Siamak Khorram
Computer Graphics Center
North Carolina State University
Raleigh, NC 27695-7106
Heather M. Cheshire
Department of Forestry
North Carolina State University
Raleigh, NC 27695-8002

Remote Sensing of Water Quality in the Neuse River Estuary, North Carolina

The coefficients of determination were observed to be high for salinity and turbidity, relatively high for chlorophyll *a*, and medium for total suspended solids.

Abstract: *The objective of this study was to use Landsat Multispectral Scanner (MSS) digital data combined with surface measurements for water quality mapping of the Neuse River Estuary, North Carolina. The water quality parameters of interest included salinity, chlorophyll* a, *turbidity, and total suspended solids. The approach involved acquisition of water quality samples from boats of 75 sample sites simultaneous with Landsat satellite overpass. All of the remotely-sensed data and boat-acquired data were obtained from 8:45* A.M. *to 9:50* A.M. *local time on 24 September 1982. Regression models were developed between each of the salinity and suspended solids measurements from boats and the* MSS *digital data for 46 of the sample sites. Bottom reflection from shallow parts of the estuary appeared to cause difficulties in developing models for chlorophyll* a *and turbidity. Sample sites were stratified based on water depth. Chlorophyll* a *and turbidity measurements for sample sites greater than 10 feet in depth were used to develop the statistical models for these parameters. The models developed for each of the four water quality parameters were applied to the remaining sites (those sites not used in model development) for statistical determination of their predictive value. The verified models were then applied to the entire study area. The results include a series of color-coded maps, each pertaining to one of the water quality parameters, along with the statistical summaries. This study constitutes the first effort to use Landsat digital data for mapping water quality parameters in this geographic area.*

Introduction

Major estuarine systems are of particular importance to North Carolina's economy as sources of recreation and as nursery grounds supporting commercial and sport fisheries. Several government agencies and research groups are attempting to gather water quality data in these estuarine systems for planning and evaluating the results of various water management activities such as dredging operations on the coast or the damming of tributaries up river. Water quality data are also needed to aid in the establishment and enforcement of various regulations that pertain to meeting specific water quality standards. For years, these researchers have relied on a series of sampling stations and interpolation techniques to study the distributions of various water quality parameters. The large size of the estuaries and the spatial variability of water quality parameters has limited the effectiveness of these investigations.

Remotely-sensed data acquired from Landsat satellites may have the potential for providing these agencies with an alternative cost-effective proce-

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dure for mapping water quality. The advantages of satellite data over conventional sampling procedures include repetitive coverage of a given area every 16 days, a synoptic view which is unobtainable by conventional methods, and almost instantaneous spatial data over the areas of interest. Once it is possible to combine a limited number of surface truth measurements with the complete coverage provided by Landsat sensors, a greatly improved means becomes available for mapping and monitoring surface water quality parameters.

Landsat and aircraft multispectral scanner digital data have been used for water quality mapping of inland and estaurine systems by many investigators. Grew (1973), Scherz *et al.* (1975), and Hergenrader (1976) utilized multispectral data to study the distributions of pollutants and algae in oceans and inland waters. Landsat Multispectral Scanner (MSS) data have been used to map concentrations of suspended sediments (Klemas, 1973; Williamson and Grabeau, 1973). Johnson *et al.* (1975), Rogers *et al.* (1975), Fleischer *et al.* (1976), and Marshall *et al.* (1976) applied regression techniques to calibrate Landsat data and map distributions of chlorophyll and other water quality parameters. The same technique has been used to map turbidity and total suspended solids (Yarger *et al.*, 1973; Kritikos *et al.*, 1974; Barker, 1975; Brooks, 1975; Khorram, 1981). Landsat data have also been used to map salinity in estaurine systems (Khorram, 1982). Several investigators have studied the applicability of Landsat data in determining and monitoring water quality in reservoirs, lakes, and estaurine systems (McKeon and Rogers, 1976; Rogers *et al.*, 1976; Smith *et al.*, 1977; Johnson and Harriss, 1980). In the case of salinity, a search of the literature indicates that there are no significant differences in the reflectance characteristics of saline water and freshwater. It is our opinion that we may be detecting one or more parameters which are strongly correlated with salinity. One of these parameters may be turbidity, which was found to be correlated with salinity in our input dataset.

There is a need to investigate the usefulness of Landsat MSS digital data for mapping water quality parameters in this geographic area. The information derived from these investigations would benefit researchers, resource managers, and land-use planners who are concerned about water quality, water pollution, and the impacts of land-use practices on estuarine systems. The research results can be used in (1) establishing and meeting the water quality standards in this area by government agencies, (2) planning and evaluating the results of water management activities, (3) enforcing various water quality-related environmental regulations, and (4) further understanding of the biological and hydrologic characteristics of these aquatic ecosystems and the environmental impacts of the land-use practices within the surrounding environment.

Increased population, industrial expansion, and changing land-use practices have had detrimental impacts on estuarine systems. Based upon current studies, in recent years the area chosen for study has begun to exhibit symptoms of degradation similar to those seen in other estuaries. Projected upstream land development practices may contribute to the adverse impacts on water quality in this estuarine environment. Upstream reservoirs, built recently, are expected to increase the nutrient load of the river at certain times of the year. The headwaters of the Neuse Riber pass through one of the fastest growing ceters of population in the state, and intensive agricultural practices are carried out throughout its course.

Objective and Study Area

The objective of this study was to investigate the usefulness of Landsat Multispectral Scanner (MSS) digital data for mapping selected water quality parameters in the Neuse River Estuary, North Carolina. The water quality parameters of interest included salinity, chlorophyll *a*, turbidity, and total suspended solids.

The Neuse River Estuary is formed by the Neuse River entering Pamlico Sound near the mid-part of the North Carolina coast. The study area is approximately 50 miles long and reaches a maximum width of about 7 miles at the beginning of the Pamlico Sound. This estuary is influenced very little by diurnal tides but is strongly influenced by winds. Shallow sand bars (<10 feet below the surface) are common but seldom are found beyond 500 yards from the shoreline.

