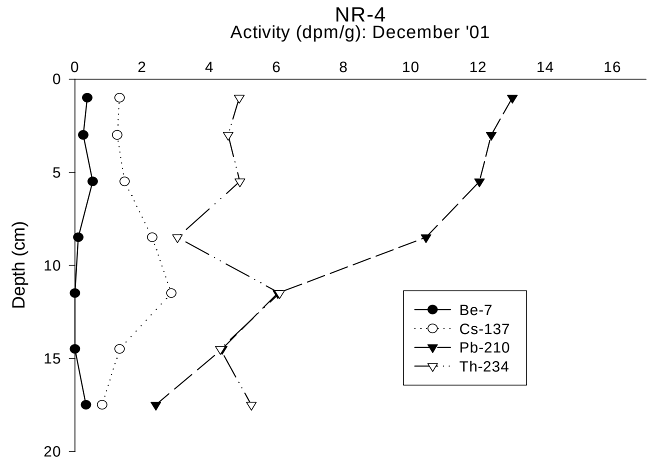

PR-2
Activity (dpm/g): October '01
0 2 4 6 8 10 12 14 16
Depth (cm)
0 5 10 15 20
Be-7
Cs-137
Pb-210
Th-234

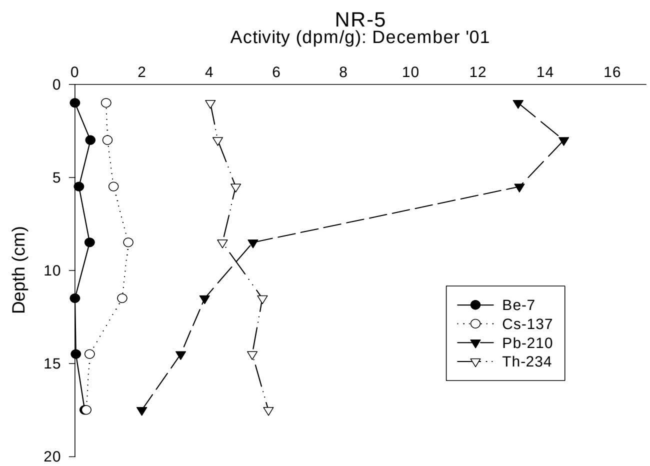

PR-3
Activity (dpm/g): October '01
0 2 4 6 8 10 12 14 16
Depth (cm)
0 5 10 15 20
Be-7
Cs-137
Pb-210
Th-234

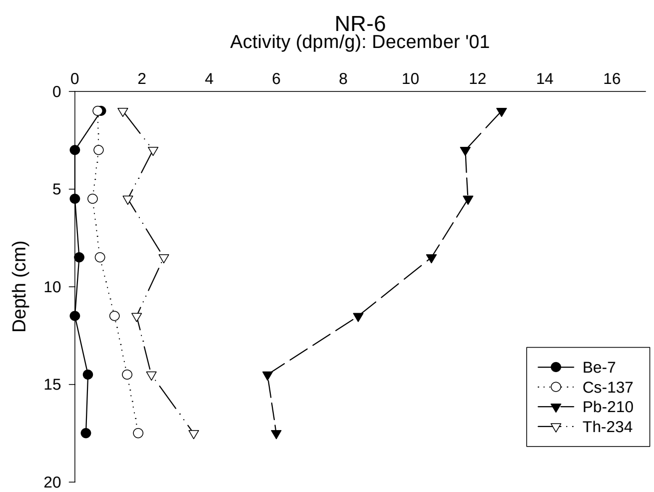

NR-1
Activity (dpm/g): December '01
0
2
4
6
8
10
12
14
16
0
5
10
15
20
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234

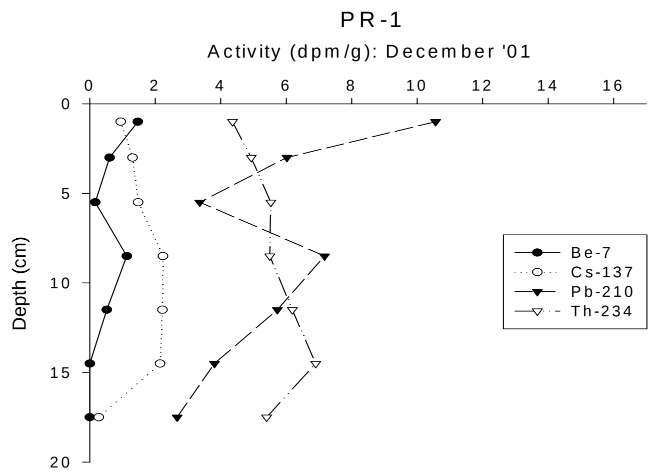

NR-2
Activity (dpm/g): December '01
0
2
4
6
8
10
12
14
16
0
5
10
15
20
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234

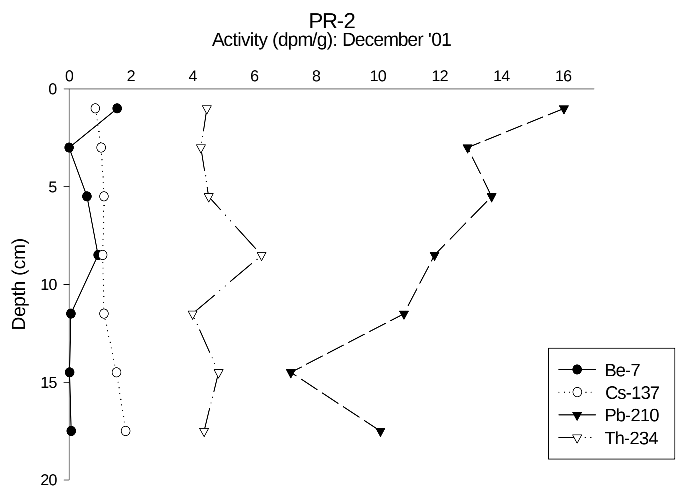

NR-3
Activity (dpm/g): December '01
0
2
4
6
8
10
12
14
16
0
5
10
15
20
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234

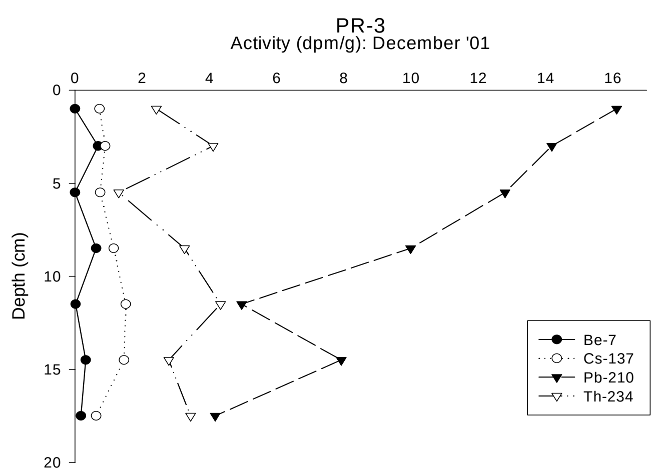

NR-4
Activity (dpm/g): December '01
0 2 4 6 8 10 12 14 16
Depth (cm)
0 5 10 15 20
Be-7
Cs-137
Pb-210
Th-234

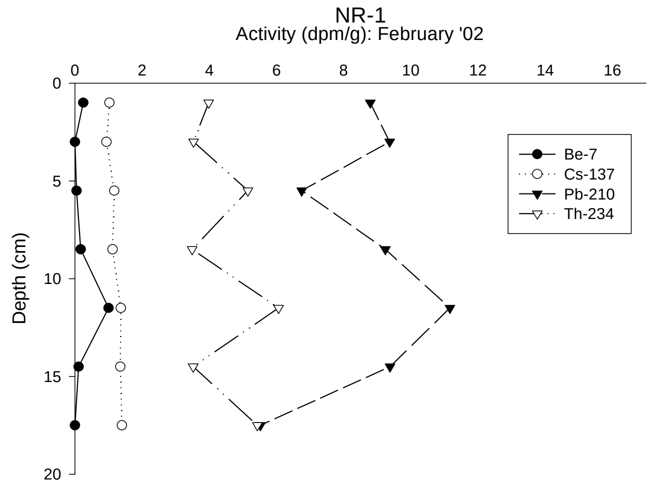

NR-5
Activity (dpm/g): December '01
0 2 4 6 8 10 12 14 16
Depth (cm)
0 5 10 15 20
Be-7
Cs-137
Pb-210
Th-234

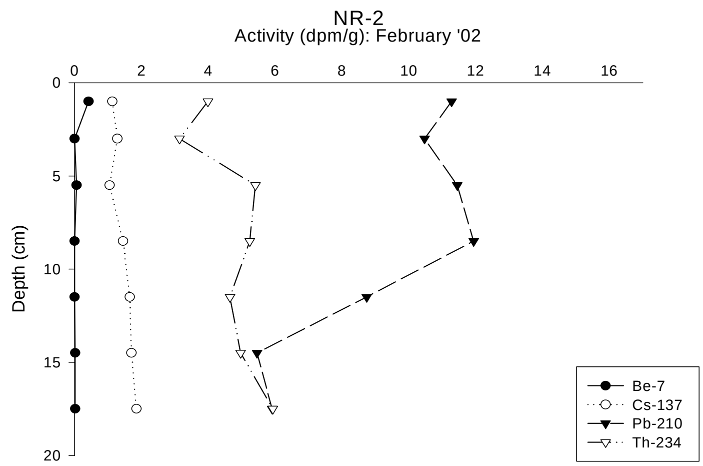

NR-6
Activity (dpm/g): December '01
0 2 4 6 8 10 12 14 16
Depth (cm)
0 5 10 15 20
Be-7
Cs-137
Pb-210
Th-234

