ASSIMILATIVE CAPACITY OF THE WACCAMAW RIVER AND THE ATLANTIC INTRACOASTAL WATERWAY NEAR MYRTLE BEACH, SOUTH CAROLINA, 1989-92

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 95-4111

Prepared in cooperation with the
WACCAMAW REGIONAL PLANNING AND DEVELOPMENT COUNCIL

ASSIMILATIVE CAPACITY OF THE WACCAMAW RIVER AND THE ATLANTIC INTRACOASTAL WATERWAY NEAR MYRTLE BEACH, SOUTH CAROLINA, 1989-92

By Paul A. Drewes and Paul A. Conrads

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 95-4111

Prepared in cooperation with the
WACCAMAW REGIONAL PLANNING AND DEVELOPMENT COUNCIL

Columbia, South Carolina
1995

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, *Secretary*

U.S. GEOLOGICAL SURVEY

Gordon P. Eaton, *Director*

For additional information write to:

District Chief
U.S. Geological Survey
Stephenson Center- Suite 129
720 Gracern Road
Columbia, SC 29210-7651

Copies of this report can be purchased from:
U.S. Geological Survey
Earth Science Information Center
Open-File Reports Section
Box 25286, Mail Stop 517
Denver Federal Center
Denver, CO 80225

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS--Continued

TABLES

CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	To obtain
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per second (ft/s)	0.3048	meter per second
mile (mi)	1.609	kilometer
million gallons per day (Mgal/d)	0.04381	cubic meter per second
pound avoirdupois (lb avdp)	0.4536	kilogram
square foot (ft^2)	929.0	square centimeter
square foot (ft^2)	0.09294	square meter
square foot per second (ft^2/s)	0.09294	square meter per second
square mile (mi^2)	2.590	square kilometer

Temperature: In this report, temperature is given in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by the following equation:

$$°F = 1.8\ (°C) + 32$$

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from a general adjustment of the first-order level nets of both the United State and Canada, formerly called Sea Level Datum of 1929.

Water Year: The 12-month period October 1 through September 30. The water year is designated by the calendar year in which it ends and that includes 9 of the 12 months.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Other units used in report:

milligram = mg
milligrams per liter = mg/L
pounds per day = lb/d

Abbreviations used in this report:

ADR - analog digital recorders
AIW - Atlantic Intracoastal Waterway
BLTM - Branched Lagrangian Transport Model
BOD - biochemical oxygen demand
BOD_5 - five-day biochemical oxygen demand
CBOD - carbonaceous biochemical oxygen demand
DCP - data-collection platforms
DIS-P - dissolved phosphorous
FW - freshwater
K - Specific conductance, microseimens
N - nitrogen
NH_3 - ammonia
NO_2 - nitrite
NO_3 - nitrate
NPDES - National Pollutant Discharge Elimination System
ON - organic nitrogen
O_2 - oxygen
pH - in units
SA - tidal saltwaters suitable for primary and secondary contact
SCDHEC - South Carolina Department of Health and Environmental Control
SOD - sediment oxygen demand
T - water temperature, degrees Celsius
UOD - ultimate oxygen demand
USACOE - U.S. Army Corps of Engineers
USGS - U.S. Geological Survey
1-D - One-dimensional

ASSIMILATIVE CAPACITY OF THE WACCAMAW RIVER AND THE ATLANTIC INTRACOASTAL WATERWAY NEAR MYRTLE BEACH, SOUTH CAROLINA, 1989-92

By Paul A. Drewes and Paul A. Conrads

ABSTRACT

The assimilative capacities of selected reaches of the Waccamaw River and the Atlantic Intracoastal Waterway near Myrtle Beach, South Carolina, were determined using results from water-quality simulations by the Branched Lagrangian Transport Model. The study area included tidally influenced sections of the Waccamaw River, the Pee Dee River, Bull Creek, and the Atlantic Intracoastal Waterway. Hydrodynamic data for the Branched Lagrangian Transport Model were simulated using the U.S. Geological Survey BRANCH one-dimensional unsteady-flow model. Assimilative capacities were determined for four locations using low-, medium-, and high-flow conditions and the average dissolved-oxygen concentration for a 7-day period. Results indicated that for the Waccamaw River near Conway, the ultimate oxygen demand is 370 to 6,740 pounds per day for 7-day average streamflows of 17 to 1,500 cubic feet per second. For the Waccamaw River at Bucksport, the ultimate oxygen demand is 580 to 7,300 pounds per day for 7-day average streamflows of 62 to 1,180 cubic feet per second. For the Atlantic Intracoastal Waterway near North Myrtle Beach, simulations indicate ultimate oxygen demand is 5,100 to 10,000 pounds per day for 7-day average streamflows of 110 to 465 cubic feet per second. The ultimate oxygen demand for the Waccamaw River near Murrells Inlet is 11,000 to 230,000 pounds per day for 7-day average streamflows of 2,240 to 13,700 cubic feet per second.

INTRODUCTION

The Grand Strand is a rapidly growing resort area in Horry and Georgetown Counties on the northeastern coast of South Carolina. It includes the cities of Myrtle Beach and North Myrtle Beach, and several other coastal communities. The Grand Strand is bounded on the west by the Atlantic Intracoastal Waterway (AIW) and the Waccamaw River; on the south by Winyah Bay; on the east by the Atlantic Ocean; and on the north by Little River Inlet (fig. 1). As the Grand Strand continues to grow, there are increasing demands on the water resources in the area. The AIW, Bull Creek, and the Waccamaw River are receiving streams for municipal wastewater-treatment plants. In order to protect the aquatic life of these streams, there is a need to determine the quantity of treated wastewater that the AIW and its tributaries in the Grand Strand area can assimilate without violating State water-quality standards. Many municipalities in the Grand Strand area have either constructed new wastewater-treatment facilities or are investigating construction of additional facilities. The U.S. Geological Survey (USGS), in cooperation with the Waccamaw Regional Planning and Development Council, initiated an investigation to determine the capability of the surface-water systems to assimilate treated wastewater from various locations within the Grand Strand.

