

Application of digital bathymetry data in an analysis of flushing times of two large estuaries

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Abstract

The objectives of this study were: (1) define the best method of using digital bathymetric data to compute estuarine flushing time using the fraction of freshwater method and (2) use this method to compare flushing times of two neighboring estuaries of different trophic state. We examined the sensitivity of the fraction of freshwater method to various methods of calculating estuarine volume using digital bathymetric data. Raster and vector bathymetry data are available from the National Geophysical Data Center (NGDC), and can be used to calculate estuarine volume using a geographic information system (GIS). The vector data was of higher spatial resolution than the raster data (NGDC Coastal Relief Model) and produced a higher estuarine volume, but did not produce significantly different flushing times than the raster data. Water column salinity data can be used to quantify segmented vertical freshwater volumes for integration along the estuary, thereby providing a two-dimensional freshwater distribution profile of the estuary. The vertical representation of water column salinity did not produce flushing times significantly different from a vertically averaged salinity method. Processing and analysis of the Coastal Relief Model raster data is faster and less complex than processing the vector data available from the NGDC. We conclude that the Coastal Relief Model raster data is the preferred bathymetric data source, and that representation of vertical salinity distribution is unnecessary for the analysis of estuaries with morphology similar to the Cape Fear River's. After using the Cape Fear River estuary as a test site for the above comparisons, we applied the preferred method to the New River estuary. In addition to having a direct connection with the ocean, the Cape Fear River has much higher freshwater inflow than the New River, and therefore has a much faster mean flushing time. The Cape Fear River estuary flushing time ranged from 1 to 22 days, while the New River estuary ranged from 8 to 187 days. Similar seasonal patterns were observed in both estuaries: short flushing times occurred during the high-flow winter months and long flushing times occurred during the low-flow summer months.

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1. Introduction

The concept of estuarine flushing time has been increasingly used as a descriptor of estuarine function. Biologic and chemical transformations within the estuary have been described as functions of estuarine flushing time. Furthermore, recent research has developed models to estimate nitrogen uptake, export, and

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denitrification within estuaries (Dettmann, 2001). As these tools of estuarine assessment are developed, it will be increasingly common for researchers to quantify estuarine flushing times. Numerous methods are available for this analysis across a wide range of complexity, cost, and data requirements. Recent development of digital bathymetric data sets for the United States allows researchers an expedient way to obtain the bathymetric data required to analyze the flushing time of an estuary.

Estuarine flushing time has been defined in several ways (Hagy, 1996). In this study we measured the freshwater replacement time using the fraction of freshwater method. This method has been widely used for measuring flushing time when limited resources are available, and general trends of an estuary's hydrology are sought (Dyer, 1997; Kumar et al., 1999; Alber and Sheldon, 1999; Eyre, 2000). The fraction of freshwater method calculates the time required for river discharge into an estuary to replace the resident volume of freshwater within the estuary. This integrative measure of estuarine function should not be confused with estuarine residence time, which is the time required for a water parcel to move through the estuary (see Monsen et al. (2002) for a helpful comparison of these concepts). The ability to assess flushing time over a multi-annual time scale using a modicum of hydrologic data is why the fraction of freshwater method remains a popular tool for flushing time assessment.

In past studies involving the fraction of freshwater method, estuarine volume has been approximated using bathymetry data compiled in nautical charts (Alber and Sheldon, 1999; Guo and Lordi, 2000; Pilson, 1985; Boynton et al., 1995), or by field investigation using sonar (Eyre, 2000). We propose a faster method of quantifying estuarine volume that can be applied to any estuary in the United States. The National Geophysical Data Center (NGDC) has produced two products with which estuarine volume can easily be quantified for any estuary. These digital data can be analyzed in a variety of ways to determine the volume of an estuary. Therefore, our objective was to determine the easiest way to accurately apply these data to the fraction of freshwater flushing time equation. In this study, estuarine volume was derived using two sources of digital bathymetric data: a raster data model and a vector data model. The NGDC's Coastal Relief Model is a raster data set of bathymetry and topographic data integrated temporally and spatially to produce a seamless representation of coastal elevation and water depths with a resolution of 90 m. The second source of bathymetry data used was from the NGDC's GEODAS Database, which allows users to extract bathymetric soundings in vector format from research cruises conducted from 1930 to the present. The vector data allows construction of a triangulated irregular network (TIN) that represents bathymetry more accurately than

the Coastal Relief Model raster data. Despite its coarse resolution (relative to the vector data), the raster-based Coastal Relief Model is a more convenient format to use and does not require as much processing as the GEODAS data. We compared the flushing times calculated using volume measurements made from both bathymetric surface models (grid and TIN).

Calculation of freshwater volume relies upon the methods described above, as well as the method of representing salinity within a vertical profile of the estuary. The digital representation of bathymetry allows partitioning of the water column into vertical segments. Water column salinity data can then be used to determine the vertical distribution of freshwater within the estuary. Alternatively, salinity data collected at the surface, middle, and bottom of the water column can be averaged and applied to the entire river segment to derive freshwater volume. In a partially stratified estuary such as the Cape Fear River in North Carolina, these two methods may produce different freshwater volumes, and consequently influence the calculation of estuarine flushing time. We tested for significant difference between flushing times of the Cape Fear River calculated using these two techniques.