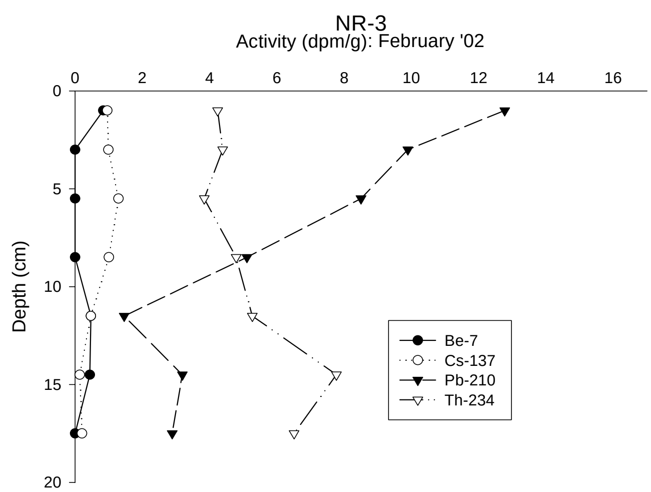

PR-1
Activity (dpm/g): December '01
Depth (cm)
0 2 4 6 8 10 12 14 16
0 5 10 15 20
Be-7
Cs-137
Pb-210
Th-234

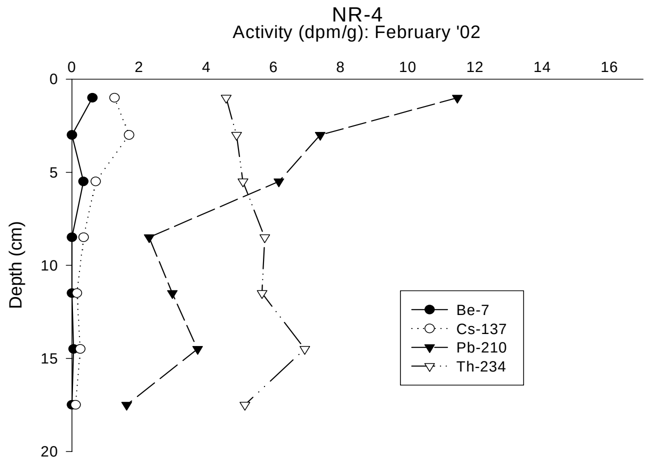

PR-2
Activity (dpm/g): December '01
Depth (cm)
0 2 4 6 8 10 12 14 16
0 5 10 15 20
Be-7
Cs-137
Pb-210
Th-234

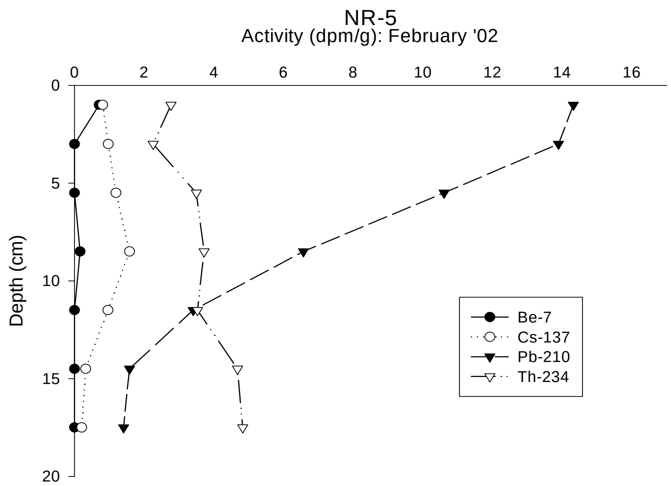

PR-3
Activity (dpm/g): December '01
Depth (cm)
0 2 4 6 8 10 12 14 16
0 5 10 15 20
Be-7
Cs-137
Pb-210
Th-234

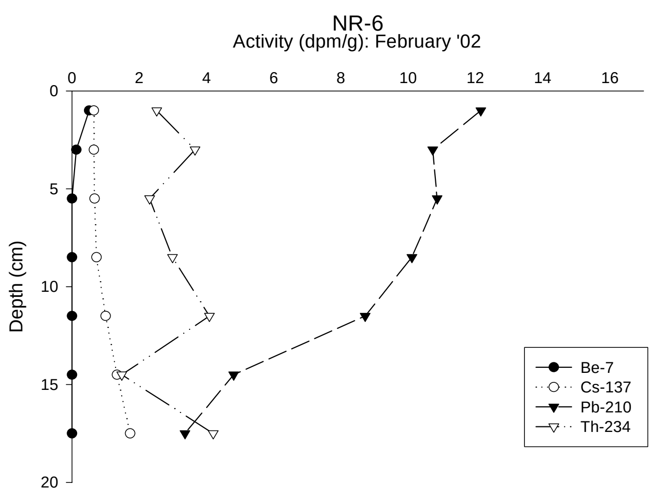

NR-1
Activity (dpm/g): February '02
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234

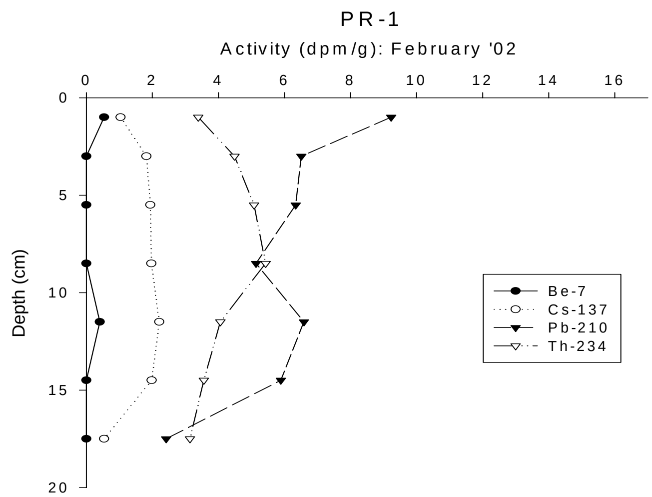

NR-2
Activity (dpm/g): February '02
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234

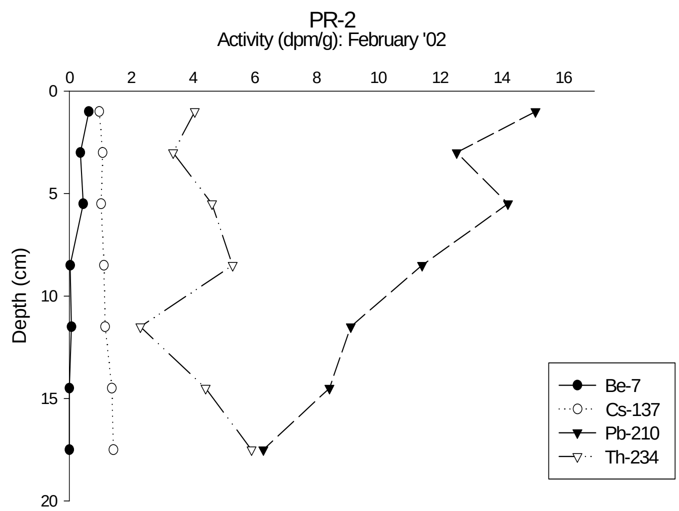

NR-3
Activity (dpm/g): February '02
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234

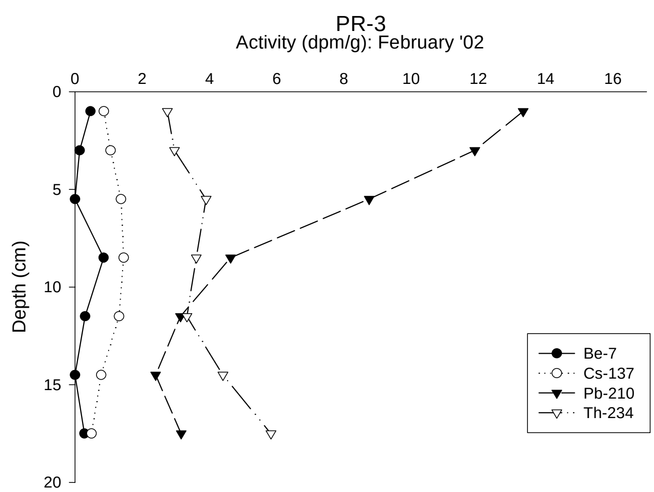

NR-4
Activity (dpm/g): February '02
0
2
4
6
8
10
12
14
16
0
5
10
15
20
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234


NR-5
Activity (dpm/g): February '02
0
2
4
6
8
10
12
14
16
0
5
10
15
20
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234


NR-6
Activity (dpm/g): February '02
0
2
4
6
8
10
12
14
16
0
5
10
15
20
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234


PR-1
Activity (dpm/g): February '02
0
2
4
6
8
10
12
14
16
0
5
10
15
20
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234


PR-2
Activity (dpm/g): February '02
0
2
4
6
8
10
12
14
16
0
5
10
15
20
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234


PR-3
Activity (dpm/g): February '02
0
2
4
6
8
10
12
14
16
0
5
10
15
20
Depth (cm)
Be-7
Cs-137
Pb-210
Th-234