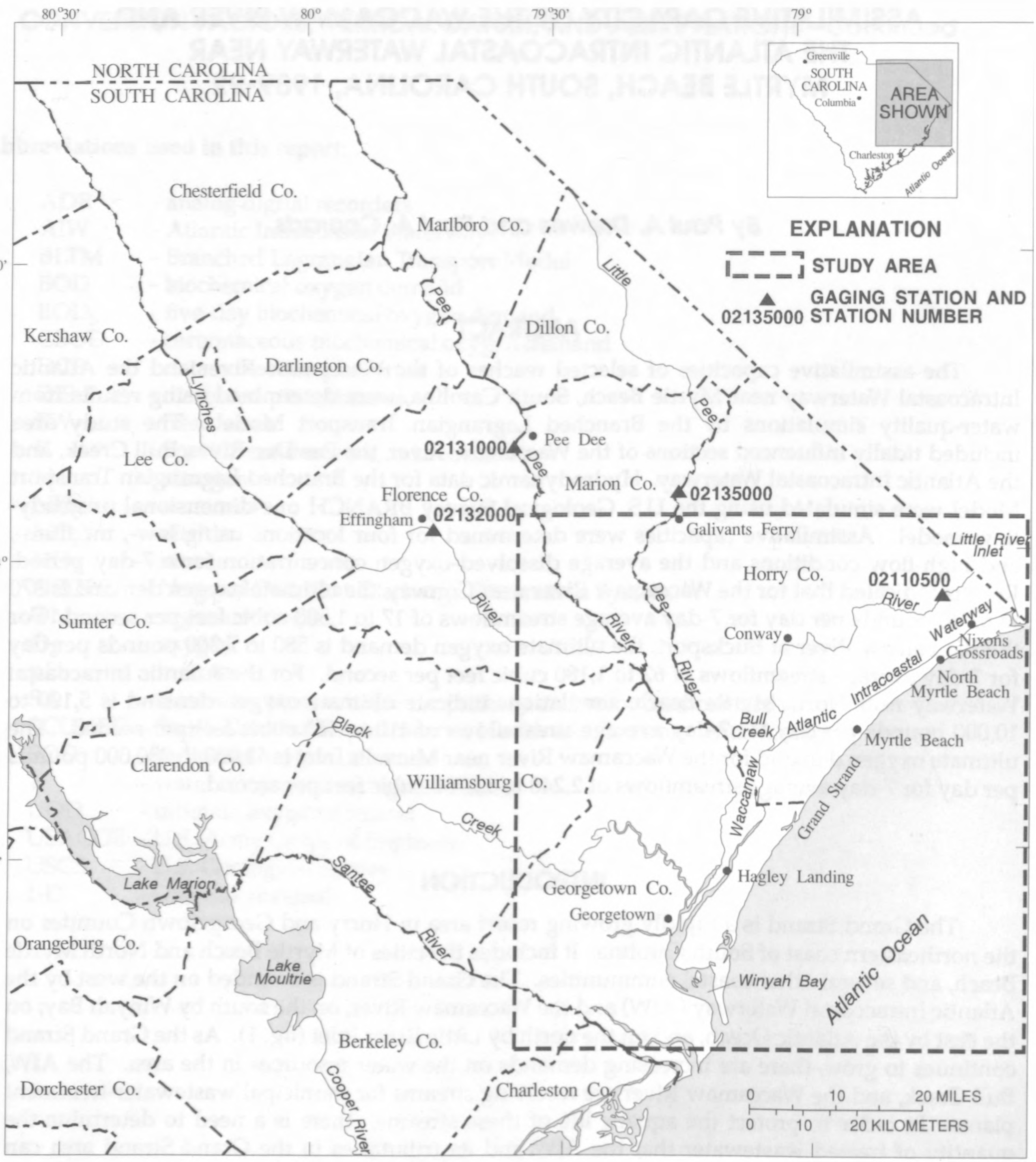

Figure 1.--Location of study area and streamflow gaging stations on rivers and major tributaries contributing flow to the study area.

Purpose and Scope

This report describes the results of an investigation to determine the assimilative capacity of the AIW and tidally affected reaches of the Waccamaw River. The calibration and verification of the one-dimensional unsteady-flow model (BRANCH) (Schaffranek and others, 1981) and the water-quality transport model, the Branched Lagrangian Transport Model (BLTM) (Jobson and Schoellhamer, 1987), are documented. Estimates of ultimate oxygen demands (UOD) were developed from water-quality modeling results to determine the assimilative capacity at various locations and flows within the Grand Strand.

Previous Studies

Effluent-discharge limits in the Grand Strand area are currently (1995) based on a steady-state water-quality model (Moore, Gardner, and Associates, 1975). The steady-state model does not have the ability to vary the assimilative capacity with time. Carswell and others (1988) documented the variability in streamflow of the AIW, and suggested that a determination of varying assimilative capacity could be obtained by using an unsteady water-quality model that accurately simulates the dynamic nature of the system.

Acknowledgments

The authors would like to thank Jan Davis, Waccamaw Regional Planning and Development Council, who provided support and coordination of all participants in the project and arranged quarterly status meetings. The authors are indebted to Larry Turner of the S.C. Department of Health and Environmental Control (SCDHEC), for providing technical assistance and information on effluent releases, and to Terry Sicherman, formerly of SCDHEC, for her valuable technical assistance. The U.S. Army Corps of Engineers (USACOE), Charleston District, supplied data on the channel geometry along the AIW from the Waccamaw River to Little River Inlet.