Finally, we calculated flushing time for the New River estuary using the technique defined as most appropriate for the fraction of freshwater method using the methods outlined above. Differences in flushing time between these systems could then be analyzed. The morphology of these two neighboring estuaries has been used to explain their differences in primary productivity (Mallin et al., 2000). The lower phytoplankton concentrations in the Cape Fear River estuary compared with those in the New River estuary have been suspected to be due, in part, to the faster flushing time of the Cape Fear River estuary (Mallin et al., 2000), which inhibits algal bloom formation. However, the flushing times of these two estuaries have not been quantified to allow a direct comparison between the two systems. A brief summary of the two estuaries follows.

The Cape Fear River estuary in New Hanover and Brunswick Counties, North Carolina, is a deep, narrow, fast-flowing water body with an estuarine surface area of 100 km² (NOAA, 1999). It drains a watershed of 24,144 km², with a population density of 62 persons/km² (NCDWQ, 2000) (Fig. 1). The mainstem Cape Fear River is a sixth-order piedmont stream, fed by two fifth-order coastal plain streams (the Black River and the Northeast Cape Fear River). This estuary is unique among other North Carolina estuaries because it is well flushed and has high light attenuation (due to turbidity and blackwater inputs from upstream), which inhibits algal bloom formation (Mallin et al., 1999). Phytoplankton production in the upper estuary is light-limited, while production in the lower estuary is nitrogen limited in summer and phosphorus limited in spring (Mallin

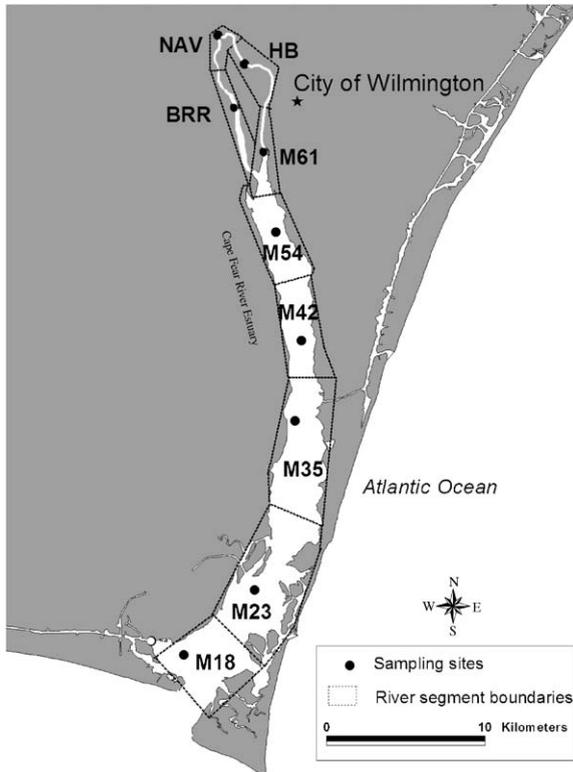


Fig. 1. Salinity data collection stations and river segments of Cape Fear River estuary, North Carolina.

et al., 1999). A NOAA survey of estuarine water quality ranked the Cape Fear River estuary as moderately eutrophic (Bricker et al., 1999).

The New River estuary in Onslow County, North Carolina is broad, shallow water body with an estuarine surface area of 88 km² (NOAA, 1999). The New River is a fourth-order coastal plain stream. It is surrounded almost entirely by the Camp Lejeune United States Marine Corps (USMC) Base. It drains a watershed of 1197 km², and has a population density of 118 persons/km² (NCDWQ, 1997) (Fig. 2). The estuary has been described as highly eutrophic in several studies (Burkholder et al., 1997; Mallin et al., 1997, 2000; NCDWQ, 1997; Bricker et al., 1999). Excessive nutrient inputs from municipal waste water treatment plants in the 1980s and 1990s led to massive algal blooms and hypoxic conditions in the estuary. Phytoplankton production in the New River estuary is strongly nitrogen limited (Mallin et al., 1997).

Extensive hydrological research has been conducted on the Cape Fear River and equations have been developed to estimate freshwater flow into the estuary based on daily flow at three United States Geological Service (USGS) stream gaging sites (Giese et al., 1985; Lawler et al., 1980; Carolina Power and Light Com-