APPENDIX B

Nutrient Results

WRRI-Water Samples - May 2001

Sample	Depth	NO3+NO2 mg/l	NH4 mg/l	PO4 mg/l
NR-1	Surface	0.030	0.014	0.0050
NR-1	Bottom	0.005	0.011	0.0050
NR-2	Surface	0.002	0.012	0.0010
NR-2	Bottom	0.001	0.011	0.0020
NR-3	Surface	0.002	0.011	0.0020
NR-3	Bottom	0.003	0.010	0.0030
NR-4	Surface	0.003	0.010	0.0001
NR-4	Bottom	0.003	0.010	0.0020
NR-5	Surface	0.004	0.010	0.0010
NR-5	Bottom	0.005	0.011	0.0050
NR-6	Surface	0.003	0.011	0.0040
NR-6	Bottom	0.004	0.011	0.0050
PR-1	Surface	0.035	0.029	0.0090
PR-1	Bottom	0.003	0.011	0.0100
PR-2	Surface	0.003	0.011	0.0050
PR-2	Bottom	0.002	0.011	0.0030
PR-3	Surface	0.003	0.010	0.0040
PR-3	Bottom	0.003	0.011	0.0050

WRRI-Porewater Samples- May 2001

Sample	Depth	NO3+NO2 mg/l	NH4 mg/l	PO4 mg/l
NR-1	0-2	0.005	1.460	1.140
	2-4	0.007	2.930	2.040
	4-7	0.003	3.380	2.140
	7-10	0.002	5.880	6.620
NR-2	0-2	0.002	0.681	0.592
	2-4	0.001	0.922	0.677
	4-7	0.002	1.760	1.490
	7-10	0.004	4.370	3.320
NR-3	0-2	0.004	0.483	0.218
	2-4	0.006	0.914	0.422
	4-7	0.011	1.790	1.420
	7-10	0.008	2.090	1.740
NR-4	0-2	0.034	0.466	0.218
	2-4	0.054	0.752	0.269
	4-7	0.025	2.130	0.966
	7-10	0.003	4.880	2.800
NR-5	0-2	0.002	1.840	0.813
	2-4	0.028		1.590
	4-7	0.001	4.390	2.730
	7-10	0.040	6.090	3.320
NR-6	0-2	0.006	3.170	1.600
	2-4		5.370	3.170
	4-7	0.012	7.510	7.440
	7-10	0.012	9.450	10.500
PR-1	0-2	0.010	0.752	0.490
	2-4	0.007	0.894	0.363
	4-7	0.009	1.250	1.100
	7-10	0.008	1.870	1.590
PR-2	0-2	0.004	0.042	0.864
	2-4	0.003	3.530	1.580
	4-7	0.003	5.510	3.660
	7-10	0.004	8.730	6.980
PR-3	0-2	0.002	1.850	0.686
	2-4	0.003	2.990	1.970
	4-7	0.003	3.750	2.240
	7-10	0.003	4.980	2.730

WRRI-Water Samples - July 2001

Sample	Depth	NO3+NO2 mg/l	NH4 mg/l	PO4 mg/l
NR-1	Surface	0.132	0.015	0.042
NR-1	Bottom	0.008	0.115	0.157
NR-2	Surface	0.012	0.014	0.045
NR-2	Bottom	0.021	0.022	0.066
NR-3	Surface	0.002	0.010	0.049
NR-3	Bottom	0.005	0.015	0.068
NR-4	Surface	0.005	0.008	0.042
NR-4	Bottom	0.006	0.018	0.075
NR-5	Surface	0.005	0.007	0.023
NR-5	Bottom	0.006	0.012	0.049
NR-6	Surface	0.002	0.015	0.031
NR-6	Bottom	0.003	0.014	0.026
PR-1	Surface	0.002	0.021	<0.0002
PR-1	Bottom	0.005	0.029	0.017
PR-2	Surface	0.002	0.012	0.019
PR-2	Bottom	0.002	0.026	0.119
PR-3	Surface	0.009	0.009	0.014
PR-3	Bottom	0.004	0.015	0.017

WRRI-Porewater Samples- July 2001

Sample	Depth	NO3+NO2 mg/l	NH4 mg/l	PO4 mg/l
NR-1	0-2	0.011	3.16	2.000
	2-4	0.006	4.75	3.180
	4-7	0.043	5.15	3.430
	7-10	0.004	8.11	8.240
NR-2	0-2		14.60	
	2-4	0.006		1.390
	4-7	0.009	6.91	5.290
	7-10	0.003	8.04	6.000
NR-3	0-2	0.004	3.65	1.740
	2-4	0.007	14.90	2.760
	4-7	0.011	4.75	3.040
	7-10	0.011	4.08	3.380
NR-4	0-2	0.004	2.87	0.380
	2-4	0.004	4.03	2.020
	4-7	0.005	4.93	1.960
	7-10	0.011	5.13	3.200
NR-5	0-2	0.003	4.16	1.910
	2-4	0.008	5.25	3.020
	4-7	0.004	5.63	3.750
	7-10	0.009	6.53	3.480
NR-6	0-2	0.013	4.31	1.330
	2-4	0.011	7.19	4.910
	4-7	0.018	8.01	6.650
	7-10	0.010	9.57	4.950
PR-1	0-2	0.009	2.06	0.494
	2-4	0.004	2.20	0.996
	4-7	0.008	2.01	2.100
	7-10	0.009	2.45	3.250
PR-2	0-2	0.009	3.81	1.920
	2-4	0.007	5.84	3.280
	4-7	0.006	7.99	5.320
	7-10	0.004	8.86	4.700
PR-3	0-2	0.003	2.38	0.917
	2-4	0.007	3.97	1.820
	4-7	0.003	4.06	2.000
	7-10	0.006	4.30	1.860

WRRI-Water Samples - August 2001

Sample	Depth	NO3+NO2 mg/l	NH4 mg/l	PO4 mg/l
NR-1	Surface	0.467	0.109	0.056
NR-1	Bottom	0.013	0.418	0.616
NR-2	Surface	0.188	0.131	0.173
NR-2	Bottom	0.007	0.250	0.504
NR-3	Surface	0.015	0.015	0.151
NR-3	Bottom	0.019	0.084	0.142
NR-4	Surface	0.015	0.008	0.246
NR-4	Bottom	0.010	0.016	0.112
NR-5	Surface	0.010	0.008	0.115
NR-5	Bottom	0.009	0.093	0.164
NR-6	Surface	0.010	0.009	0.104
NR-6	Bottom	0.011	0.019	0.072
PR-1	Surface	0.319	0.013	0.056
PR-1	Bottom	0.002	0.233	0.353
PR-2	Surface	0.012	0.008	0.095
PR-2	Bottom	0.013	0.181	0.226
PR-3	Surface	0.004	0.007	0.031
PR-3	Bottom	0.006	0.013	0.044

WRRI-Porewater Samples- August 2001

Sample	Depth	NO3+NO2 mg/l	NH4 mg/l	PO4 mg/l
NR-1	0-2	0.032	5.00	3.74
	2-4	0.036	7.16	6.23
	4-7	0.064	8.63	7.66
	7-10	0.095	10.00	9.12
NR-2	0-2	0.039	6.96	5.42
	2-4	0.039	11.10	9.55
	4-7	0.029	12.40	8.80
	7-10	0.036	12.20	9.27
NR-3	0-2	0.021	5.04	2.66
	2-4	0.029	7.82	6.33
	4-7	0.019	7.53	6.76
	7-10	0.023	6.34	4.37
NR-4	0-2	0.036	6.94	3.08
	2-4	0.023	8.34	2.72
	4-7	0.025	7.95	3.24
	7-10	0.023	7.22	4.76
NR-5	0-2	0.026	5.78	4.76
	2-4	0.027	9.20	6.90
	4-7	0.023	10.90	6.76
	7-10	0.024	11.10	6.60
NR-6	0-2	0.022	7.45	6.31
	2-4	0.020	11.10	6.17
	4-7	0.022	12.70	7.78
	7-10	0.030	15.70	13.10
PR-1	0-2	0.018	3.82	3.12
	2-4	0.022	4.03	3.02
	4-7	0.025	4.13	3.07
	7-10	0.027	4.13	4.29
PR-2	0-2	0.019	5.10	1.45
	2-4	0.039	10.20	6.09
	4-7	0.112	13.50	7.38
	7-10	0.036	14.00	7.81
PR-3	0-2	0.013	2.23	1.52
	2-4	0.017	3.86	1.79
	4-7	0.015	4.67	2.35
	7-10	0.027	6.21	3.40

WRRI-Water Samples - October 2001

Sample	Depth	NO3+NO2 mg/l	NH4 mg/l	PO4 mg/l
NR-1	Surface	0.001	0.004	0.021
NR-1	Bottom	0.001	0.007	0.015
NR-2	Surface	0.001	0.003	0.017
NR-2	Bottom	0.001	0.006	0.017
NR-3	Surface	0.003	0.008	0.019
NR-3	Bottom	0.001	0.003	0.017
NR-4	Surface	0.002	0.003	0.019
NR-4	Bottom	0.002	0.006	0.015
NR-5	Surface	0.003	0.003	0.027
NR-5	Bottom	0.003	0.006	0.025
NR-6	Surface	0.002	0.002	0.027
NR-6	Bottom	0.003	0.003	0.019
PR-1	Surface	0.001	0.007	0.008
PR-1	Bottom	0.001	0.009	0.015
PR-2	Surface	0.001	0.003	0.017
PR-2	Bottom	0.001	0.003	0.019
PR-3	Surface	0.047	0.004	0.017
PR-3	Bottom	0.003	0.003	0.021