DESCRIPTION OF STUDY AREA

The study area is located in Horry and Georgetown Counties in the northeastern Coastal Plain of South Carolina in the lower part of the Pee Dee and Waccamaw River Basins (fig. 1). The Pee Dee River Basin (approximately 13,000 mi^2) and Waccamaw River Basin (approximately 1,300 mi^2) supply freshwater inflow to the system. Saltwater enters the system through Winyah Bay to the south and Little River Inlet to the north. The AIW is affected by tides throughout its entire reach with a mean tide range of 4.0 ft at Nixons Crossroads and 3.5 ft at Hagley Landing (National Oceanic and Atmospheric Administration, 1994). The Pee Dee and Waccamaw Rivers are tidally affected within the study area during low and medium streamflows. Extensive swamps border much of the study area to the northwest and south.

As the Pee Dee River enters the study area, it branches into three smaller creeks (fig. 2). The first branch south of the U.S. Highway 701 bridge forms Bull Creek. The second branch forms Thoroughfare Creek, and a third branch forms Schooner Creek. The three creeks eventually flow into the AIW, and the net flow from these creeks is to the south through Winyah Bay. The majority of freshwater flow to the AIW from the Pee Dee River Basin is carried by Bull Creek. The annual average streamflow from the Pee Dee Basin upstream of the study area is about 14,100 ft^3/s, which is the combined streamflow of the three major rivers (Pee Dee, Little Pee Dee, and Lynches Rivers) (Carswell and others, 1988) (table 1).

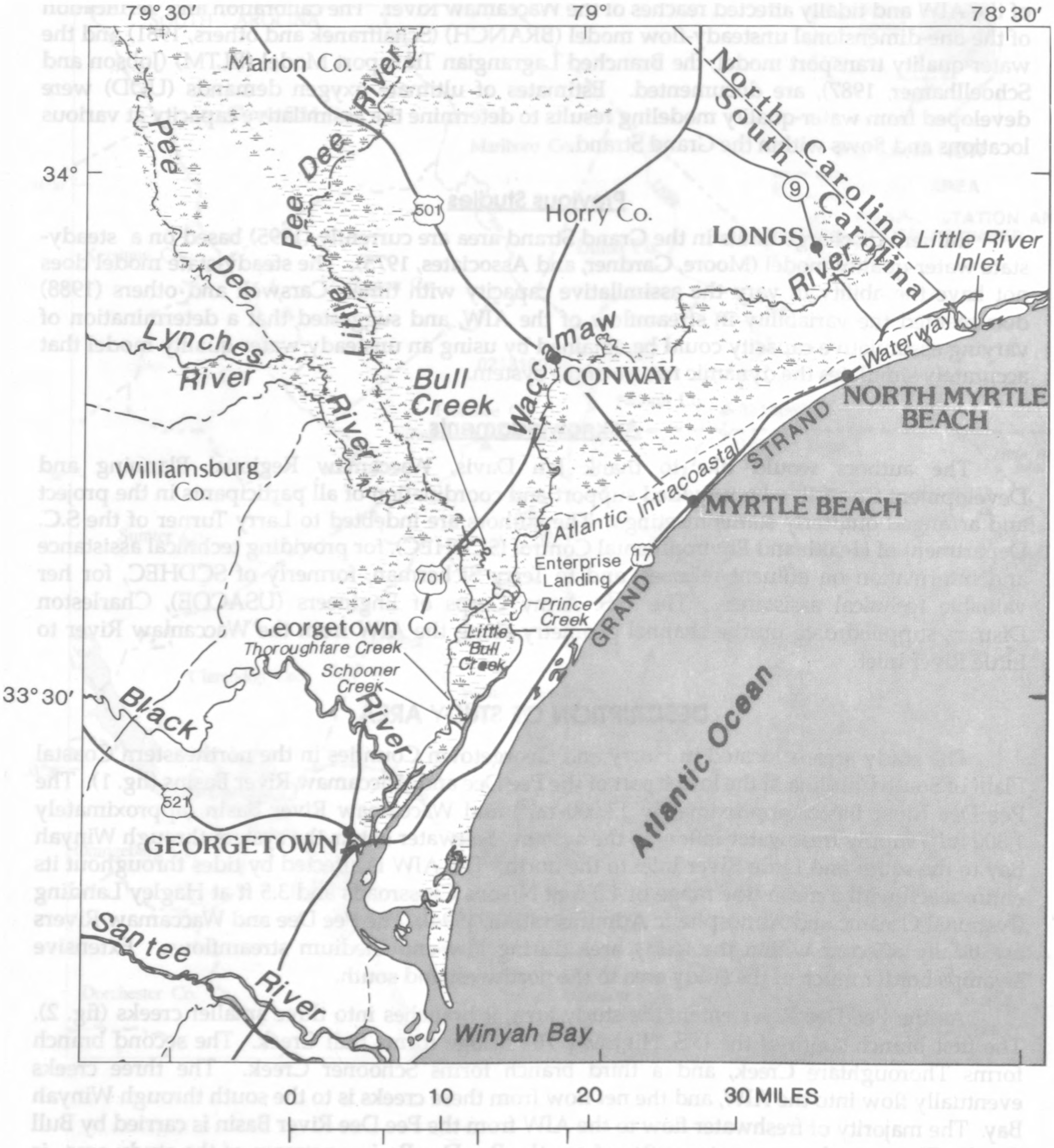

Figure 2.--Study area.

Table 1.--*Drainage area and annual average streamflow on major tributary streams of the Atlantic Intracoastal Waterway in the vicinity of Myrtle Beach, S.C.*

Station number (fig. 1)	Station name	Drainage area (square miles)	Annual average streamflow (cubic feet per second)
	Waccamaw River Basin		
02110500	Waccamaw River near Longs, S.C.	1,110	1,220
	Pee Dee River Basin		
02131000	Pee Dee River at Pee Dee, S.C.	8,830	9,870
02132000	Lynches River at Effingham, S.C.	1,030	1,040
02135000	Little Pee Dee River at Galivants Ferry, S.C.	2,790	3,200
Totals for Pee Dee River Basin		12,650	14,100

The Waccamaw River originates in North Carolina and enters the AIW about 10 miles north of the mouth of Bull Creek. Prior to the 1930's, the Waccamaw River flowed to the south towards Winyah Bay. In the 1930's, the USACOE constructed a canal to form the AIW from Enterprise Landing to Little River Inlet. The reach of the Waccamaw River from the confluence with the AIW south to Winyah Bay, is commonly referred to as the Waccamaw River and the AIW. The annual average streamflow of the Waccamaw River at Longs, S.C., upstream of the study area, is 1,220 ft^3/s (Carswell and others, 1988).