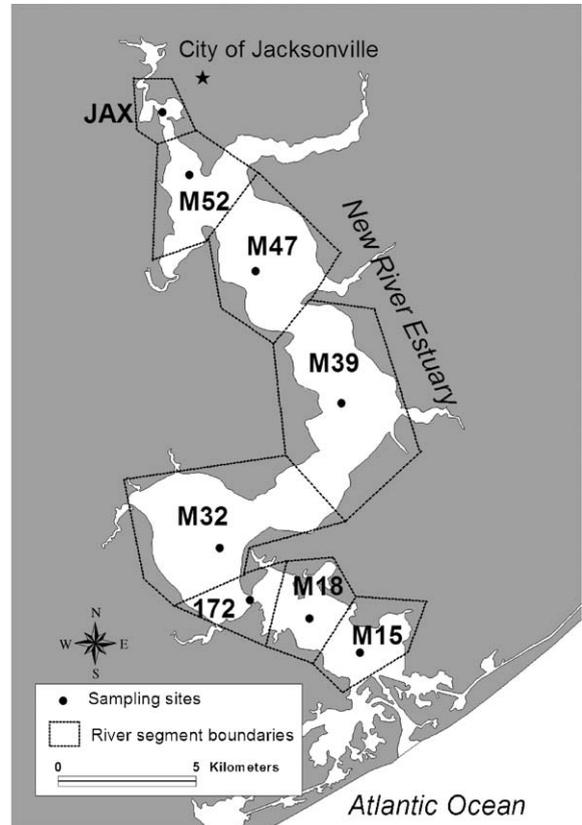


Fig. 2. Salinity data collection stations and river segments of New River estuary, North Carolina.

pany, 1979; Carpenter and Yonts, 1979; Wilder and Hubbard, 1968). The New River has not been studied as extensively as the Cape Fear River and consequently, part of the present study required developing daily freshwater inflow estimates for this estuary. Gaged stream flow from the upper New River watershed was used to estimate ungaged flow below the gage based on drainage area size. Similar studies of watershed hydrology have used this flow per unit area methodology for watershed-scale analysis over an extended period (Guo and Lordi, 2000; Lampman et al., 1999; Pilson, 1985; Alber and Sheldon, 1999; Hagy, 1996; Eyre, 2000).

2. Methods

2.1. Flushing time of the Cape Fear River estuary

2.1.1. Salinity data collection

Monthly salinity data from nine sites in the Cape Fear River estuary were collected from February 1996 to February 2001 at the surface, middle, and bottom of the water column. Salinity was measured using a YSI 6560

salinity/conductivity probe calibrated prior to each sampling run. Transects were initiated on a high ebb tide at the most downstream site, moving upstream against the ebb tide.

2.1.2. Raster bathymetry data processing for the Cape Fear River estuary

Raster bathymetry data were extracted from the National Geophysical Data Center's Coastal Relief Model. Using the NGDC's Grid Translator's Design-a-Grid function, an area defined as 78°5'W and 34°19'N by 77°53'W and 33°50'N was extracted. The following conditions were applied in the Design-a-Grid request: sea cells only, 2 byte integer, and empty cell value=0. Only sea cells were used because these would represent the bathymetry data, not terrestrial elevations. Empty cell values were set to equal zero because this would allow calculation of volume from the grid by summing all grid cells. This grid was converted to an ASCII raster file and imported into Environmental System Research Institute's (ESRI) ArcView GIS using the Import Data Source option. ArcView's Convert to Grid function was used to convert the ASCII raster file into an ArcView grid (Fig. 3A).

The nine river segments used in this analysis are drawn around the nine Lower Cape Fear River Program salinity data collection sites in the Cape Fear River

estuary (Fig. 1). The NAV salinity data collection site is located at the head of the estuary where the annual average salinity is 1.1. The bottom of the estuary was defined as being 3 km downstream from the M18 salinity data collection site. The boundaries of the nine river segments were digitized on-screen to create a shapefile of river segment boundaries (Fig. 1).

2.1.3. Vector bathymetry data processing

Using the NGDC's GEODAS software, a search was performed for bathymetry data collected within the bounds of the latitude and longitude described in the *Raster Bathymetry Data Processing* section. The five data files found by the search were extracted from the GEODAS database and saved as text files. Next, these text files were converted to database files, opened as tables in ArcView, and then added as event themes in an ArcView view. All themes were converted to shapefiles and then the five shapefiles were merged into a single point shapefile.

Bathymetry soundings were separated into files for each river segment, and overlaid with the river segment boundaries. With ArcView's 3D Analyst extension, a TIN was made from the bathymetry soundings for each river segment using the river segment polygons as hardbreak lines (Fig. 3B). The volume of each of these nine TINs was calculated using 3D Analyst's Area and Volume Statistics command. A freshwater volume of the estuary on each day of salinity data collection was calculated by adding the nine segment freshwater volumes calculated using the fraction of freshwater method.

2.1.4. Unstratified segment volumes of the Cape Fear River estuary

Using ArcView's "Summarize by Zone" command, bathymetry cell values were summed within each segment of the estuary. This sum was used to calculate the volume of each segment by multiplying by the grid cell size. The following formula was used to determine freshwater volume, V_f , of an estuarine segment:

$$V_f = ((S_S - S_i) / S_S) V, \quad (1)$$

where S_S is the end member salinity of the estuary (35); S_i the salinity of the segment; V the volume of the segment.