WRRI-Porewater Samples- October 2001

Sample	Depth	NO3+NO2 mg/l	NH4 mg/l	PO4 mg/l
NR-1	0-2	0.025	3.94	2.90
	2-4	0.008	6.08	3.79
	4-7	0.022	8.96	5.42
	7-10	0.051	11.00	7.13
NR-2	0-2	0.007	3.96	2.49
	2-4	0.007	5.36	3.90
	4-7	0.006	7.29	3.34
	7-10	0.005	10.10	5.75
NR-3	0-2	0.006	4.34	3.00
	2-4	0.006	6.42	4.16
	4-7	0.008	7.90	3.18
	7-10	0.009	7.98	3.57
NR-4	0-2	0.006	4.62	2.76
	2-4	0.006	7.03	3.22
	4-7	0.006	9.17	3.53
	7-10	0.005	8.58	5.14
NR-5	0-2	0.003	3.86	3.53
	2-4	0.004	7.62	6.76
	4-7	0.004	9.36	5.60
	7-10	0.001	9.89	6.60
NR-6	0-2	0.003	3.60	3.30
	2-4	0.003	8.00	7.07
	4-7	0.004	10.70	3.45
	7-10	0.000	13.30	5.48
PR-1	0-2	0.005	3.95	2.12
	2-4	0.004	4.83	2.43
	4-7	0.034	5.30	2.61
	7-10	0.009	5.74	3.44
PR-2	0-2	0.004	4.16	1.29
	2-4	0.005	8.49	3.70
	4-7	0.003	12.70	6.19
	7-10	0.003	16.40	6.13
PR-3	0-2	0.003	2.58	1.63
	2-4	0.003	5.00	2.90
	4-7	0.004	5.61	2.59
	7-10	0.003	6.52	2.87

WRRI-Water Samples - December 2001

Sample	Depth	NO3+NO2 mg/l	NH4 mg/l	PO4 mg/l
NR-1	Surface	0.1320	0.1559	0.0206
NR-1	Bottom	0.0018	0.1338	0.0263
NR-2	Surface	0.0075	0.1427	0.0110
NR-2	Bottom	0.0010	0.1391	0.0129
NR-3	Surface	0.0010	0.1365	0.0091
NR-3	Bottom	0.0001	0.1400	0.0149
NR-4	Surface	0.0010	0.1400	0.0091
NR-4	Bottom	0.0010	0.1347	0.0129
NR-5	Surface	0.0010	0.0067	0.0091
NR-5	Bottom	0.0018	0.0049	0.0263
NR-6	Surface	0.0010	0.0049	0.0129
NR-6	Bottom	0.0018	0.0049	0.0129
PR-1	Surface	0.0067	0.0155	0.0053
PR-1	Bottom	0.0043	0.0129	0.0110
PR-2	Surface	0.0043	0.0076	0.0110
PR-2	Bottom	0.0026	0.0067	0.0110
PR-3	Surface	0.0018	0.0058	0.0091
PR-3	Bottom	0.0010	0.1162	0.0091

WRRI-Porewater Samples- December 2001

Sample	Depth	NO3+NO2 mg/l	NH4 mg/l	PO4 mg/l
NR-1	0-2	0.0070	2.997	1.519
	2-4	0.0042	3.833	2.232
	4-7	0.0028	6.208	3.090
	7-10	0.0021	9.985	6.000
NR-2	0-2	0.0042	3.245	1.383
	2-4	0.0028	4.761	2.785
	4-7	0.0014	8.854	5.422
	7-10	0.0014	12.340	6.553
NR-3	0-2	0.0042	2.861	0.621
	2-4	0.0049	4.060	1.679
	4-7	0.0056	7.203	3.202
	7-10	0.0014	8.176	3.234
NR-4	0-2	0.0035	2.182	0.396
	2-4	0.0028	4.354	1.791
	4-7	0.0028	6.774	2.345
	7-10	0.0070	8.334	2.192
NR-5	0-2	0.0021	6.728	2.842
	2-4	0.0056	3.585	1.503
	4-7	0.0021	10.690	3.298
	7-10	0.0028	11.820	3.443
NR-6	0-2	0.0175	4.195	1.960
	2-4	0.0042	7.000	3.306
	4-7	0.0021	10.190	6.216
	7-10	0.0007	14.210	8.068
PR-1	0-2	0.0084	1.702	0.501
	2-4	0.0042	2.997	1.054
	4-7	0.0126	4.354	2.401
	7-10	0.0112	5.326	2.866
PR-2	0-2	0.0063	2.222	0.493
	2-4	0.0126	6.366	2.834
	4-7	0.0014	8.515	3.106
	7-10	0.0063	13.29	6.048
PR-3	0-2	0.0098	2.946	0.998
	2-4	0.0098	6.412	2.689
	4-7	0.0063	8.040	2.385
	7-10	0.0042	8.425	2.312

WRRI-Water Samples - February 2002

Sample	Depth	NO3+NO2 mg/l	NH4 mg/l	PO4 mg/l
NR-1	Surface	0.2545	0.0565	0.0118
NR-1	Bottom	0.0726	0.0186	0.0088
NR-2	Surface	0.0477	0.0089	0.0057
NR-2	Bottom	0.0201	0.0161	0.0088
NR-3	Surface	0.0038	0.0073	0.0072
NR-3	Bottom	0.0042	0.0065	0.0088
NR-4	Surface	0.0400	0.0202	0.0088
NR-4	Bottom	0.0070	0.0218	0.0072
NR-5	Surface	0.0030	0.0081	0.0057
NR-5	Bottom	0.0030	0.0105	0.0088
NR-6	Surface	0.0034	0.0073	0.0088
NR-6	Bottom	0.0042	0.0081	0.0088
PR-1	Surface	0.2637	0.0935	0.0149
PR-1	Bottom	0.0550	0.0113	0.0103
PR-2	Surface	0.0034	0.0065	0.0088
PR-2	Bottom	0.0046	0.0057	0.0118
PR-3	Surface	0.0022	0.0089	0.0088
PR-3	Bottom	0.0030	0.0145	0.0072

WRRI-Porewater Samples- February 2002

Sample	Depth	NO3+NO2 mg/l	NH4 mg/l	PO4 mg/l
NR-1	0-2	0.0115	3.662	1.290
	2-4	0.0054	5.622	2.659
	4-7	0.0046	5.364	3.314
	7-10	0.0030	8.512	4.758
NR-2	0-2	0.0042	1.603	0.631
	2-4	0.0046	6.750	1.894
	4-7	0.0030	10.630	3.558
	7-10	0.0022	8.968	2.659
NR-3	0-2	0.0046	1.613	0.402
	2-4	0.0095	3.246	2.304
	4-7	0.0079	5.127	2.138
	7-10	0.0074	4.889	3.813
NR-4	0-2	0.0050	3.068	1.131
	2-4	0.0074	6.097	3.181
	4-7	0.0046	7.720	3.647
	7-10	0.0046	7.760	4.868
NR-5	0-2	0.0046	5.186	4.213
	2-4	0.0046	12.590	3.780
	4-7	0.0030	11.380	3.870
	7-10	0.0046	10.140	4.536
NR-6	0-2	0.0034	2.771	0.916
	2-4	0.0070	5.701	5.498
	4-7	0.0062	7.800	5.276
	7-10	0.0079	11.610	4.906
PR-1	0-2	0.0140	1.752	1.267
	2-4	0.0087	2.553	2.426
	4-7	0.0046	3.484	2.826
	7-10	0.0017	5.503	3.647
PR-2	0-2	0.0017	1.702	0.475
	2-4	0.0046	2.969	1.171
	4-7	0.0026	5.266	3.802
	7-10	0.0022	9.364	5.017
PR-3	0-2	0.0046	1.445	0.546
	2-4	0.0070	3.048	1.805
	4-7	0.0046	3.721	2.027
	7-10	0.0022	4.731	2.171

APPENDIX C

Physical Parameter Measurements

May 2001

Sample Site	Latitude	Longitude	Salinity,ppt	Temperature,C	Conductivity,mS	DO,mg/l
PR-1 top	35.48006	76.98248	2.5	21.6	4.85	7.20
PR-1 bottom	35.48006	76.98248	4.2	22.4	7.58	4.95
PR-2 top	35.39547	76.7366	8.4	22.2	14.47	7.85
PR-2 bottom	35.39547	76.7366	8.8	21.9	14.10	8.14
PR-3 top	35.36227	76.6058	10.5	22.0	16.72	7.82
PR-3 bottom	35.36227	76.6058	11.6	21.4	19.46	7.84
NR-1 top	35.08048	77.00742	2.6	21.9	4.83	8.67
NR-1 bottom	35.08048	77.00742	6.1	21.7	10.86	2.27
NR-2 top	35.04103	76.97961	4.6	21.5	8.31	7.11
NR-2 bottom	35.04103	76.97961	7.6	21.4	13.03	0.67
NR-3 top	35.00874	76.92498	6.1	21.1	9.89	7.18
NR-3 bottom	35.00874	76.92498	9.3	21.0	15.69	3.20
NR-4 top	34.96257	76.8652	8.0	21.4	12.89	7.44
NR-4 bottom	34.96257	76.8652	10.3	21.8	16.19	7.35
NR-5 top	34.96759	76.74043	11.5	21.9	19.36	8.09
NR-5 bottom	34.96759	76.74043	11.9	21.7	19.50	8.09
NR-6 top	35.04324	76.63003	13.4	22.0	22.18	7.85
NR-6 bottom	35.04324	76.63003	14.0	21.3	23.12	6.45