Withdrawals from the study area include 15 Mgal/d by a water-treatment facility located on Bull Creek, and 20 Mgal/d by a water-treatment facility located along the AIW near 10th Avenue North, Myrtle Beach. Nine facilities are permitted to discharge wastewater effluent into the Waccamaw River and the AIW at seven locations. The current National Pollutant Discharge Elimination System (NPDES) permit limits for wastewater-treatment facilities are listed in table 2 and the locations are shown in figure 3.

Table 2.--*Current National Pollutant Discharge Elimination System permit limits for wastewater-treatment facilities in the Waccamaw River and the Atlantic Intracoastal Waterway, April 7, 1993*

[Mgal/d, million gallons per day; BOD_5, biochemical oxygen demand; NH_3-N, ammonia-nitrogen; DO, dissolved oxygen; UOD, ultimate oxygen demand; AIW, Atlantic Intracoastal Waterway; NPDES, National Pollutant Discharge Elimination System; mg/L, milligrams per liter; lb/d, pounds per day]

Site (fig. 3)	Receiving waters	Effluent (Mgal/d)	Current NPDES permit limits[1]			
			BOD_5 (mg/L)	NH_3-N (mg/L as N)	DO (mg/L)	UOD (lb/d)
1	Waccamaw River	2	30	20	5	2,252
2	Waccamaw River	1.2	30	20	1	1,351
3	Waccamaw River	.2	30	20	1	228
[2]4	Waccamaw River	17	30	11	4	13,511
[2]4	Waccamaw River	9.5	21.3	15	4	7,871
[2]4	Waccamaw River	.75	30	10	1	563
5	Waccamaw River	2	30	20	1	2,275
6	AIW	2.1	10	2	6	423
7	AIW	3.4	10	2	6	685

[1]L.E. Turner, S.C. Department of Environmental Control, written commun., 1993

[2]Site 4 includes three permitted discharges at one location.

APPROACH

The assimilative capacity of a stream is its ability to absorb a particular pollutant, usually as it relates to a minimum instream water-quality standard. The ability of a stream to assimilate oxygen-demanding substances is a function of streamflow, temperature, velocity, depth, and channel configuration, along with its ability to absorb oxygen from the atmosphere. In terms of water management, this capacity is expressed in terms of pounds per day (lbs/d) of UOD that can be assimilated at certain streamflows without causing a violation of the State water-quality standards.

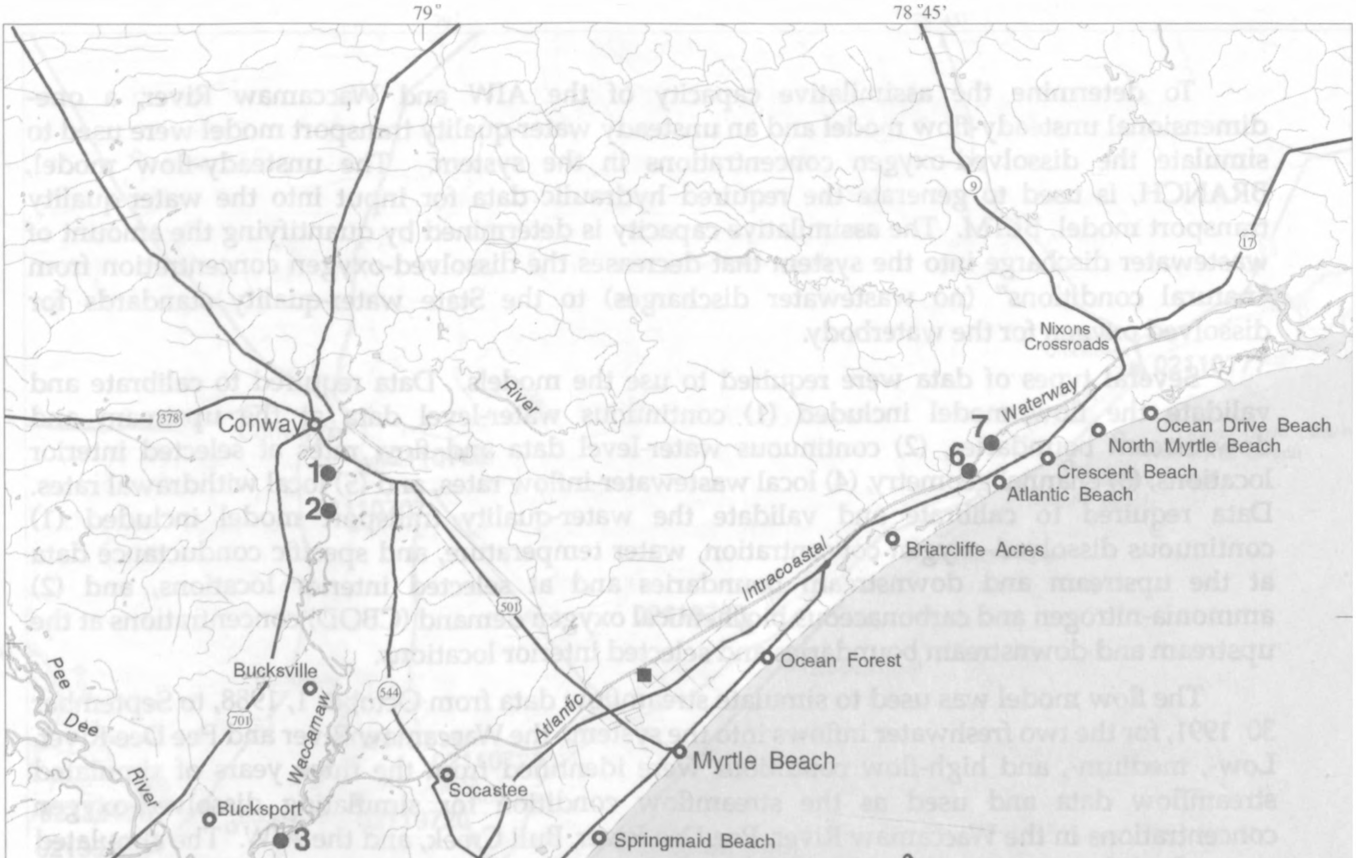

Figure 3.--Location of water- and wastewater-treatment plants.