Materials and Methods

The general approach involved the simultaneous acquisition of remotely-sensed data and water quality samples from boats. A sampling network was designed and water quality samples were collected from 75 sites within less than 1.5 hours of the Landsat overpass on 24 September 1982. Regression models were developed between each of the water quality parameters and the Landsat MSS data. After statistical verification, these models were extended to the entire study area to map the spatial distribution of the water quality parameters.

Collection and Laboratory Analysis of Water Quality Parameters

On 24 September 1982, water quality samples were collected from the top 10 cm of the water surface at each of 75 sample sites on the Neuse River Estuary (Figure 1). Samples were collected from 11 boats between 8:45 and 9:50 A.M. Landsat-3 overpass was at 9:08 A.M. EST. Surface truth data were collected by personnel from the Division of Environmental Management and the Division of Marine

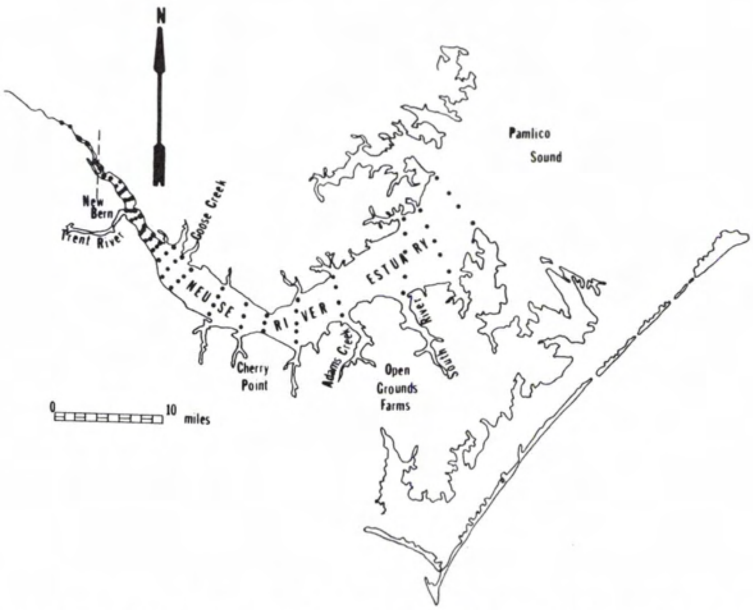

FIG. 1. Location of the water quality sampling stations and referenced features in the Neuse River Estuary. The study area extends from latitude 34° 53′ to 35° 12′ north and longitude 76° 25′ to 77° 10′ west. Sample stations were numbered one to 75 from west to east. The dashed line indicates the western limit of Landsat-3 coverage.

Fisheries, North Carolina Department of Natural Resources and Community Development (NRCD), and the Division of Inland Fisheries, North Carolina Wildlife Resources Commission (WRC).

Sample sites were plotted on nautical charts which were followed by the boat crews during water quality sample collection. To achieve maximum uniformity, a sampling procedure was prepared and distributed among all of the crews.

Following conventional survey techniques, all of the water quality samples were iced in the field and taken to the laboratory for analysis. Salinity measurements were made *in situ* using a conductivity bridge and were checked at NRCD's mobile laboratory which was stationed in New Bern, North Carolina during data collection. Chlorophyll *a* samples were also analyzed in the mobile laboratory immediately following data collection. Samples were collected by vacuum filteration on glass fiber filters, pretreated, and analyzed by the fluorometric method. Turbidity was measured using a Hach turbidometer. Total suspended solids were analyzed by the gravimetric method.

ACQUISITION AND ANALYSIS OF MULTISPECTRAL SCANNER DIGITAL DATA

The Multispectral Scanner carried by Landsat is a line scanning device which detects reflected energy in four spectral intervals or bands. These intervals are 0.5 to 0.6 micrometers (green); 0.6 to 0.7 micrometers (red); 0.7 to 0.8 micrometers (near-infrared); and 0.8 to 1.1 micrometers (near-infrared). The value recorded for each of these bands depends on the intensity or brightness of the reflecting objects. The effective ground resolution of the MSS detector is about 80 m. This single sample unit is referred to as a pixel (picture element). Landsat-3 orbits the Earth at an altitude of about 570 miles.

Landsat Computer Compatible Tapes (CCTs) were obtained from the Earth Resources Observation System (EROS) Data Center in Sioux Falls, South Dakota. Band 7 (infrared) of the Landsat data is shown in Figure 2. These data were reformatted to be compatible with our local image processing system at North Carolina State University.

A minimum of nine control points were located on the nautical charts and on each of the Landsat image files at full resolution. The water quality sample points were then located on the Landsat data through transformations to latitude and longitude. The coordinate transformation was based on a fifth-order polynomial regression equation.

The mean count values on all four MSS bands were extracted for the nine pixel blocks encompassing each sample site. These mean count values were used as independent variables in the regression models. The land/water interface was identified and masked so that only water would be analyzed. Pixel values corresponding to land were set to zero as a result of the masking function. The Landsat-3 MSS had line start problems which resulted in a loss of