July 2001

Sample Site	Latitude	Longitude	Salinity,ppt	Temperature,C	Conductivity,mS	DO,mg/l
PR-1 top	35.48006	76.98248	2.6	27.8	4.95	9.05
PR-1 bottom	35.48006	76.98248	4.8	26.7	8.68	0.26
PR-2 top	35.39547	76.7366	8.7	27.2	14.93	7.03
PR-2 bottom	35.39547	76.7366	11.6	27.2	19.55	0.15
PR-3 top	35.36227	76.6058	10	27.0	17.05	6.98
PR-3 bottom	35.36227	76.6058	12.6	27.1	21.13	2.65
NR-1 top	35.08048	77.00742	2.0	28.6	3.84	10.39
NR-1 bottom	35.08048	77.00742	9.2	26.8	15.81	0.23
NR-2 top	35.04383	76.96809	5.1	28.3	9.10	10.54
NR-2 bottom	35.04383	76.96809	9.4	26.8	16.19	0.49
NR-3 top	35.00874	76.92498	11.1	27.4	18.80	7.95
NR-3 bottom	35.00874	76.92498	11.6	26.6	17.41	0.21
NR-4 top	34.96257	76.8652	9.9	27.3	16.87	7.16
NR-4 bottom	34.96257	76.8652	12.7	27.0	21.28	2.06
NR-5 top	34.96759	76.74043	12.5	27.1	20.91	6.07
NR-5 bottom	34.96759	76.74043	13.8	27.2	22.86	1.08
NR-6 top	35.04324	76.63003	13.4	26.9	22.24	5.85
NR-6 bottom	35.04324	76.63003	12.6	27.1	21.09	5.80

August 2001

Sample Site	Latitude	Longitude	Salinity,ppt	Temperature,C	Conductivity,mS	DO,mg/l
PR-1 top	35.4801	76.98248	0.4	27.3	0.83	7.10
PR-1 bottom	35.4801	76.98248	8.8	27.3	15.21	0.17
PR-2 top	35.3955	76.7366	8.4	27.3	14.48	7.40
PR-2 bottom	35.3955	76.7366	13.5	28.0	22.49	0.23
PR-3 top	35.3623	76.6058	12.0	27.6	20.19	7.14
PR-3 bottom	35.3623	76.6058	14.9	28.0	24.76	2.93
NR-1 top	35.0805	77.00742	1.4	28.1	2.70	5.92
NR-1 bottom	35.0805	77.00742	14.6	27.1	24.14	0.17
NR-2 top	35.0438	76.96809	3.9	28.5	7.16	6.15
NR-2 bottom	35.0438	76.96809	15.8	27.1	26.01	0.16
NR-3 top	35.0087	76.92498	8.3	27.6	14.44	6.53
NR-3 bottom	35.0087	76.92498	16.5	27.2	26.97	0.14
NR-4 top	34.9626	76.8652	12.0	27.8	20.33	6.18
NR-4 bottom	34.9626	76.8652	18.0	27.4	29.16	0.20
NR-5 top	34.9676	76.74043	14.2	28.3	23.58	6.23
NR-5 bottom	34.9676	76.74043	20.8	28.3	33.35	0.91
NR-6 top	35.0432	76.63003	17.1	28.3	27.92	5.53
NR-6 bottom	35.0432	76.63003	17.1	28.3	27.94	5.37

October 2001

Sample Site	Latitude	Longitude	Salinity,ppt	Temperature,C	Conductivity,mS	DO,mg/l
PR-1 top	35.48006	76.98248	9.2	21.6	15.53	8.06
PR-1 bottom	35.48006	76.98248	9.7	20.2	16.07	0.23
PR-2 top	35.39547	76.7366	12.0	21.0	20.34	8.01
PR-2 bottom	35.39547	76.7366	12.5	19.1	21.48	6.02
PR-3 top	35.36227	76.6058	12.7	20.3	21.46	7.97
PR-3 bottom	35.36227	76.6058	13.7	19.1	23.40	6.83
NR-1 top	35.08048	77.00742	6.4	21.0	11.13	11.09
NR-1 bottom	35.08048	77.00742	13.1	18.8	22.06	2.93
NR-2 top	35.04383	76.96809	8.2	21.4	14.15	9.97
NR-2 bottom	35.04383	76.96809	12.2	18.7	20.40	0.19
NR-3 top	35.00874	76.92498	12.1	21.6	20.29	8.43
NR-3 bottom	35.00874	76.92498	13.9	19.0	22.94	0.23
NR-4 top	34.96257	76.8652	13.0	20.4	21.49	8.34
NR-4 bottom	34.96257	76.8652	16.4	19.2	26.68	7.76
NR-5 top	34.96759	76.74043	17.8	19.8	28.75	7.84
NR-5 bottom	34.96759	76.74043	18.4	19.6	29.66	6.91
NR-6 top	35.04324	76.63003	20.3	20.2	32.36	7.51
NR-6 bottom	35.04324	76.63003	20.3	20.0	29.39	6.80

December 2001

Sample Site	Latitude	Longitude	Salinity,ppt	Temperature,C	Conductivity,mS	DO,mg/l
PR-1 top	35.48006	76.98248	9.6	14.8	15.79	9.86
PR-1 bottom	35.48006	76.98248	10.5	15.3	17.71	0.18
PR-2 top	35.39547	76.7366	11.5	15.3	20.01	8.58
PR-2 bottom	35.39547	76.7366	11.9	15.4	19.60	8.37
PR-3 top	35.36227	76.6058	11.3	15.2	19.03	9.34
PR-3 bottom	35.36227	76.6058	11.6	15.4	19.44	5.60
NR-1 top	35.08048	77.00742	8.6	15.6	16.07	8.62
NR-1 bottom	35.08048	77.00742	13.5	15.9	22.31	0.12
NR-2 top	35.04383	76.96809	10.4	15.7	17.37	8.94
NR-2 bottom	35.04383	76.96809	11.4	16.0	19.16	0.17
NR-3 top	35.00874	76.92498	12.3	15.5	20.47	8.89
NR-3 bottom	35.00874	76.92498	13.3	16.4	22.03	0.16
NR-4 top	34.96257	76.8652	12.6	15.6	20.80	9.31
NR-4 bottom	34.96257	76.8652	13.8	16.3	22.70	0.38
NR-5 top	34.96759	76.74043	13.7	15.7	22.74	8.94
NR-5 bottom	34.96759	76.74043	14.6	16.3	24.07	7.74
NR-6 top	35.04324	76.63003	14.6	15.6	24.88	8.80
NR-6 bottom	35.04324	76.63003	15.5	15.6	25.44	8.69

February 2002

Sample Site	Latitude	Longitude	Salinity,ppt	Temperature,C	Conductivity,mS	DO,mg/l
PR-1 top	35.48006	76.98248	7.6	10.4	13.14	9.40
PR-1 bottom	35.48006	76.98248	14.3	11.8	23.57	0.21
PR-2 top	35.39547	76.7366	16.8	11.9	27.27	10.04
PR-2 bottom	35.39547	76.7366	19.0	12.0	30.55	9.61
PR-3 top	35.36227	76.6058	19.0	12.0	30.43	9.63
PR-3 bottom	35.36227	76.6058	19.3	11.9	30.89	8.30
NR-1 top	35.08048	77.00742	7.0	9.1	12.21	10.95
NR-1 bottom	35.08048	77.00742	12.3	9.4	20.59	8.64
NR-2 top	35.04383	76.96809	12.7	8.8	21.27	10.22
NR-2 bottom	35.04383	76.96809	13.6	8.9	22.39	9.72
NR-3 top	35.00874	76.92498	14.7	9.2	24.28	9.46
NR-3 bottom	35.00874	76.92498	13.4	9.4	22.50	9.19
NR-4 top	34.96257	76.8652	12.7	9.0	21.19	9.93
NR-4 bottom	34.96257	76.8652	14.0	9.1	23.22	0.62
NR-5 top	34.96759	76.74043	15.3	9.3	25.25	10.09
NR-5 bottom	34.96759	76.74043	19.5	10.4	31.40	9.08
NR-6 top	35.04324	76.63003	20.2	9.4	32.52	9.56
NR-6 bottom	35.04324	76.63003	20.3	9.4	32.54	9.48

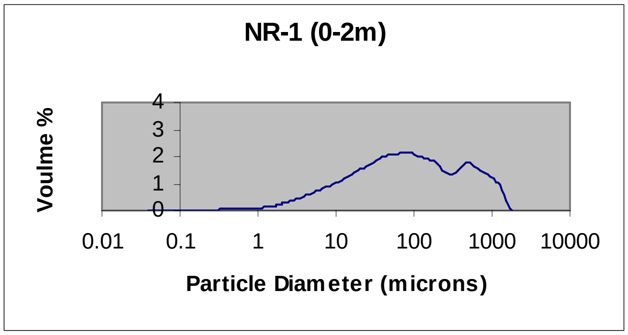
APPENDIX D

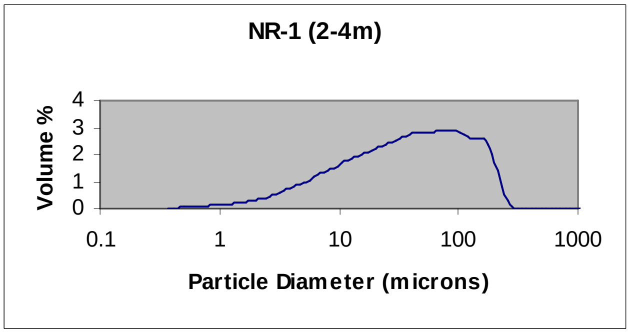
Total Suspended Solids Results

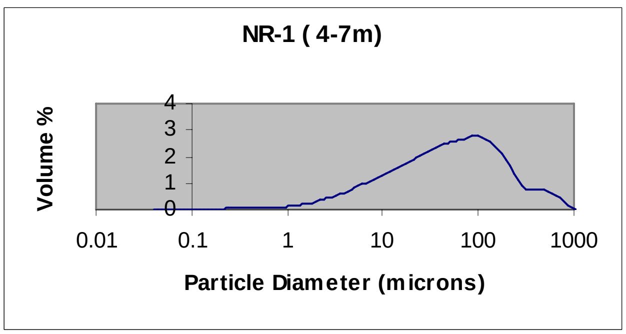
Sample Site	May'01 TSS (mg/l)	Jul'01 TSS	Aug'01 TSS	Oct'01 TSS	Dec'01 TSS	Feb'02 TSS
PR-1 top	7.00	7.25	7.40	5.58	6.20	7.00
PR-1 bottom	14.00	8.20	4.80	15.20	2.20	7.00
PR-2 top	14.80	7.60	8.00	4.50	4.60	7.00
PR-2 bottom	4.69	3.80	5.00	7.84	3.40	6.20
PR-3 top	6.20	5.60	5.20	5.48	4.20	3.60
PR-3 bottom	8.60	11.78	5.20	8.60	3.60	6.00
NR-1 top	6.80	7.20	4.60	8.02	5.80	36.15
NR-1 bottom	6.50	3.80	5.60	4.18	4.20	39.62
NR-2 top	3.40	8.22	6.80	5.11	5.70	22.64
NR-2 bottom	7.20	7.20	5.40	8.20	5.40	40.54
NR-3 top	4.40	11.20	6.60	3.88	3.20	30.38
NR-3 bottom	3.50	5.40	5.40	7.32	13.60	56.92
NR-4 top	12.40	5.60	8.00	4.00	1.60	56.47
NR-4 bottom	5.17	7.20	4.40	8.90	7.20	133.13
NR-5 top	1.88	9.80	6.60	3.30	3.20	12.80
NR-5 bottom	33.00	11.40	3.40	7.46	2.80	9.60
NR-6 top	6.57	7.40	12.40	4.04	6.40	6.40
NR-6 bottom	12.40	7.00	17.80	7.52	7.40	8.40