2.1.5. Stratified segment volumes of the Cape Fear River estuary

Using ArcView's Spatial Analyst, a "Map Query" was used to select the cells of the bathymetry grid that occupied different vertical segments of the water column. The surface of the water column was defined as the top 4 m, the middle was defined as the middle 4 m, and the bottom as depths below 8 m. Three queries were performed: cells <4 m, cells \geq 4 m and <8 m, and cells

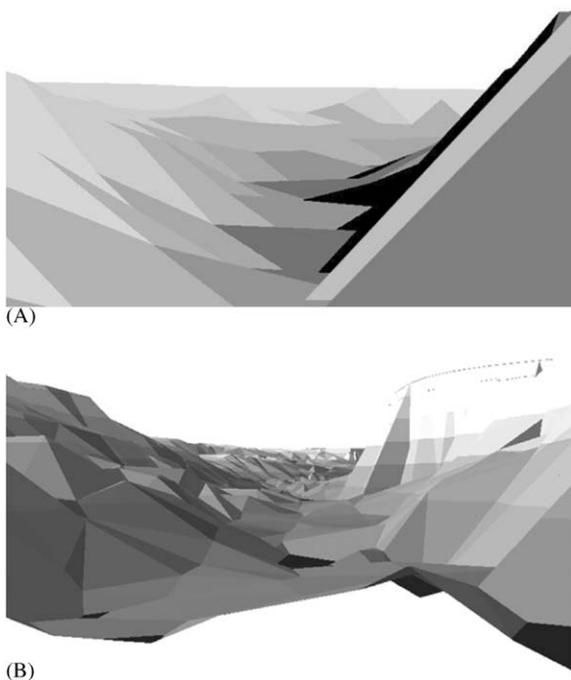


Fig. 3. Cross-section images of Cape Fear River segment M18: (A) Coastal Relief Model raster data (B) TIN produced from GEODAS vector data.

≥ 8 m. Each of these three queries returned a grid with 1 and 0 values representing True and False values, respectively. Each of these grids was multiplied by the original bathymetry grid using Map Calculator.

The following equations were used to derive surface, middle, and bottom volumes:

$$\text{surface volume} = \{[A] + [(n_1 + n_2)(3.99)]\} \{a\}, \quad (2)$$

$$\text{middle volume} = \{[B] - [(n_1)(3.99)] + [(n_2)(3.99)]\} \{a\}, \quad (3)$$

$$\text{bottom volume} = \{[C] - [(n_2)(7.99)]\} \{a\}, \quad (4)$$

where A is the sum of surface depth measurements (cells 0–3.99 m); B the sum of middle depth measurements (cells 4–7.99 m); C the sum of bottom depth measurements (cells ≥ 8 m); a the area of grid cell; n_1 the number of grid cells between 4 and 7.99 m; n_2 the number of grid cells ≥ 8 m.

The result of this process is a surface, middle and bottom volume for each segment of the estuary. Freshwater volume of each horizontal segment was determined using surface, middle, and bottom salinity data in conjunction with Eq. (1). The sum of surface, middle, and bottom freshwater volumes represented freshwater volume of each segment, and collectively represented the freshwater volume of the estuary on the day of salinity data collection.

2.1.6. River discharge data processing

Daily discharge data from January 1, 1996 to March 31, 2001 was requested from the United States Geological Survey for the following gaging stations: Cape Fear River Lock and Dam 1 (#02105769), Black River (#02106500), and the Northeast Cape Fear River (#02108000). The equations developed by the [Carolina Power and Light Company \(1979\)](#) in “Appendices A&B to Dye Tracer and Current Meter Studies, Cape Fear River estuary, NC, 1976, 1977, and 1978” were used to estimate freshwater inflow to the Cape Fear River estuary. These equations sum the gaged flow from the three USGS stations listed above and use a series of runoff coefficients to estimate additional river discharge below the gaged portion of the watershed.

2.1.7. Flushing time calculation

The freshwater replacement time, calculated by the fraction of freshwater method ([Dyer, 1997](#)), was derived by dividing the freshwater volume of the estuary on the day of salinity data collection by the freshwater inflow rate on that day. The freshwater replacement time, T , of an estuary can be calculated as

$$T = \frac{\sum_{i=1}^n (V_{fi})}{Q_f} \quad (5)$$

where V_{fi} is the freshwater volume of segment i and Q_f the freshwater inflow.

The date-specific method of [Alber and Sheldon \(1999\)](#) was used to determine the appropriate time period to average freshwater flow into the estuary for a given freshwater volume. The date-specific procedure was performed by calculating flushing time repeatedly using the same freshwater volume, but using flow averaged over increasingly longer time periods prior to the day of sampling until the time period used to average flow was equal to the flushing time calculated in this way. This procedure was performed three times for each sampling date (once a month from February 1996 to February 2001) using the three different measurements of freshwater volume produced as described in the previous sections.