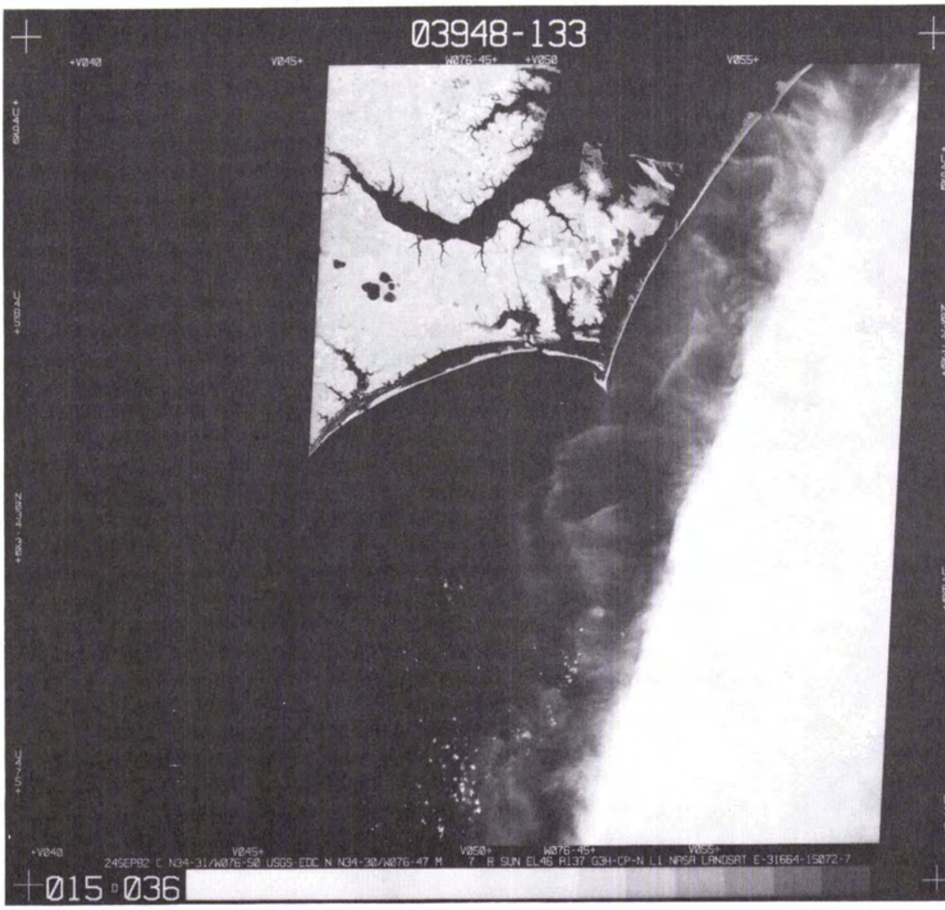

FIG. 2. Location of the study area on Landsat-3 raw data, band 7 (infrared). The clouds are apparent in the right margin of this image. The study area consists of just the Neuse River Estuary shown in Figure 1 (about 1 percent of the entire scene).

data for the first five sample points located above New Bern.

DEVELOPMENT OF WATER QUALITY MODELS

Of the original sample sites, the first five sites were outside the Landsat scene. The next two sample sites (#6 and #7) were dropped due to the high deviations between the single pixel count values for the sample sites and the mean count values for the nine pixel blocks (including the single pixel) encompassing these two sample sites. These discrepancies can be caused by noise in the MSS data. Because these deviations occurred only in the narrow part of the river above New Bern, they are more likely the result of spectral values from land being included in the nine pixel block.

For sampling strategy, the estuary was divided into three regions: up river (above Goose Creek); mid river (Goose Creek to Adams Creek); and near the mouth of the estuary (below Adams Creek) (see Figure 1 for locations.) The sample sites were further broken down to "near shore" and "near center channel." From these six categories, 46 sample sites were randomly selected for modeling. The remaining 22 sites were later used for verification of the models. Later, when there appeared to be a problem with modeling chlorophyll *a* and turbidity due to bottom reflectance, the 46 sites were further broken down by depth. Eighteen deep sites, greater than 10 feet in depth, were used in the development of the models for chlorophyll *a* and turbidity. For chlorophyll *a* and turbidity, verifications were made using only the 12 deep sites out of the 50 sites not used for modeling.

A series of statistical models developed by investigators in other geographic areas were first tested for their applicability in this area. These models were developed by Khorram (1981b, 1982) for salinity, turbidity, and suspended solids based on Landsat MSS data for the San Francisco Bay Delta. Also, Landsat MSS-based models developed to analyze turbidity in Lake Malaren, Sweden, by Lindell

(1981) were tested. Other multispectral scanners, such as the Ocean Color Scanner (OCS) and Daedalus DS-1250, have been used to map salinity, chlorophyll *a*, turbidity, and total suspended solids (Khorram, 1981a; Uno *et al.*, 1980). Spectral bands used in these investigations were combined to make the models compatible with Landsat MSS data. However, none of the previously developed models proved to be applicable to this geographic area. Factors which contributed to their failure may be the difference in physical, chemical, and biological conditions. Flow conditions and atmospheric conditions may also contribute to these failures.

Statistical analysis was done using the Statistical Analysis System (SAS). Correlation matrices were produced for all water quality parameters and for four MSS bands and a number of band combinations and ratios. The band combinations and ratios used included variations of models selected from previous work (Lindell, 1981; Khorram, 1981a, 1981b), as well as new combinations. The bands and band combinations chosen based on the correlation matrices were used in the SAS analysis of all possible combinations. The series of statistical models which resulted from this approach were examined for determining the best relationship between each of the water quality parameter measurements and the mean count values from Landsat bands 4, 5, 6, and 7, and their ratios and combinations.

The best regression fit for each one of the selected water quality parameters was determined based on R^2 values, the "F" values, the significance levels of these "F" values, the residual values, and the simplicity of the model. An effort was made to reduce collinearity between the independent variables. Models were verified by their application to the remaining sample sites that were not used for developing the models.

ACQUISITION AND ANALYSIS OF AERIAL PHOTOGRAPHY

Oblique color-infrared and vertical true color panoramic photography were obtained for the study area simultaneous with water quality sample collection. This photography was made using the EPA's Enviropod which was mounted on a Cessna 172 and flown at an altitude of 5000 ft. The Enviropod carries two reconnaissance cameras and is attached to the underside of the fuselage. The resultant high resolution, variable scale photography was visually interpreted for mapping the water quality parameters of interest.

Results and Discussion

The results of the laboratory analyses of the water quality samples for all 75 sample sites are shown in Table 1. The mean count values for the 68 sample sites used for the development and verification of models are shown in Table 2.