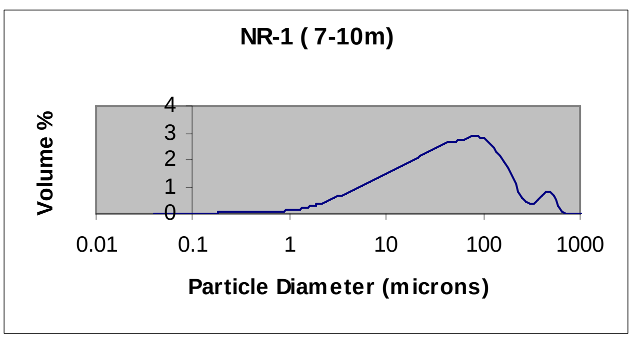
APPENDIX E

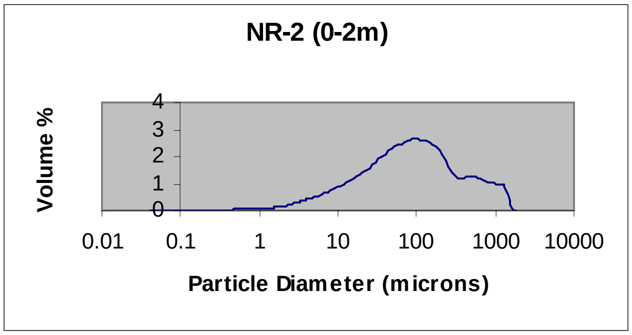
Grain Size Distributions

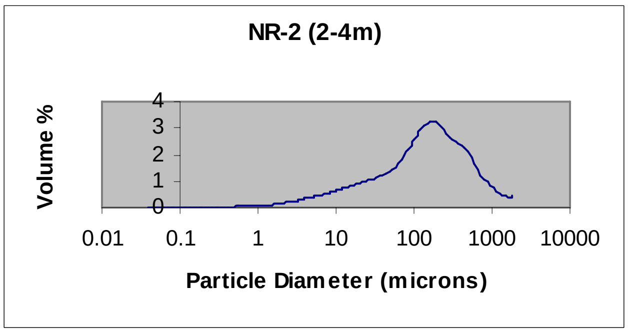

NR-1 (0-2m)
Voulme %
4
3
2
1
0
0.01
0.1
1
10
100
1000
10000
Particle Diameter (microns)

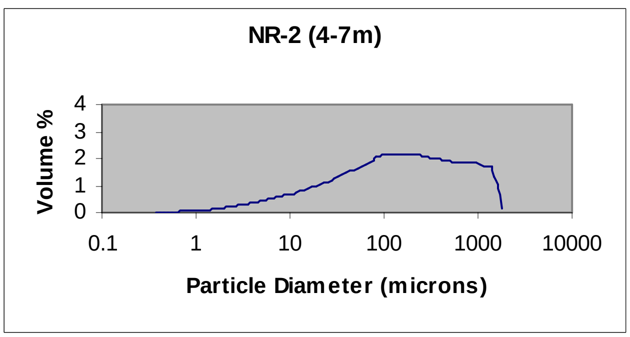

NR-1 (2-4m)
Volume %
4
3
2
1
0
0.1
1
10
100
1000
Particle Diameter (microns)

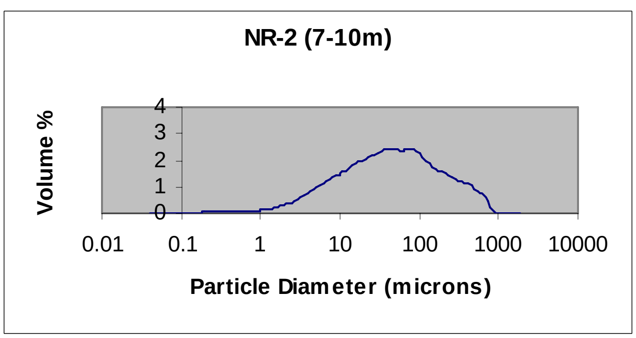

NR-1 (4-7m)
Volume %
4
3
2
1
0
0.01
0.1
1
10
100
1000
Particle Diameter (microns)

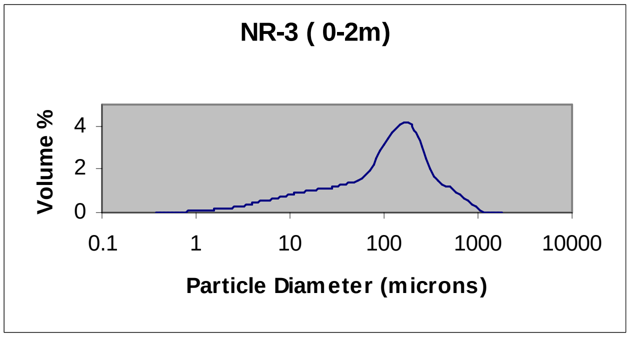

NR-1 (7-10m)
Volume %
4
3
2
1
0
0.01
0.1
1
10
100
1000
Particle Diameter (microns)

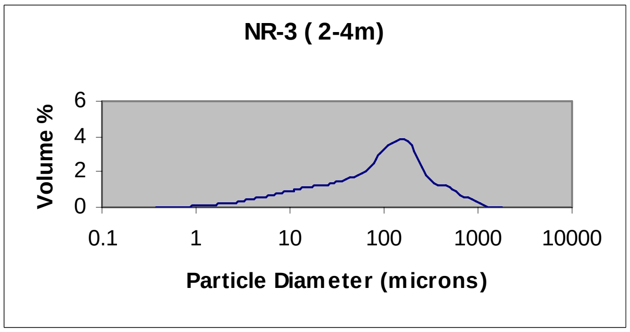

NR-2 (0-2m)
Volume %
4
3
2
1
0
0.01
0.1
1
10
100
1000
10000
Particle Diameter (microns)

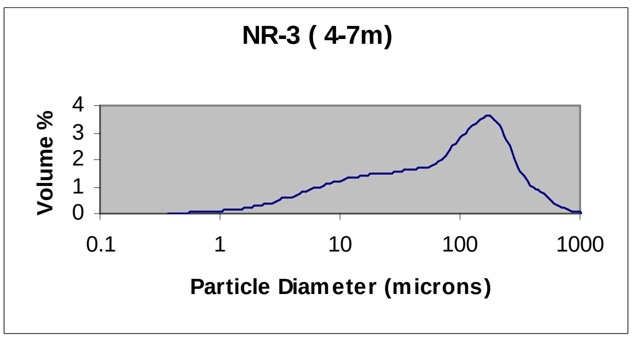

NR-2 (2-4m)
Volume %
4
3
2
1
0
0.01
0.1
1
10
100
1000
10000
Particle Diameter (microns)

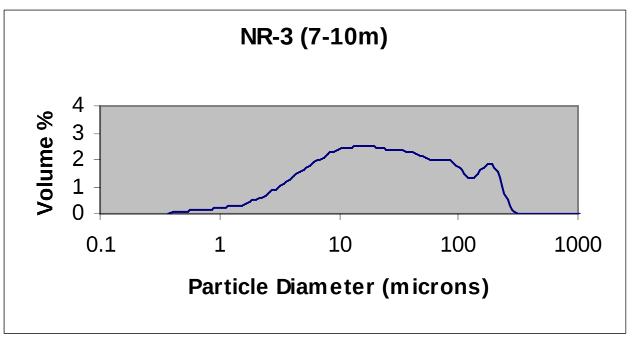

NR-2 (4-7m)
Volume %
4
3
2
1
0
0.1
1
10
100
1000
10000
Particle Diameter (microns)

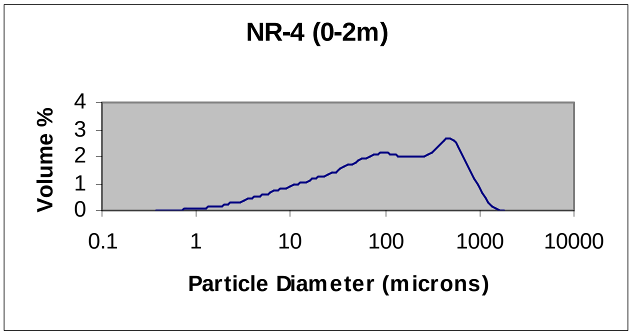

NR-2 (7-10m)
Volume %
4
3
2
1
0
0.01
0.1
1
10
100
1000
10000
Particle Diameter (microns)