2.1.8. Statistical analysis

The differences among flushing times produced by the three methods (raster model using stratified salinity, raster model using averaged salinity, and vector model using average salinity) used in this study were tested for significance. SAS Institute’s software was used for all statistical analysis. The three data sets were first tested for normality using the Shapiro-Wilk W test. If this test showed a data set to be non-normally distributed, the natural log function was used to normalize the data. Next, a paired T -test was used to test the hypotheses that there was no significant difference in flushing time as calculated by the stratified salinity method versus the averaged salinity method, and that there was no significant difference in flushing time as measured by the vector-based method versus the raster-based method using average water column salinity data.

2.2. Flushing time of the New River

2.2.1. Bathymetry data processing

This portion of the project was completed after results were obtained from the above analysis of the Cape Fear River estuary. Based upon those results, it was deemed appropriate to use the NGDC’s Coastal Relief Model in conjunction with vertically averaged salinities. Raster bathymetry data was extracted from the National Geophysical Data Center’s Coastal Relief Model. Using the NGDC’s Grid Translator’s Design-a-Grid function, a polygon with the coordinates $77^\circ 30'W$ by $34^\circ 48'N$ and $77^\circ 18'W$ by $34^\circ 30'N$ was extracted. The upper boundary of the New River estuary was defined as the US Highway 17 bridge in Jacksonville, NC ([Fig. 2](#)), where the average annual salinity at the salinity sampling site nearest the bridge (JAX) is 6.2. The lower boundary of the estuary was defined as being 1 km downstream from the M15 salinity sampling station ([Fig. 2](#)). Salinity data was gathered monthly at eight sites on the New River estuary from the Intracoastal Waterway to Jacksonville,

using identical equipment and techniques as were used in the Cape Fear River estuary. Surface and bottom salinity measurements were averaged and used to determine freshwater volume with Eq. (1) (given an end-member salinity of 35). Middle water column measurements were not made due to the shallow depth of the New River estuary (~ 3 m). The same procedures were followed for spatial data processing, estuary segment delineation, and flushing time calculation as were performed previously.

2.2.2. River discharge data processing

The USGS gaging station #02093000 on the New River was used to determine the daily flow ($\text{m}^3 \text{s}^{-1}$) per km^2 in the watershed above this site. This coefficient was applied to the watershed area below the gaging site (not including the surface area of the estuary) on a daily basis, and daily flows for the period of study were thus estimated. Total ungaged watershed area of the New River estuary was calculated by subtracting the gaged area and estuarine surface area from the total area of the watershed.

3. Results

The two bathymetric interpolation methods tested produced slightly different volume measurements of the Cape Fear River estuary. The vector-based TIN produced an estuarine volume of 262 million m^3 while the raster-based Coastal Relief Model produced a volume of 253 million m^3 (Table 1). The 3.6% larger estuarine volume calculated by the TIN was responsible for the calculation of a 5.5% larger volume of freshwater in the estuary on average (134 million m^3) than that calculated by the Coastal Relief Model bathymetry (127 million m^3), with concomitantly longer flushing times. A

comparison of salinity data processing (in conjunction with the Coastal Relief Model) showed that averaging water column salinities produced higher estimates of freshwater volume (127 million m^3) than did representation of surface, middle, and bottom components of the water column (121 million m^3) (Table 1). Lower values of freshwater volume in the latter method would be expected because, with the exception of NAV and BRR, the bottom component comprises 38–63% of the volume of each river segment (Fig. 4). Because a higher salinity is being attributed to a higher proportion of the water column than surface and middle salinity values, the calculated fraction of freshwater decreased.

The Coastal Relief Model using the stratified salinity method for determining freshwater volume produced mean and median flushing times of 9.0 days and 7.4 days, respectively, for the Cape Fear River estuary (Table 2). The Coastal Relief Model using the averaged salinity method produced mean and median flushing times of 7.9 and 6.7 days, respectively. The vector (TIN-based) method of interpolating estuarine bathymetry using the averaged salinity method produced mean and median flushing times of 8.4 and 6.8 days, respectively. The three sets of data were not normally distributed, and were normalized by natural log transformation. The p -value for the paired difference t -test between the raster and vector-based methods using averaged salinity was 0.69. The p -value for the paired t -test between the stratified and averaged salinity methods was 0.93. Therefore, there were no significant differences between results generated by the raster and vector methods or between results generated by the averaged salinity and stratified salinity methods. According to the averaged salinity, raster-based method, the longest flushing time estimated during the period of study in the Cape Fear River estuary was 22 days in September 1988, and the shortest flushing time (1.2 days) occurred in February

Table 1

Comparison of estuarine volumes and mean freshwater volumes of Cape Fear River and New River estuaries, February 1996–December 2000

Estuary	Parameter	Coastal Relief Model bathymetry with average water column salinity	Coastal Relief Model bathymetry with surface, middle and bottom freshwater volumes	Bathymetry from TIN, with average water column salinity
Cape Fear River estuary	Estuarine volume (million m^3)	253	253	262
	Mean freshwater volume (million m^3)	127	121	134
New River estuary	Estuarine volume (million m^3)	130	—	—
	Mean freshwater volume (million m^3)	67	—	—