Results of the Landsat analysis include (1) a series

Table 1. Results of Water Quality Measurements from Sample Data Collected 24 September 1982

Boat #	Station #	Depth (feet)	Salinity (ppt)	Chlorophyll *a* (μg/l)	Turbidity (NTU)	Total Suspended Solids (mg/l)
1	1	—	0.00	15	5	3
	2	—	0.00	17	5	5
	3	—	0.00	14	4	4
	4	—	0.00	19	3	4
	5	—	0.00	12	4	2
	6	—	0.00	10	3	1
2	7	—	0.90	8	4	4
	8	13	1.10	12	4	4
	9	8	1.50	8	3	4
	10	8	1.80	8	4	3
	11	8	1.75	8	4	4
	12	7	1.85	8	4	3
	13	5	2.50	10	4	5
	14	7	2.60	12	4	5
	15	11	2.80	15	3	1
	16	4	2.80	12	4	6
3	17	7	3.00	10	3	5
	18	8	3.20	27	3	7
	19	4	3.90	14	2	5
	20	14	4.00	41	4	7
	21	9	4.10	15	3	6
	22	6	4.40	21	3	7
	23	7	4.10	58	4	8
	24	17	4.20	81	3	6
	25	3	4.30	17	2	6

TABLE 1.—*Continued*

Boat #	Station #	Depth (feet)	Salinity (ppt)	Chlorophyll *a* (μg/l)	Turbidity (NTU)	Total Suspended Solids (mg/l)
4	26	7	4.85	17	5	8
	27	12	5.00	46	4	9
	28	6	5.30	69	4	9
	29	9	5.30	41	4	8
	30	12	5.80	35	4	7
	31	3	6.80	58	3	9
	32	12	6.10	25	4	6
	33	10	6.80	31	3	9
	34	8	7.90	33	4	7
5	35	9	8.60	46	4	10
	36	9	8.10	19	3	7
	37	11	8.00	27	3	7
	38	7	9.10	52	4	10
	39	6	9.00	29	4	6
	40	12	9.60	33	4	7
	41	10	8.40	31	3	8
	42	5	11.00	39	5	8
6	43	8	9.40	23	4	7
	44	13	10.30	19	3	6
	45	13	11.00	25	3	4
	46	3	11.10	31	4	2
	47	10	9.80	25	4	6
	48	13	10.20	41	4	5
	49	14	12.20	35	4	8
7	50	3	9.90	21	5	8
	51	20	10.80	19	3	6
	52	8	12.90	27	3	5
	53	11	11.40	19	4	7
	54	14	11.40	37	4	10
	55	17	12.00	33	3	6
	56	14	12.20	19	3	6
	57	6	13.00	31	3	6
8	58	12	13.20	14	3	6
	59	13	13.70	25	2	8
	60	19	14.60	14	2	2
	61	9	15.20	17	2	7
9	62	3	14.60	25	2	21
	63	18	14.90	12	2	15
	64	22	17.00	11	2	12
	65	8	16.90	12	3	9
	66	6	16.70	19	4	12
10	67	15	15.20	14	2	8
	68	22	16.30	12	1	8
	69	22	17.20	12	2	7
	70	19	17.20	12	3	13
	71	2	16.80	11	3	15
11	72	7	17.90	7	2	10
	73	15	17.90	6	2	24
	74	22	17.90	10	2	6
	75	20	17.40	12	2	10

of models for predicting water quality parameters; (2) statistical summaries for the models and accuracy assessment; and (3) a series of color-coded maps of the Neuse River Estuary, each pertaining to a water quality parameter of interest.

The following models were selected to represent

TABLE 2. MEAN COUNT VALUES FOR THE NINE PIXEL BLOCK ENCOMPASSING EACH OF THE 68 SAMPLE SITES USED FOR ANALYZING LANDSAT-3 DATA

Station No.	Band 4	Band 5	Band 6	Band 7
8	13.333	8.555	5.777	4.000
9	13.555	8.888	6.111	2.333
10	12.555	9.555	6.444	3.888
11	13.333	10.222	6.444	2.777
12	12.333	8.555	5.888	3.666
13	13.333	8.111	6.222	3.222
14	14.888	10.555	7.111	4.777
15	13.111	8.555	6.333	4.111
16	12.888	9.111	6.111	2.444
17	12.666	8.222	5.777	3.555
18	12.333	8.666	5.888	3.666
19	13.666	8.333	6.333	3.333
20	13.111	9.111	6.666	4.111
21	12.666	8.666	5.666	3.444
22	13.222	8.666	6.222	4.000
23	13.888	8.777	6.777	4.111
24	12.444	9.444	6.000	4.000
25	13.666	8.333	5.555	3.888
26	13.111	9.000	6.444	3.888
27	13.222	9.222	7.111	2.777
28	13.444	8.555	6.111	2.555
29	13.444	9.111	5.777	2.777
30	13.666	8.777	5.555	3.333
31	13.555	9.222	6.222	3.333
32	13.555	8.555	5.111	3.000
33	13.333	8.555	5.222	3.333
34	13.000	9.000	6.111	3.222
35	13.555	8.444	5.666	3.444
36	12.444	9.222	4.888	2.000
37	12.444	9.333	5.444	2.333
38	12.777	8.777	5.333	4.000
39	13.222	8.777	5.777	3.000
40	12.555	9.333	5.111	1.666
41	13.111	8.777	5.444	2.888
42	13.777	9.222	5.666	3.666
43	13.777	9.000	5.111	3.444
44	12.444	8.666	4.333	1.333
45	13.000	8.444	4.444	2.777
46	14.222	9.111	5.111	3.000
47	13.111	8.888	6.222	2.111
48	13.888	9.000	5.444	2.555
49	14.000	9.000	4.888	2.777
50	13.111	8.888	5.333	3.000
51	13.666	9.222	5.555	2.777
52	13.888	9.000	5.666	3.000
53	13.666	9.000	5.666	2.444
54	13.666	9.000	5.000	3.333
55	12.777	8.888	5.111	1.888
56	13.222	9.444	5.555	3.222
57	13.444	9.111	5.111	2.888
58	14.666	10.111	5.222	3.111
59	12.777	8.777	4.333	2.111
60	13.444	8.777	4.666	2.000
61	14.000	8.777	4.000	2.666
62	13.666	9.888	4.666	3.333
63	14.555	9.555	5.111	2.000
64	14.777	10.000	4.111	2.555
65	14.888	9.777	4.222	2.555
66	16.666	10.666	5.000	2.111
67	13.888	8.888	4.333	1.777
68	15.111	9.666	4.333	2.555
69	14.000	8.666	4.222	2.888
70	13.555	9.555	4.666	1.888
71	16.555	11.333	5.111	2.111
72	14.666	10.333	4.888	2.444
73	14.666	9.555	4.111	2.000
74	14.000	8.888	4.333	1.000
75	14.555	9.444	4.333	2.111

the best statistical relationship between the water quality measurements obtained from boats and the mean count values of the corresponding Landsat MSS data.