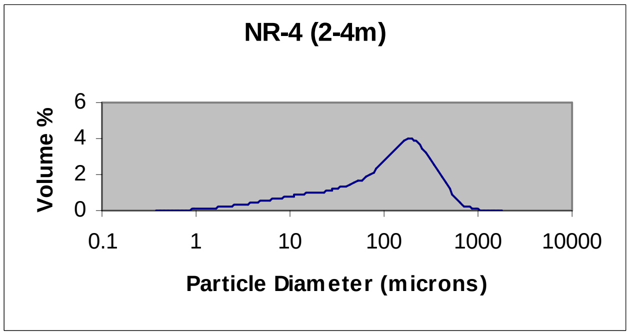

NR-3 (0-2m)
Volume %
4
2
0
0.1
1
10
100
1000
10000
Particle Diameter (microns)

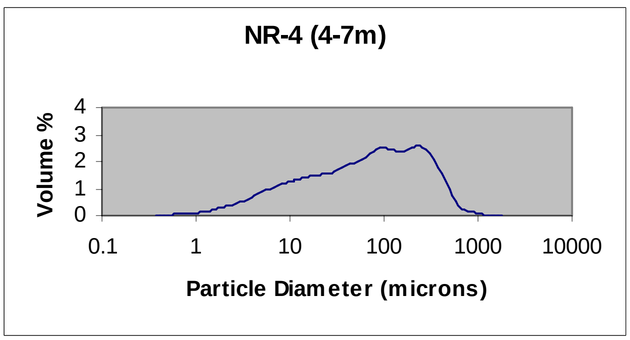

NR-3 (2-4m)
Volume %
6
4
2
0
0.1
1
10
100
1000
10000
Particle Diameter (microns)

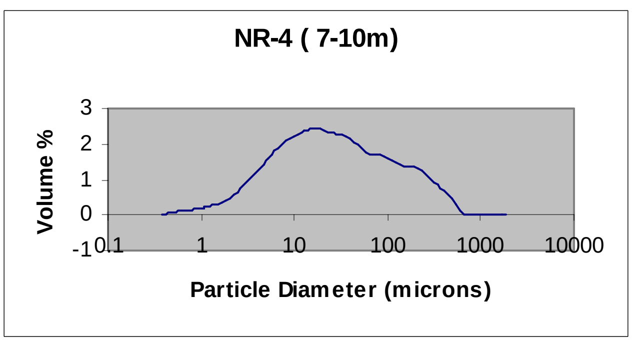

NR-3 (4-7m)
Volume %
4
3
2
1
0
0.1
1
10
100
1000
Particle Diameter (microns)

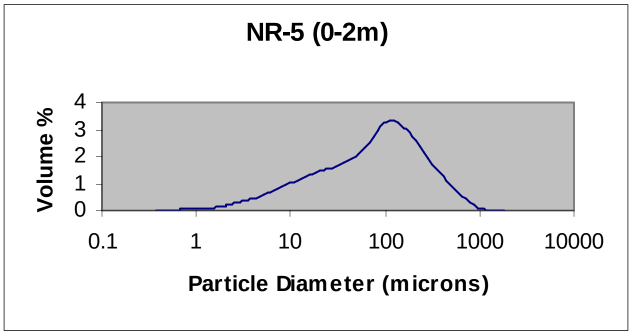

NR-3 (7-10m)
Volume %
4
3
2
1
0
0.1
1
10
100
1000
Particle Diameter (microns)

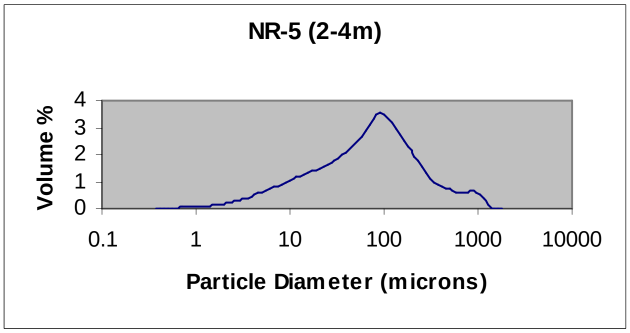

NR-4 (0-2m)
Volume %
4
3
2
1
0
0.1
1
10
100
1000
10000
Particle Diameter (microns)

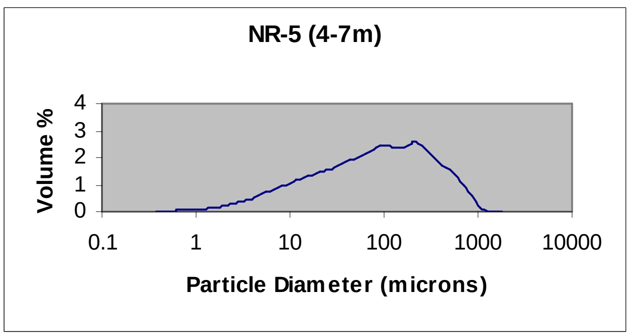

NR-4 (2-4m)
Volume %
6
4
2
0
0.1
1
10
100
1000
10000
Particle Diameter (microns)

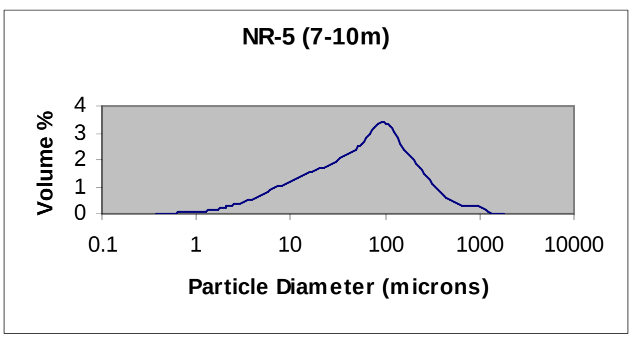

NR-4 (4-7m)
Volume %
4
3
2
1
0
0.1
1
10
100
1000
10000
Particle Diameter (microns)

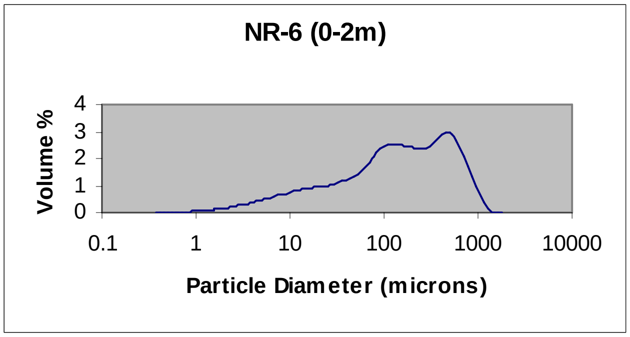

NR-4 (7-10m)
Volume %
3
2
1
0
-1
0.1
1
10
100
1000
10000
Particle Diameter (microns)

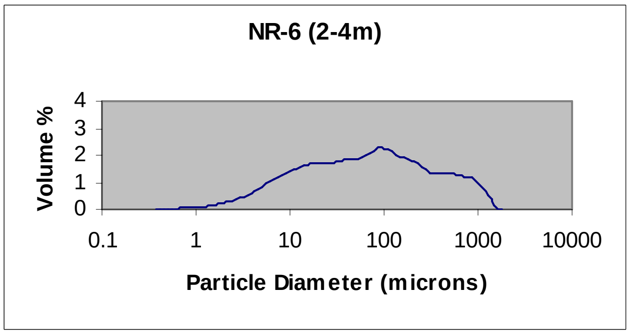

NR-5 (0-2m)
Volume %
4
3
2
1
0
0.1
1
10
100
1000
10000
Particle Diameter (microns)

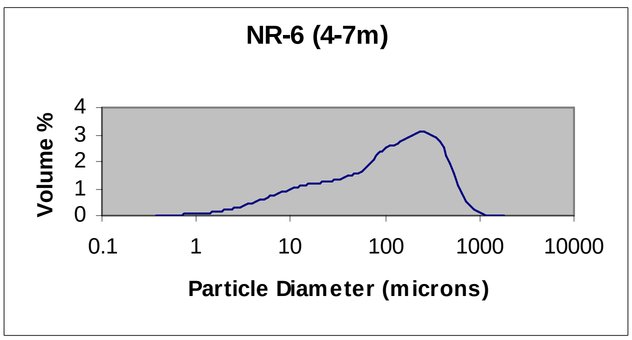

NR-5 (2-4m)
Volume %
4
3
2
1
0
0.1
1
10
100
1000
10000
Particle Diameter (microns)

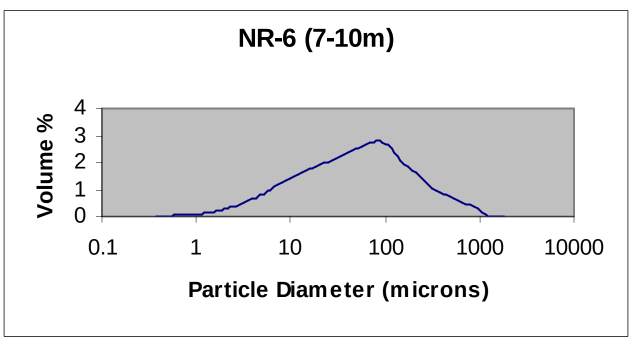

NR-5 (4-7m)
Volume %
4
3
2
1
0
0.1
1
10
100
1000
10000
Particle Diameter (microns)