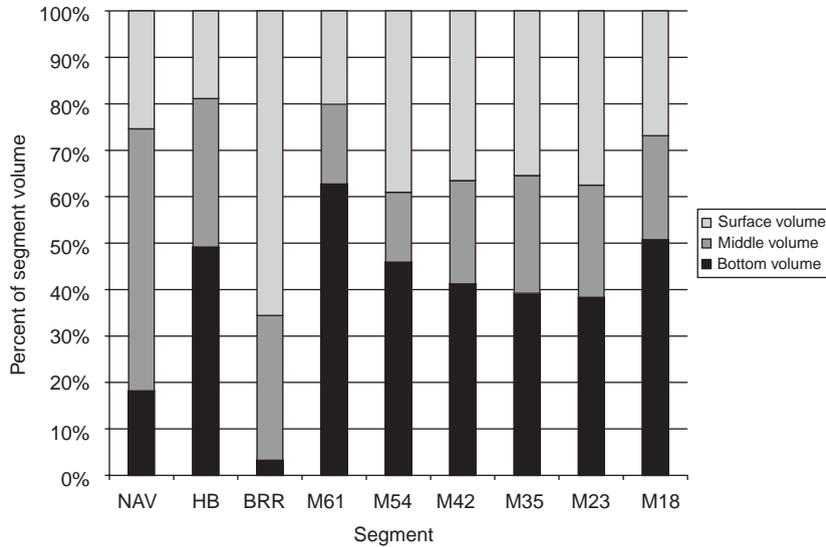


Fig. 4. Vertical water column segment volumes from the Cape Fear River estuary.

Table 2

Comparison of methods used to calculate flushing time of the Cape Fear River and New River estuaries, February 1996–December 2000

Estuary	Statistic	Coastal Relief Model bathymetry with average water column salinity	Coastal Relief Model bathymetry with surface, middle and bottom salinities	Bathymetry from TIN, with average water column salinity
Cape Fear River estuary	Mean flushing time (days)	7.9	9.0	8.4
	Median flushing time (days)	6.7	7.4	6.8
	Maximum flushing time (days)	22.2	25.1	24.9
	Minimum flushing time (days)	1.2	1.3	1.3
New River estuary	Mean flushing time (days)	69.9	—	—
	Median flushing time (days)	63.5	—	—
	Maximum flushing time (days)	187.3	—	—
	Minimum flushing time (days)	7.9	—	—

1998. In general, shortest flushing times occurred during winter, and longest flushing times occurred during summer.

Flushing times in the New River estuary ranged from 8 to 187 days, with a mean 70 days and median of 64 days (Table 2, Fig. 5). The shortest flushing time occurred in September 1999 in response to Hurricane

Floyd. The longest flushing time in the New River estuary occurred in October 1997. With the exception of hurricane-derived rainfall events (Bertha in July, 1996; Fran in August 1996; Bonnie in September 1998; Floyd in September 1999) longest flushing times occurred in spring and summer and shortest flushing times occurred in winter.

4. Discussion

The salinity averaging technique described above may not be applicable to estuaries with morphologies very different from the Cape Fear River. For example, consider a broad, shallow estuary with a narrow, deep channel and significant salinity stratification. In this case, application of an unweighted average water column salinity may underestimate the estuarine freshwater volume (the New River estuary does not lend itself to test this hypothesis because it does not have a well defined, deep channel). Given these caveats, we recommend using the NGDC's raster-based Coastal Relief Model to others interested in using a GIS to derive estuarine freshwater volumes for use with the fraction of freshwater method. Though a TIN of estuarine bathymetry offers a higher degree of resolution, it does not significantly alter the flushing time calculated using the fraction of freshwater method. Furthermore, for simplicity, we recommend using average water column salinity in conjunction with the Coastal Relief Model. Though the vertically stratified salinity method provides a higher degree of resolution to represent salinity gradients in the vertical dimension, using this method did not significantly alter the flushing time calculated using the fraction of freshwater method.

A clear, seasonal trend is apparent for both the Cape Fear River estuary flushing time and the New River estuary flushing time (Figs. 5–7). Shorter flushing times occur during the winter months (November–March) when freshwater inflow is highest. Longer flushing times occur during the summer months (May–October) when freshwater inflow is lowest. Periodic punctuations in

flushing time occur during the summer months as the Southeastern United States is impacted by the heavy rainfall brought by hurricanes, and subsequently higher river flows. The geomorphology of these estuaries also influences their flushing times. The restriction of the lower New River estuary probably lengthens flushing time by reducing tidal exchange through the mouth of the estuary, whereas the Cape Fear River estuary has an open connection with the ocean and consequently higher tidal exchange (Figs. 1 and 2).