SALINITY MODEL

$Y_{SAL} = a - bx_1$

where Y_{SAL} = salinity expressed in parts per thousand,

x_1 = Band 6/(Band 4 + Band 5), and

$a = 38.52$ and $b = 120.86$.

CHLOROPHYLL *a* MODEL

$Y_{LCH} = a + bx_1 - cx_2 - dx_3^2$

where Y_{LCH} = the natural log of chlorophyll *a* concentrations expressed in ug/l,

x_1 = Band 4/Band 5,

x_2 = Band 4 × Band 6 × Band 7,

x_3 = Band 4/(Band 5 + Band 6 + Band 7), and

$a = 2.14$, $b = 5.19$, $c = 0.01$, and $d = 7.74$.

TURBIDITY MODEL

$Y_{TURB} = -a + bx_1 - cx_2 + dx_3 - ex_4$

where Y_{TURB} = turbidity expressed in Nephelometric Turbidity Units,

x_1 = [Band 4 − (Band 5 × Band 7)] /[Band 5 − (Band 6 × Band 7)],

x_2 = Band 4/Band 6,

x_3 = Band 4/(Band 4 + Band 5 + Band 6),

x_4 = [Band 4 − (Band 5 × Band 6)] /[Band 5 − (Band 6 × Band 7)], and

$a = 4.54$, $b = 0.09$, $c = 0.43$, $d = 21.9$, and $e = 0.03$.

SUSPENDED SOLIDS MODEL

$Y_{SS} = a - bx_1 + cx_2 + dx_3 + ex_4 - fx_5 + gx_6$

where Y_{SS} = suspended solids expressed in mg/l,

x_1 = [Band 4 − (Band 5 × Band 7)] /[Band 5 − (Band 6 × Band 7)],

x_2 = (Band 5/Band 6)^2,

x_3 = (Band 5 − Band 6)/(Band 6 − Band 7),

x_4 = Band 5/(Band 4 + Band 5 + Band 6),
x_5 = (Band 6/Band 4) + (Band 5/Band 6),
x_6 = [Band 4 − (Band 5 × Band 6)] /[Band 5 − (Band 6 × Band 7)], and
$a = 285.65$, $b = 1.22$, $c = 85.80$, $d = 2.47$, $e = 1203.36$, $f = 439.21$, and $g = 0.19$.

The relationship between actual values measured at the sample sites and values predicted by the models is shown in Figure 3. The coefficients of determination (R^2), the corresponding "F" values, the root-mean-square errors and residual ranges for all four water quality models are shown in Table 3. All of the "F" values were statistically significant at the 0.01 level. The coefficients of determination for the best models were observed to be high for salinity, relatively high for chlorophyll *a* and turbidity, and medium for total suspended solids. Correlations between the various parameters and the four Landsat bands are shown in Table 4. All the parameters in the models for salinity, chlorophyll, and total suspended solids were significant at the 95 percent confidence level using the T-test. In the turbidity model, two parameters (X_1 and X_4) were not significant at the 95 percent level.

The bottom reflectance in shall parts of the estuary appeared to have some influence (depending