To determine the assimilative capacity of the AIW and Waccamaw River, a one-dimensional unsteady-flow model and an unsteady water-quality transport model were used to simulate the dissolved-oxygen concentrations in the system. The unsteady-flow model, BRANCH, is used to generate the required hydraulic data for input into the water-quality transport model, BLTM. The assimilative capacity is determined by quantifying the amount of wastewater discharge into the system that decreases the dissolved-oxygen concentration from "natural conditions" (no wastewater discharges) to the State water-quality standards for dissolved oxygen for the waterbody.

Several types of data were required to use the models. Data required to calibrate and validate the flow model included (1) continuous water-level data at the upstream and downstream boundaries, (2) continuous water-level data and flow rates at selected interior locations, (3) channel geometry, (4) local wastewater-inflow rates, and (5) local withdrawal rates. Data required to calibrate and validate the water-quality transport model included (1) continuous dissolved-oxygen concentration, water temperature, and specific conductance data at the upstream and downstream boundaries and at selected interior locations, and (2) ammonia-nitrogen and carbonaceous biochemical oxygen demand (CBOD) concentrations at the upstream and downstream boundaries and selected interior locations.

The flow model was used to simulate streamflow data from October 1, 1988, to September 30, 1991, for the two freshwater inflows into the system: the Waccamaw River and Pee Dee River. Low-, medium-, and high-flow conditions were identified from the three years of simulated streamflow data and used as the streamflow condition for simulating dissolved-oxygen concentrations in the Waccamaw River, Pee Dee River, Bull Creek, and the AIW. The simulated streamflow data were input to the BLTM, and the results were used to quantify the amount of wastewater-discharge loading into the system needed to decrease the dissolved-oxygen concentration to the State standard. An UOD, in lbs/d of oxygen, was calculated from the wastewater discharges. Graphs showing UOD for low-, medium-, and high-flow conditions were generated for each site.

DATA COLLECTION

Data collected to calibrate and validate the models included (1) continuous water-level data at 17 gaging stations, (2) tidal-cycle flows at low, medium, and high streamflows at 15 locations, (3) continuous water-quality data (specific conductance, dissolved oxygen, and (or) water temperature) at 15 gaging stations, (4) tidal-cycle nutrient data at 15 locations, and (5) channel and flood-plain geometry data. Wastewater-discharge data from treatment plants and freshwater withdrawal rates for water-treatment plants were provided by the S.C. Department of Health and Environmental Control (L.E. Turner, South Carolina Department of Health and Environmental Control, written commun., 1993).

Water-Level Data

Water-level data were collected at 15-minute intervals by analog digital recorders (ADR) and data-collection platforms (DCP) at stilling-well gages. Station datums were determined by surveys from established benchmarks. Daily mean water levels from several days of concurrent record from stations on the AIW were compared to detect significant errors in datum on the assumption that local mean-tide elevations should be nearly equal. Locations of all water-level gages are shown in figure 4 and listed in table 3.