The relationship between flushing time and flow is a negative power function because flow is the denominator in the fraction of freshwater method (Fig. 8). Note the position of the median flushing time value on this curve. As described by Alber and Sheldon (1999), the higher up the slope this median flushing time value is, the more sensitive flushing time of the estuary is to changes in freshwater inflow. Consequently, the Cape Fear River estuary's flushing time responds less dramatically to changes in freshwater inflow than the New River estuary (Figs. 5–7). As a result, the New River estuary experiences rapid flushing events after extended periods of very slow flushing. A steady increase in flushing time occurs during the transition from winter flow regimes to summer low-flow regimes. The repeated ramped pattern of flushing time exhibited during this period (March/April–September/October) is due to combined decreased flow and increased salinity. Long summer flushing time is punctuated with sudden flushing events following Hurricanes Bertha (July 1996), Fran (August 1996), Bonnie (September 1998), and Floyd (September 1999). The dramatic nature of these events in the New River estuary contrasts with the response of

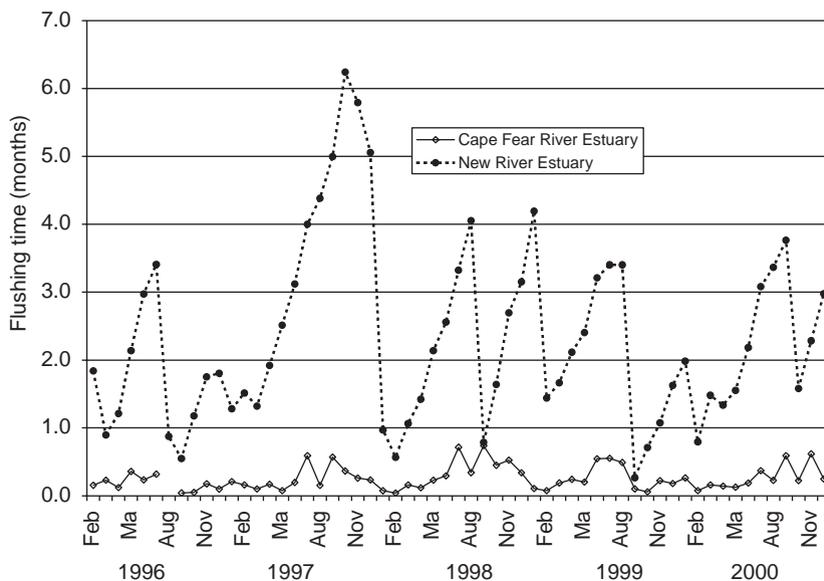


Fig. 5. Flushing times of Cape Fear River and New River estuaries.

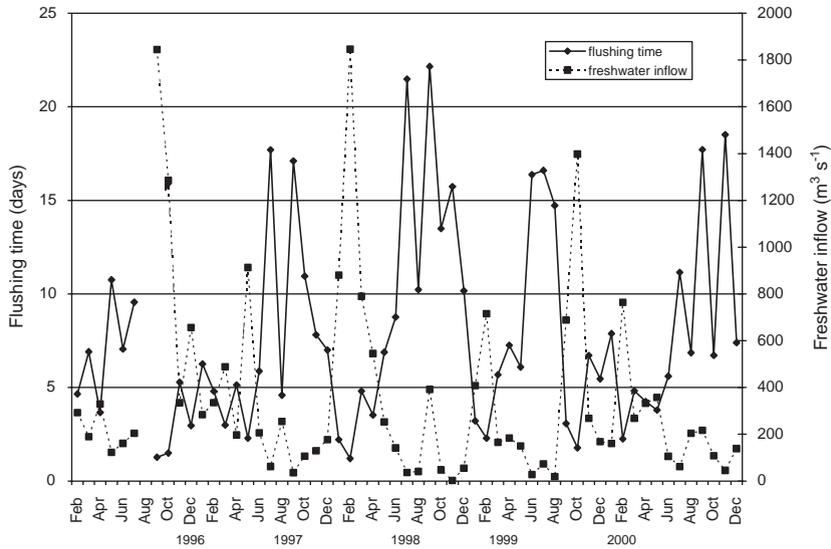


Fig. 6. Flushing times and freshwater inflow to Cape Fear River estuary; freshwater inflow values shown are for day of salinity sampling.

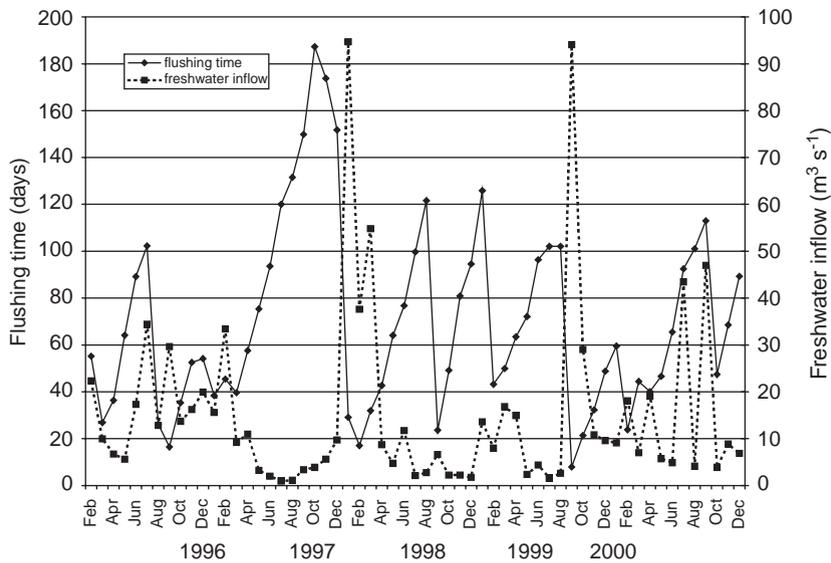


Fig. 7. Flushing times and freshwater inflow to New River estuary; freshwater inflow values shown are for day of salinity sampling.

the Cape Fear River estuary in which sudden, dramatic changes in flushing time are not seen in the period of a single month.