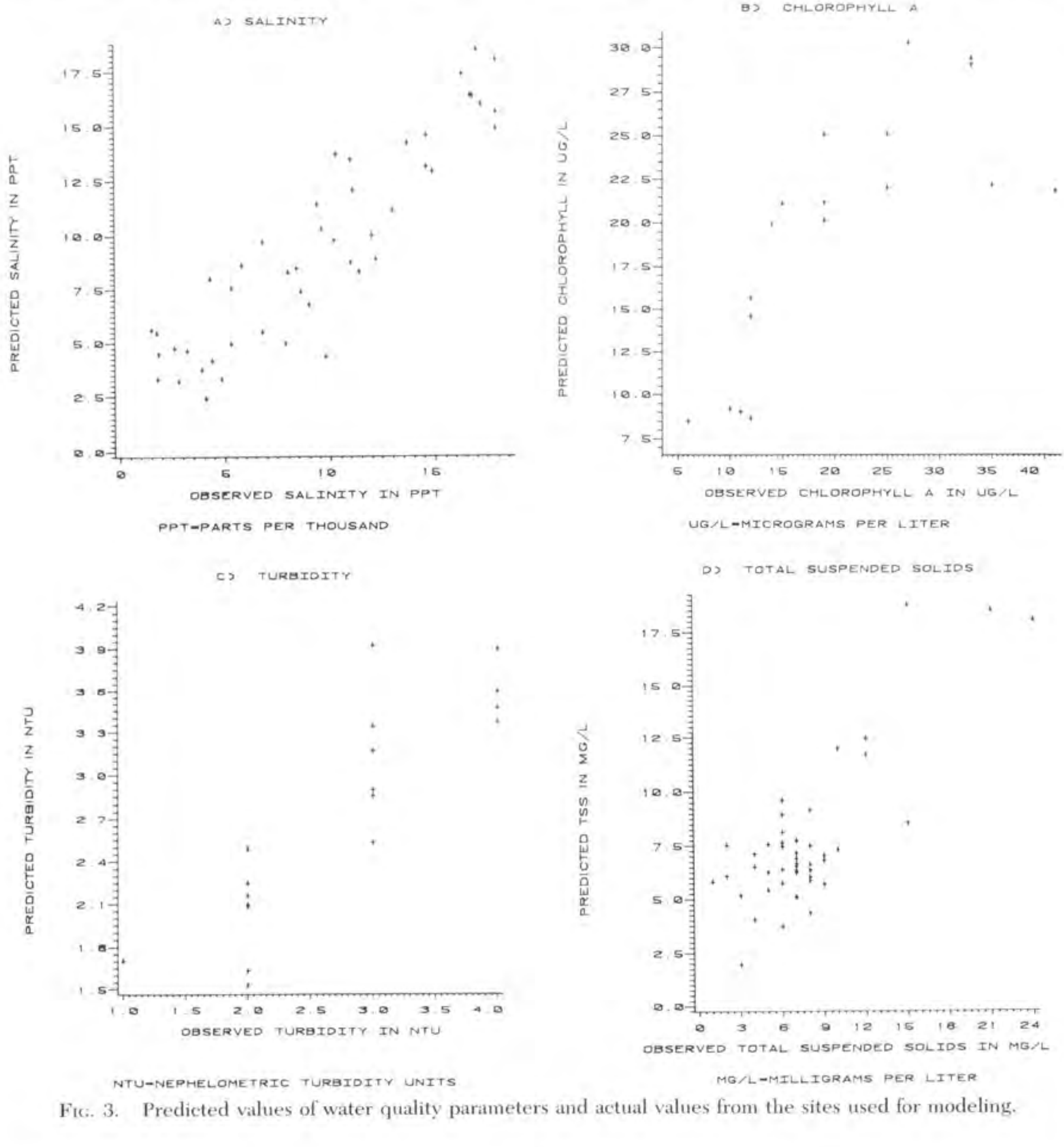

FIG. 3. Predicted values of water quality parameters and actual values from the sites used for modeling.

TABLE 3. STATISTICAL SUMMARY FOR REGRESSION MODELS BASED ON LANDSAT DATA

	df	R^2	F	Prob. > F	RMSE	Residual Ranges
Salinity	45	0.82	199.77	0.0001	2.21	−1.57 to 2.53
Chlorophyll *a*	17	0.70	11.01	0.0003	0.31	−1.52 to 2.14
Turbidity	17	0.76	10.17	0.0004	0.50	−2.07 to 1.59
Total Suspended Solids	45	0.64	11.72	0.0001	2.79	−2.13 to 2.58

on depth and transparency) on the relationship developed between some of the water quality parameters and the multispectral data. Stratification of the sample sites by depth consistently yielded better results in the development of models used for predicting chlorophyll *a* and turbidity. Bottom effects were not quantified and the data from shallow sites were not used as input in model development. This may make the performance of models unreliable in areas near the shoreline. However, most of the area of concern is greater than 10 feet in depth; therefore, the models were applied to the entire study area. However, for total suspended solids, no relationship appeared to exist between the depth of the sample sites and model development or reliability. Suspended organic and inorganic matter appeared to have contributed to the spectral response used for developing models. Although an effort was made to identify the "simplest" model, the regression model developed for suspended solids over the Neuse River Estuary was complex.

On the chlorophyll model, Landsat bands 4 and 5 correspond to wavelengths absorbed by chlorophyll and appear to be sensitive to changes in chlorophyll *a* at lower concentrations. In the case of salinity, there may be one or more surrogate parameters which influence reflectance in the visible wavelengths (bands 4 and 5). Turbidity was found to be correlated with salinity but the low range of turbidity values make any conclusions difficult.

For verification of the results, the original models were applied to the remaining sample sites, which were not used for the development of these models. The models for chlorophyll *a* and turbidity (which were developed using deep sites) were verified using the remaining deep sites. The statistical summaries for the verification are shown in Table 4. The coefficient of determination for verification of the salinity model remains relatively high. However, R^2 values for chlorophyll *a* and total suspended solids are relatively low. The relationships between actual values measured at the sample sites used in verification and values predicted by the models are shown in Figure 4.

The relationships established between the surface measurements and the Landsat digital data were extended to the entire study area (the Neuse River Estuary) and to the immediate surroundings, producing a series of class maps which were grouped and color-coded to represent the distribution of water quality parameters. The maps for salinity, chlorophyll *a*, turbidity, and total suspended solids are shown in Plates 1, 2, 3, and 4, respectively. The color changes in the right margin, east of the barrier islands in these figures, is caused by the cloud cover and should not be interpreted as water quality information. The extent of the cloud cover is shown in Figure 2.

The distributions of these surface water quality parameters throughout the Neuse River Estuary, as shown on these maps, are in complete agreement with the expected and reported values of these parameters in this geographic region. According to salinity model output, as shown on the color-coded map, salinity increases from west to east with values greater than 16 ppt occurring where the Neuse River enters Pamlico Sound. The Trent River enters the estuary at New Bern (Figure 1). Below the Trent River, the main flow of the river hugs the west bank. In this area, lower salinity and chlorophyll *a* concentrations are evident. In this same area, turbidity values (shown in red on the color-coded map) are high.

Near the mouth of the Neuse River, South River flows into the estuary from the south. The land below the estuary at this point is dominated by Open Grounds, a corporate farming enterprise. This major agricultural development covers over 50

TABLE 4. STATISTICAL SUMMARY FOR VERIFICATION OF REGRESSION MODELS USING SITES WHICH WERE NOT USED FOR MODELING

	df	R^2	F	Prob. > F	RMSE	Residual Ranges
Salinity	21	0.76	69.22	0.0001	2.60	−2.09 to 2.02
Chlorophyll *a*	11	0.48	2.49	0.127	0.545	−1.97 to 1.33
Turbidity	11	0.72	4.56	0.036	0.514	−1.60 to 1.46
Total Suspended Solids	21	0.47	2.25	0.0884	1.86	−1.79 to 1.88