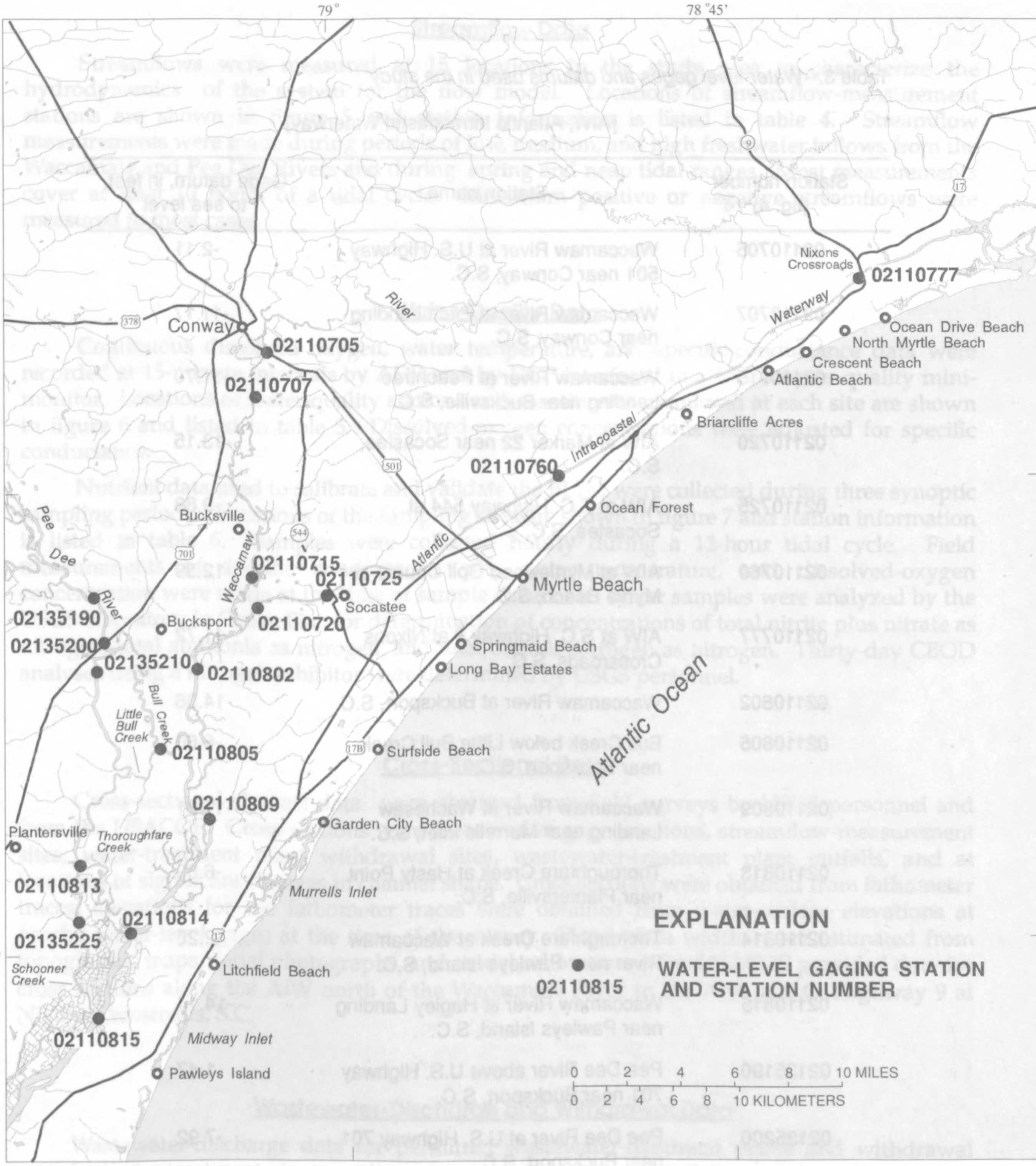

Figure 4.--Location of water-level gaging stations.

Table 3.--*Water-level gages and datums used in the study*

[AIW, Atlantic Intracoastal Waterway]

Station number (fig. 4)	Station name	Gage datum, in feet, to sea level
02110705	Waccamaw River at U.S. Highway 501 near Conway, S.C.	-2.11
02110707	Waccamaw River at Pitch Landing near Conway, S.C.	-11.17
02110715	Waccamaw River at Peachtree Landing near Bucksville, S.C.	-11.70
02110720	AIW at Marker 22 near Socastee, S.C.	-13.15
02110725	AIW at S.C. Highway 544 at Socastee, S.C.	-9.88
02110760	AIW at Myrtlewood Golf Course at Myrtle Beach, S.C.	-12.39
02110777	AIW at S.C. Highway 9 at Nixons Crossroads, S.C.	-11.72
02110802	Waccamaw River at Bucksport, S.C.	-14.36
02110805	Bull Creek below Little Bull Creek near Bucksport, S.C.	-6.60
02110809	Waccamaw River at Wachesaw Landing near Murrells Inlet, S.C.	-11.21
02110813	Thoroughfare Creek at Hasty Point near Plantersville, S.C.	-6.80
02110814	Thoroughfare Creek at Waccamaw River near Pawleys Island, S.C.	-2.20
02110815	Waccamaw River at Hagley Landing near Pawleys Island, S.C.	-14.14
02135190	Pee Dee River above U.S. Highway 701 near Bucksport, S.C.	-1.47
02135200	Pee Dee River at U.S. Highway 701 near Bucksport, S.C.	-7.92
02135210	Pee Dee River at Topsaw Landing near Plantersville, S.C.	-5.40
02135225	Pee Dee River at Arundel Plantation near Plantersville, S.C.	-12.56

Streamflow Data

Streamflows were measured at 15 locations in the study area to characterize the hydrodynamics of the system for the flow model. Locations of streamflow-measurement stations are shown in figure 5 and station information is listed in table 4. Streamflow measurements were made during periods of low, medium, and high freshwater inflows from the Waccamaw and Pee Dee Rivers and during spring and neap tidal ranges. Most measurements cover at least 10 hours of a tidal cycle. Maximum positive or negative streamflows were measured in most cases.

Water-Quality Data

Continuous dissolved oxygen, water temperature, and specific-conductance data were recorded at 15-minute intervals by ADR and by DCP interfaced to a USGS water-quality mini-monitor. Locations of water-quality stations and constituents monitored at each site are shown in figure 6 and listed in table 5. Dissolved-oxygen concentrations were adjusted for specific conductance.

Nutrient data used to calibrate and validate the BLTM were collected during three synoptic sampling periods. Locations of the sampling sites are shown in figure 7 and station information is listed in table 6. Samples were collected hourly during a 12-hour tidal cycle. Field measurements of specific conductance, pH, water temperature, and dissolved-oxygen concentration were made at the time of sample collection. Water samples were analyzed by the USGS laboratory in Ocala, Fla., for determination of concentrations of total nitrite plus nitrate as nitrogen, total ammonia as nitrogen, and total organic nitrogen as nitrogen. Thirty-day CBOD analyses using a nitrogen inhibitor were determined by USGS personnel.

Cross-Sectional Data

Cross-sectional channel data were obtained from field surveys by USGS personnel and from the USACOE. Cross sections were measured at gage locations, streamflow-measurement sites, water-treatment plant withdrawal sites, wastewater-treatment plant outfalls, and at locations of significant changes in channel shape. Cross sections were obtained from fathometer traces; elevations for the fathometer traces were obtained from water-surface elevations at nearby water-level gages at the time of the survey. Flood-plain widths were estimated from topographic maps, aerial photographs, and model calibrations. The USACOE provided data for cross sections along the AIW north of the Waccamaw River to the AIW at S.C. Highway 9 at Nixons Crossroads, S.C.

Wastewater-Discharge and Withdrawal Data

Wastewater-discharge data for permitted wastewater-treatment plants and withdrawal rates for water-treatment plants are listed in table 2 (Larry Turner, S.C. Department of Health and Environmental Control, written commun., 1993). Wastewater-discharge data were used to calibrate the water-quality transport model. Water withdrawals for water-treatment plants were considered insignificant compared to the riverine streamflows, and therefore, were not accounted for in the flow model.