The method of estimating freshwater inflow to the New River assumed that precipitation amount and subsequent surface flow were homogenous across the watershed, and extrapolated flow from a small (20%) portion of the watershed. In the wake of Hurricane Bonnie we see at least one instance where this method

produced dubious results. In August of 1998, Hurricane Bonnie struck the North Carolina coast, bringing heavy rainfall across much of eastern North Carolina. Freshwater replacement time decreased in the New River estuary by 100 days and average estuary salinity decreased from 24 to 16, indicating a significant influx of freshwater. However, estimated freshwater inflow did not show a significant increase, presumably an artifact of relatively low rainfall in the gaged portion of the

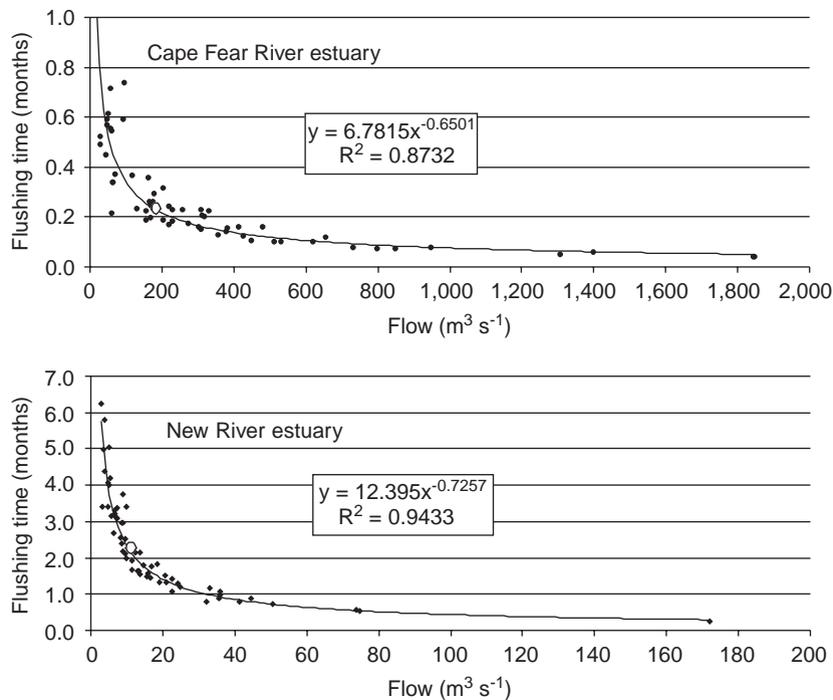


Fig. 8. Relationship between freshwater inflow and flushing time in Cape Fear and New River estuaries (open circle represents median flushing time); flushing times calculated using averaged water column salinity and raster bathymetry data (freshwater inflow values are those arrived at by date-specific method).

Table 3

Nitrogen dynamics of Cape Fear River and New River estuaries calculated from yearly mean value of flushing time

Year	Cape Fear River estuary			New River estuary		
	Flushing time (months)	Fraction of estuarine, N exported	Fraction of estuarine, N removed	Flushing time (months)	Fraction of estuarine, N exported	Fraction of estuarine, N removed
1996	0.18	0.95	0.05	1.69	0.66	0.34
1997	0.26	0.93	0.07	3.51	0.49	0.51
1998	0.34	0.91	0.09	2.03	0.62	0.38
1999	0.25	0.93	0.07	2.13	0.61	0.39
2000	0.27	0.93	0.07	2.20	0.60	0.40

watershed. The flushing time of 24 days calculated in response to this event is therefore an overestimate, as a higher, more realistic freshwater inflow would produce a shorter flushing time.

In conclusion, the large difference in flushing time between the Cape Fear River and New River estuaries has important implications for the processing of nutrients within these systems. As predicted by a recent model (Dettmann, 2001), a higher fraction of the annual nitrogen load will be removed within the New River estuary than within the Cape Fear River estuary (34–51% and 5–9%, respectively) (Table 3). The longer the

residence time of water within the estuary, the greater the nutrient uptake and subsequent cycling within the estuary. The eutrophic status of the New River is partially a result of the slow flushing time that allows greater nutrient cycling and more time for algal bloom development. In contrast, while the Cape Fear River is continually resupplied with river-borne nutrients, only a small fraction are incorporated into primary productivity and subsequently recycled, and there is limited time for algal bloom formation. Further research will quantify nutrient loads to these estuaries and develop mass-balance models of nitrogen flux.

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