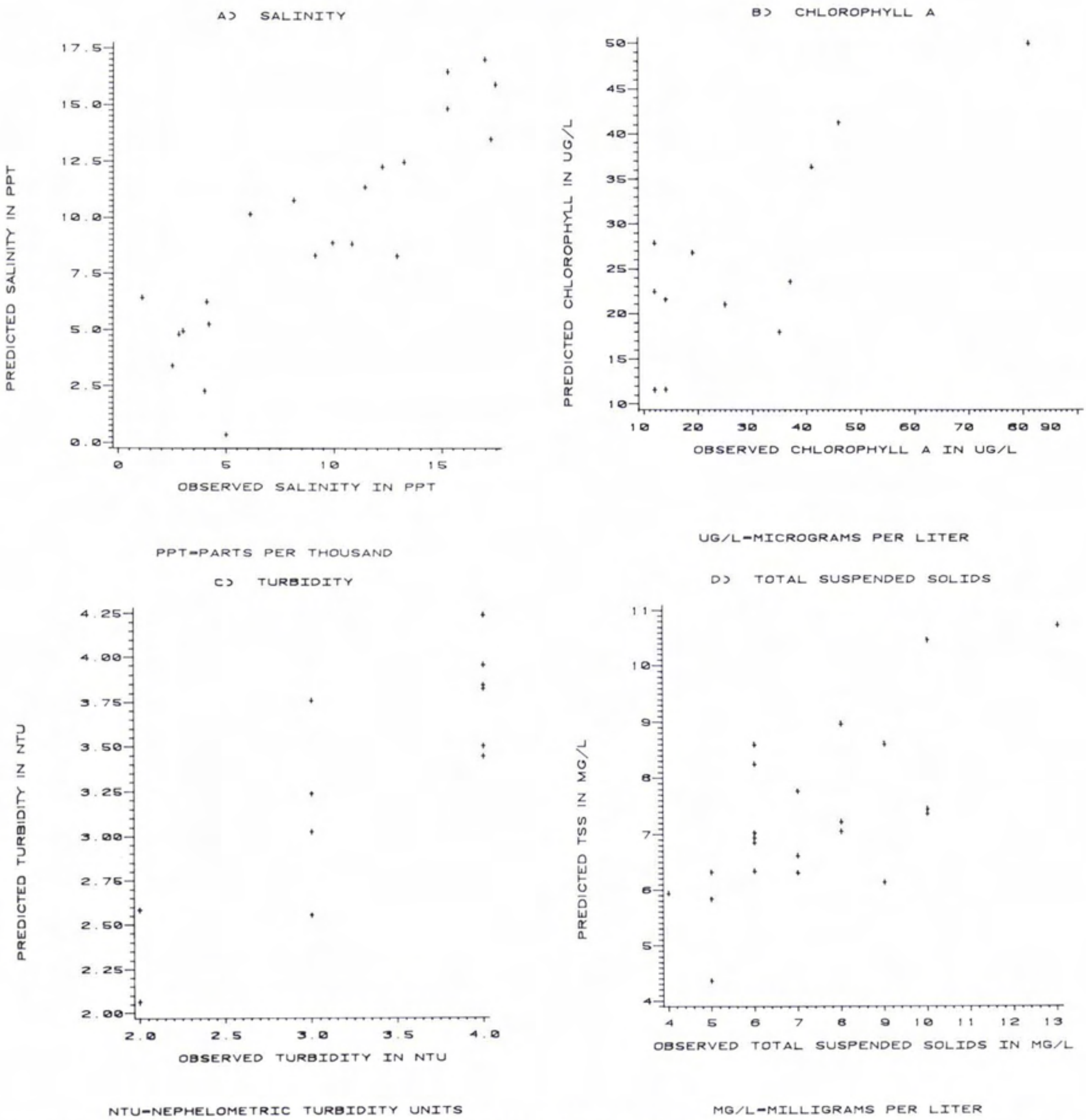

FIG. 4. Predicted values of water quality parameters and actual values from sites used for model verification.

TABLE 5. CORRELATION MATRIX FOR THE VARIOUS PARAMETERS AND THE LANDSAT BANDS

	*FLDCON	CHLOR	TSS	TURB	BAND 4	BAND 5	BAND 6	BAND 7
*FLDCOND	1.0000	−0.1255	0.5898	−0.5618	0.6085	0.4226	−0.8042	−0.6350
CHLOR	−0.0855	1.0000	0.0844	0.2764	−0.2372	−0.1999	0.1587	0.1101
TSS	0.5898	0.0844	1.0000	−0.2878	0.4360	0.4126	−0.4232	−0.3268
TURB	−0.5618	0.2764	−0.2878	1.000	−0.2423	−0.0872	0.4941	0.3015
BAND 4	0.6085	−0.2372	0.4360	−0.2423	1.0000	0.6435	−0.3096	−0.2120
BAND 5	0.4226	−0.1999	0.4126	−0.0872	0.6435	1.0000	−0.0929	−0.1444
BAND 6	−0.8042	0.1587	−0.4232	0.4941	−0.3096	−0.0929	1.0000	0.7413
BAND 7	−0.6350	0.1101	−0.3268	0.3015	−0.2120	−0.1444	0.7413	1.0000

* Salinity was calculated directly from field conductivity.

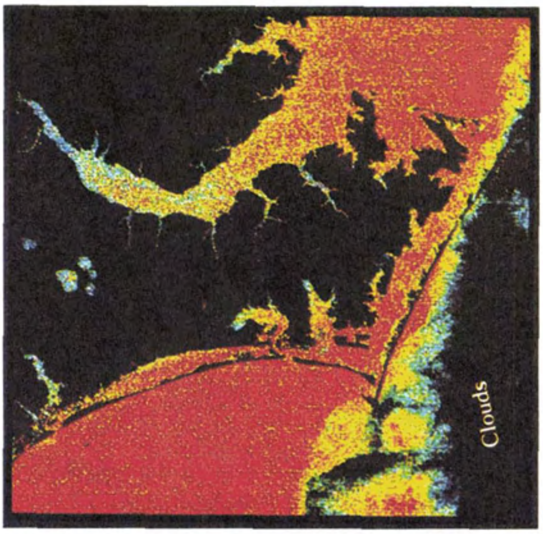

PLATE 1. Salinity distribution over the study area as derived from Landsat digital data.

Color-code	*Salinity in ppt*
Blue	<5.0
Cyan	5.0-8.0
Green	8.1-11.0
Yellow	11.1-16.0
Red	>16.0

PLATE 2. Chlorophyll distribution over the study area as derived from Landsat digital data.