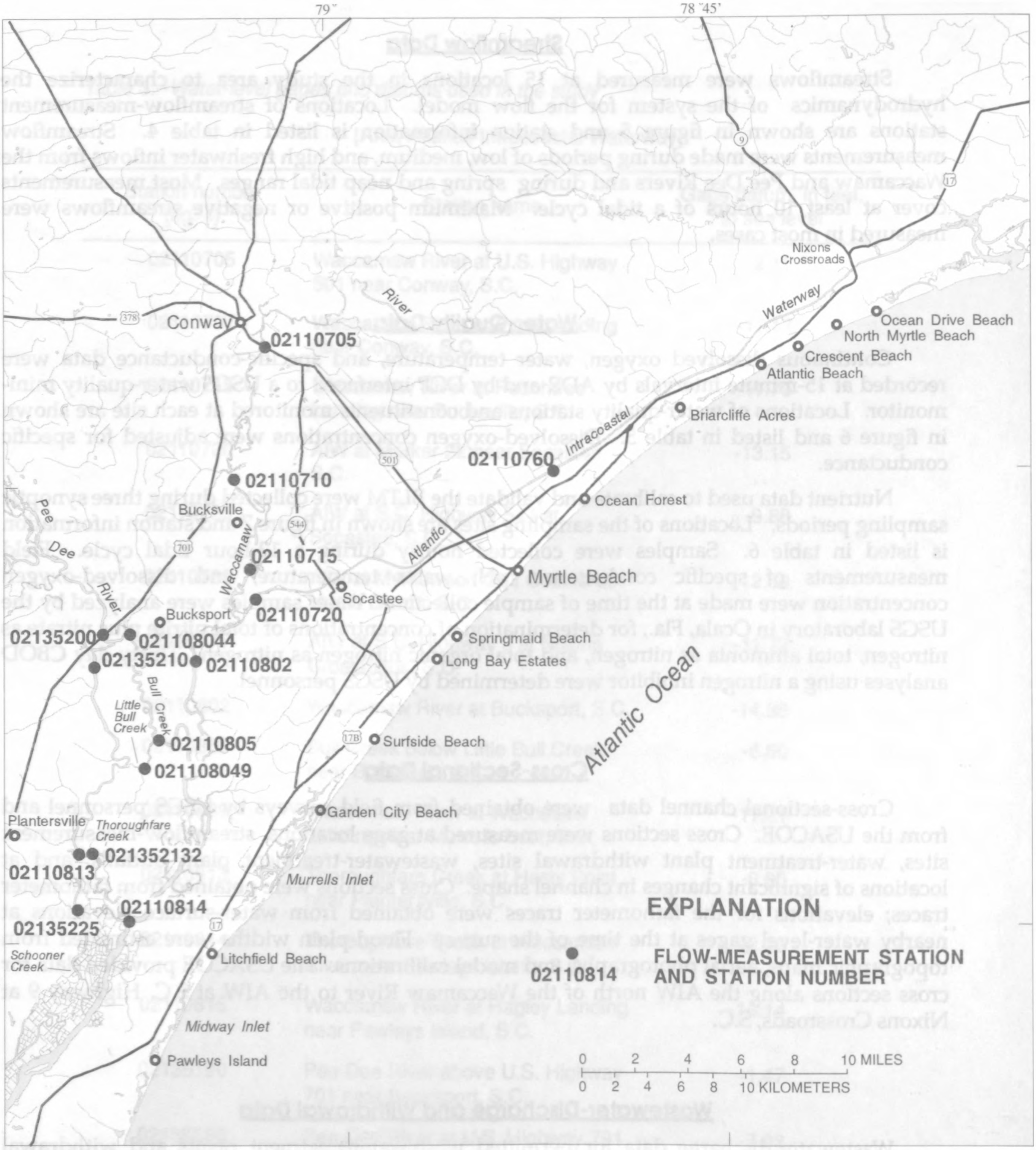

Figure 5.--Location of streamflow-measurement stations.

Table 4.--*Streamflow-measurement sites used in the study and measurement dates*

[AIW, Atlantic Intracoastal Waterway]

Station number (fig. 5)	Station name	Date
02110705	Waccamaw River at U.S. Highway 501 near Conway, S.C.	08-06-87 06-09-93
02110710	Waccamaw River at Toddville Landing near Conway, S.C.	08-15-90
02110715	Waccamaw River at Peachtree Landing near Bucksville, S.C.	03-16-88 08-17-88 04-11-89
02110720	AIW at Marker 22 near Socastee, S.C.	04-11-89
02110760	AIW at Myrtlewood Golf Course at Myrtle Beach, S.C.	03-31-87 09-09-87 03-17-88 09-21-88 04-04-89 08-15-90
02110802	Waccamaw River at Bucksport, S.C.	06-11-86 09-18-86 03-16-88 08-11-88 04-11-89
021108044	Bull Creek near Bucksport, S.C.	03-17-88 08-10-88
021108049	Little Bull Creek near Bucksport, S.C.	08-11-88
02110805	Bull Creek below Little Bull Creek near Bucksport, S.C.	08-10-88

Table 4.--*Streamflow-measurement sites used in the study and measurement dates*--Continued

[AIW, Atlantic Intracoastal Waterway]

Station number (fig. 5)	Station name	Date
02110813	Thoroughfare Creek at Hasty Point near Plantersville, S.C.	03-15-88 04-12-89
02110814	Thoroughfare Creek at Waccamaw River near Pawleys Island, S.C.	08-10-88
02135200	Pee Dee River at U.S. Highway 701 near Bucksport, S.C.	03-15-88 08-10-88 04-13-89 11-09-90 01-20-93
02135210	Pee Dee River at Topsaw Landing near Plantersville, S.C.	03-15-88 08-10-88
02135225	Pee Dee River at Arundel Plantation near Plantersville, S.C.	03-15-88 04-12-89
021352132	Pee Dee River at Hasty Point Plantation below Plantersville, S.C.	04-12-89