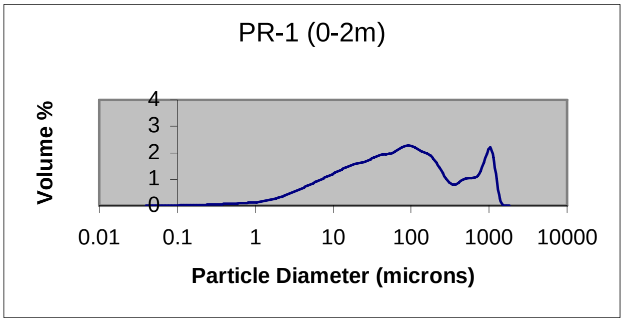

NR-5 (7-10m)
Volume %
4
3
2
1
0
0.1
1
10
100
1000
10000
Particle Diameter (microns)

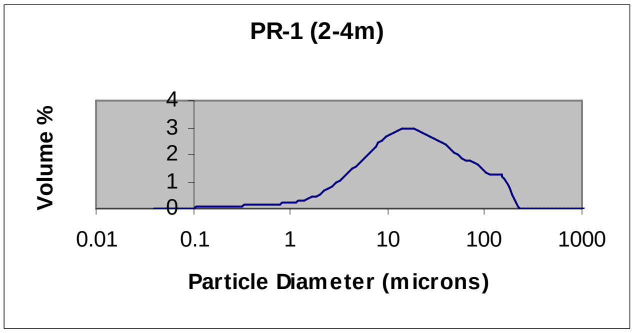

NR-6 (0-2m)
Volume %
0
1
2
3
4
0.1
1
10
100
1000
10000
Particle Diameter (microns)

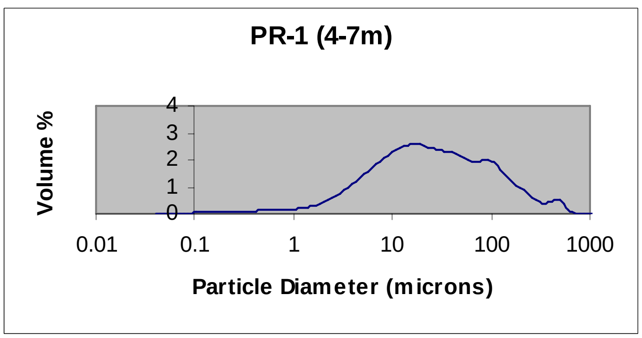

NR-6 (2-4m)
Volume %
0
1
2
3
4
0.1
1
10
100
1000
10000
Particle Diameter (microns)

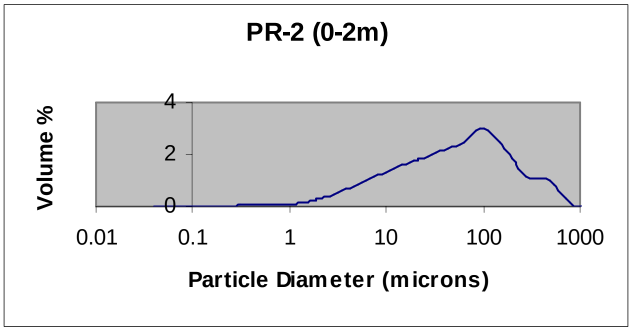

NR-6 (4-7m)
Volume %
0
1
2
3
4
0.1
1
10
100
1000
10000
Particle Diameter (microns)

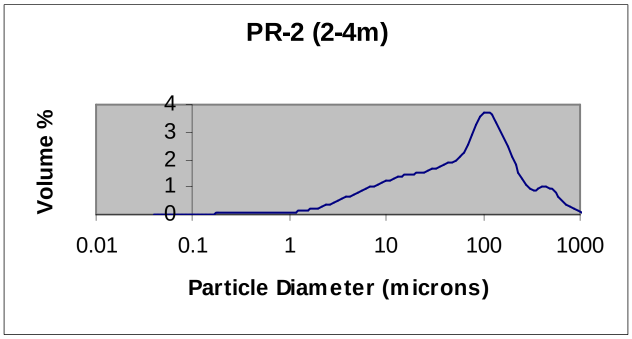

NR-6 (7-10m)
Volume %
0
1
2
3
4
0.1
1
10
100
1000
10000
Particle Diameter (microns)

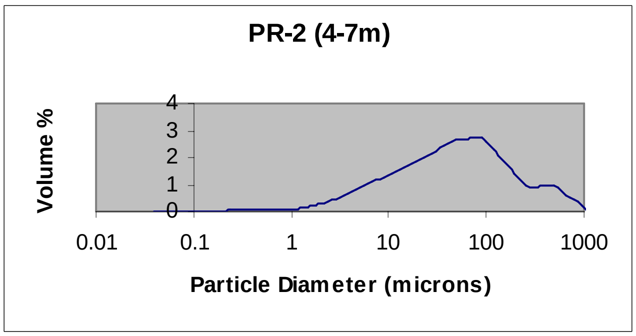

PR-1 (0-2m)
Volume %
4
3
2
1
0
0.01
0.1
1
10
100
1000
10000
Particle Diameter (microns)

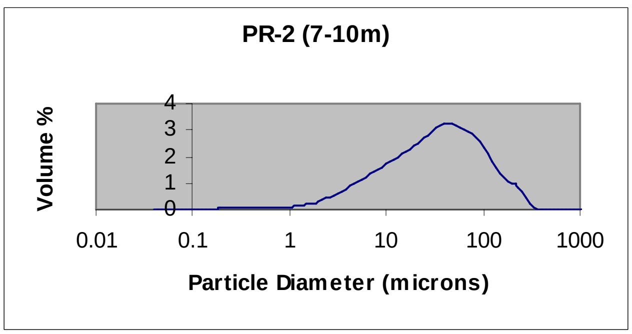

PR-1 (2-4m)
Volume %
4
3
2
1
0
0.01
0.1
1
10
100
1000
Particle Diameter (microns)

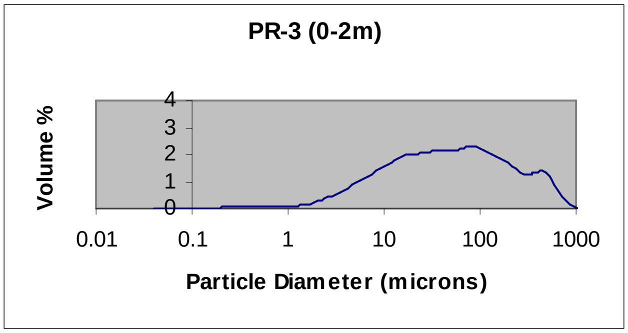

PR-1 (4-7m)
Volume %
4
3
2
1
0
0.01
0.1
1
10
100
1000
Particle Diameter (microns)

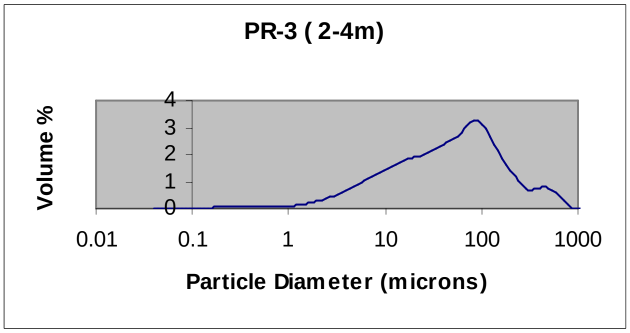

PR-2 (0-2m)
Volume %
4
2
0
0.01
0.1
1
10
100
1000
Particle Diameter (microns)

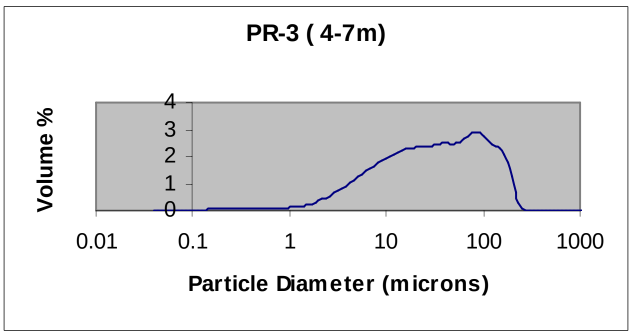

PR-2 (2-4m)
Volume %
4
3
2
1
0
0.01
0.1
1
10
100
1000
Particle Diameter (microns)

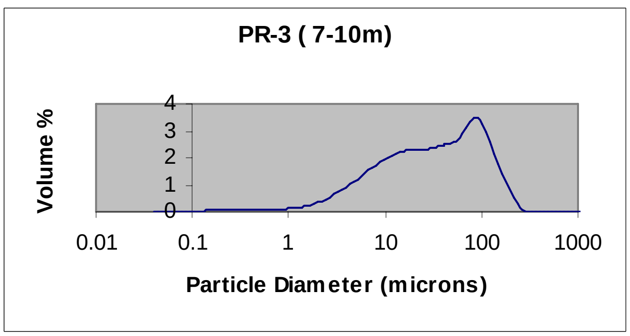

PR-2 (4-7m)
Volume %
4
3
2
1
0
0.01
0.1
1
10
100
1000
Particle Diameter (microns)


PR-2 (7-10m)
Volume %
4
3
2
1
0
0.01
0.1
1
10
100
1000
Particle Diameter (microns)


PR-3 (0-2m)
Volume %
4
3
2
1
0
0.01
0.1
1
10
100
1000
Particle Diameter (microns)


PR-3 (2-4m)
Volume %
4
3
2
1
0
0.01
0.1
1
10
100
1000
Particle Diameter (microns)


PR-3 (4-7m)
Volume %
4
3
2
1
0
0.01
0.1
1
10
100
1000
Particle Diameter (microns)


PR-3 (7-10m)
Volume %
4
3
2
1
0
0.01
0.1
1
10
100
1000
Particle Diameter (microns)