Color-code	*Chlorophyll a in ug/l*
Blue	<20.0
Cyan	20.0-40.0
Green	40.1-60.0
Yellow	60.1-80.0
Red	>80.0

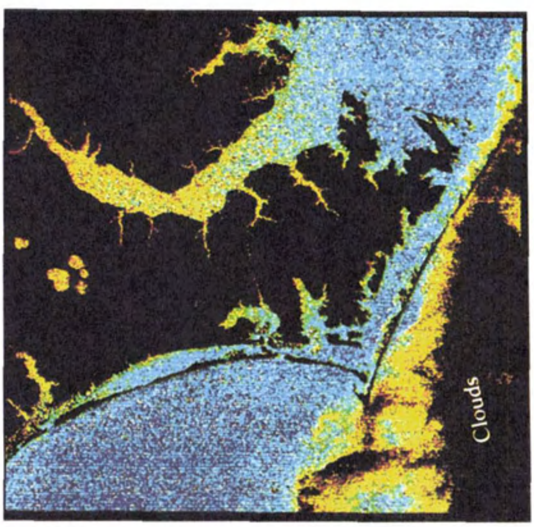

PLATE 3. Turbidity distribution over the study area as derived from Landsat digital data.

Color-code	*Turbidity in NTU*
Blue	<1.0
Cyan	1.0-2.0
Green	2.1-3.0
Yellow	3.1-4.0
Red	>4.0

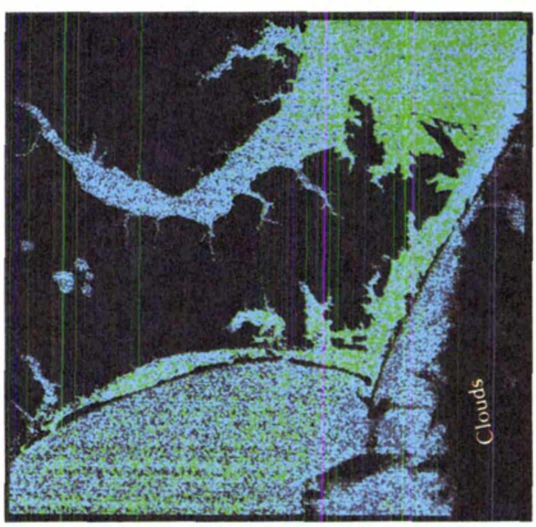

PLATE 4. Total suspended solids distribution over the study area as derived from Landsat digital data.

Color-code	*Suspended Solids in mg/l*
Blue	<5.0
Cyan	5.0-15.0
Green	>15.0

square miles at the headwaters of Adams Creek and South River. The high chlorophyll *a* concentrations in the South River, shown in red on the color-coded map, appeared to be caused by the runoff from Open Grounds to this river. A patch of high chlorophyll *a* concentration also appears in the river above New Bern.

Total suspended solids were not mapped with as much detail as the other three parameters. However, the distribution of the concentrations, as mapped, is consistent with the trends measured in the field through the use of conventional techniques. Data collected at NRCD's ambient stations indicate that most of the tributaries like the South River contain dissolved solids instead of suspended solids. This is apparent on the suspended solids map.

Although our study did not call for collecting water quality samples and mapping water quality parameters for areas outside the Neuse River Estuary, we extended our models to other areas including part of Pamlico Sound. The color-coded water quality maps include these areas. The results for areas within the original study area as well as the areas outside the study area are in agreement with the expected values and reported values of water quality parameters in this region (unpublished data, collected by DEM-NRCD and Duke Marine Lab). This indicates that these models may be successfully extended to the Pamlico Sound, although further research is needed before this conclusion can be reached.

Conclusions

To the best of our knowledge, this study constitutes the first time Landsat digital data have been used to map water quality parameters in this geographic area. Research on the distribution of surface water quality parameters on the Neuse River Estuary is needed for monitoring water quality and determining environmental impacts of land-use practices on this estuary. The environmental impacts may become more pronounced by the projected land developments in the upper Neuse River watershed.

For years, water quality mapping has been based on point sampling and interpolation techniques. The large size of estuaries and the spatial variability of water quality parameters has limited the effectiveness of this technique. This study has demonstrated the usefulness of Landsat digital data in mapping surface water quality parameters over such large areas.

Based on the results of this study, the following conclusions were reached:

- Landsat digital data can be successfully used to map some surface water quality parameters in this geographic region.
- The coefficients of determination (R^2) were observed to be high for salinity and turbidity, relatively high for chlorophyll *a*, and medium for total suspended solids. In the case of salinity, the MSS data are thought to be measuring one or more parameters related to salinity, such as turbidity.
- No quantitative assessment could be made of the surface water quality parameters by visual interpretation of aerial imagery.
- Additional studies are needed at different times of the year and under different flow conditions in order to develop generalized models.
- Further studies using Landsat data for surface water quality mapping should investigate the use of Landsat-4 Thematic Mapper data, particularly for mapping chlorophyll *a* and total suspended solids.
- Repetitive remotely-sensed data may be considered by agencies as having the potential to provide an alternative method for gathering and processing surface water quality information.

Recommendations

In addition to the MSS, the Landsat-5 satellite carries a Thematic Mapper (TM) with 30-metre resolution. The TM is a line scanning device which detects reflected energy in six visible and reflected infrared bands, which have a narrower range than the four MSS bands, and one thermal band. More accurate models for chlorophyll *a* and turbidity concentrations have been developed using Ocean Color Scanner (OCS) data (Khorram, 1981a) which has narrower wavelength ranges such as TM data. Landsat TM data may produce better results for chlorophyll *a* and turbidity due to the improved spatial (30 m versus 80 m), spectral (7 channels versus 4 channels), and radiometric (8 bit versus 7 bit) characteristics of the data.

For distributions of total suspended solids, a less complex model may be developed with the narrower band widths provided by the Landsat-4 TM data without sacrificing any reliability. Additional laboratory analysis of suspended solids along with multiband radiometric data may be used to identify those suspended materials which contribute most to the spectral response.

Results of this study indicate that data collected by Landsat satellites may provide a means for developing more timely and cost-effective methods for gathering and displaying important surface water quality information. However, more research is needed to develop a series of generalized models for this geographic area. Conditions in the Neuse River and other North Carolina coastal water vary considerably at different times of the year and under different flow conditions. Additional studies are needed to determine the effects of seasonal and climatic changes on data collection and analysis.

Landsat data which have been available for the past decade may also provide a means for monitoring slowly progressing changes which are occurring in coastal waters. The cumulative effects of years of upstream development and land-use changes are apparent in many North Carolina estuaries. Time sequence studies may help provide a better understanding of how these changes affect water quality over time.

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