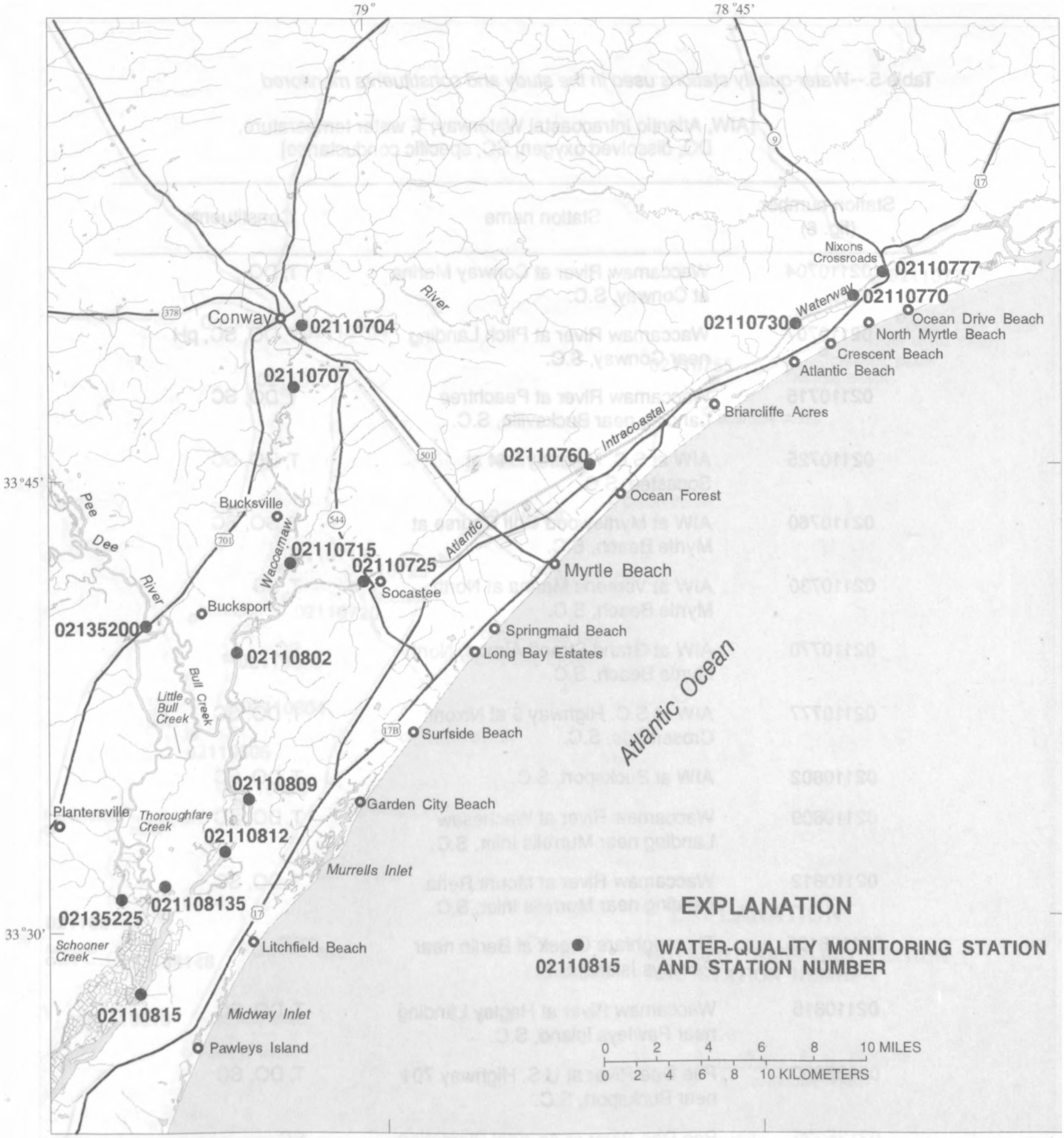

Figure 6.--Location of water-quality monitoring stations.

Table 5.--*Water-quality stations used in the study and constituents monitored*

[AIW, Atlantic Intracoastal Waterway; T, water temperature, DO, dissolved oxygen; SC, specific conductance]

Station number (fig. 6)	Station name	Constituents
02110704	Waccamaw River at Conway Marina at Conway, S.C.	T, DO
02110707	Waccamaw River at Pitch Landing near Conway, S.C.	T, DO, SC, pH
02110715	Waccamaw River at Peachtree Landing near Bucksville, S.C.	T, DO, SC
02110725	AIW at S.C. Highway 544 at Socastee, S.C.	T, DO, SC
02110760	AIW at Myrtlewood Golf Course at Myrtle Beach, S.C.	T, DO, SC
02110730	AIW at Vereens Marina at North Myrtle Beach, S.C.	T, SC
02110770	AIW at Grand Strand Airport, North Myrtle Beach, S.C.	SC
02110777	AIW at S.C. Highway 9 at Nixons Crossroads, S.C.	T, DO, SC
02110802	AIW at Bucksport, S.C.	T, DO, SC
02110809	Waccamaw River at Wachesaw Landing near Murrells Inlet, S.C.	T, DO, SC
02110812	Waccamaw River at Mount Rena Landing near Murrells Inlet, S.C.	T, DO, SC
021108135	Thoroughfare Creek at Berlin near Pawleys Island, S.C.	SC
02110815	Waccamaw River at Hagley Landing near Pawleys Island, S.C.	T, DO, SC
02135200	Pee Dee River at U.S. Highway 701 near Bucksport, S.C.	T, DO, SC
02135225	Pee Dee River at Arundel Plantation near Plantersville, S.C.	SC

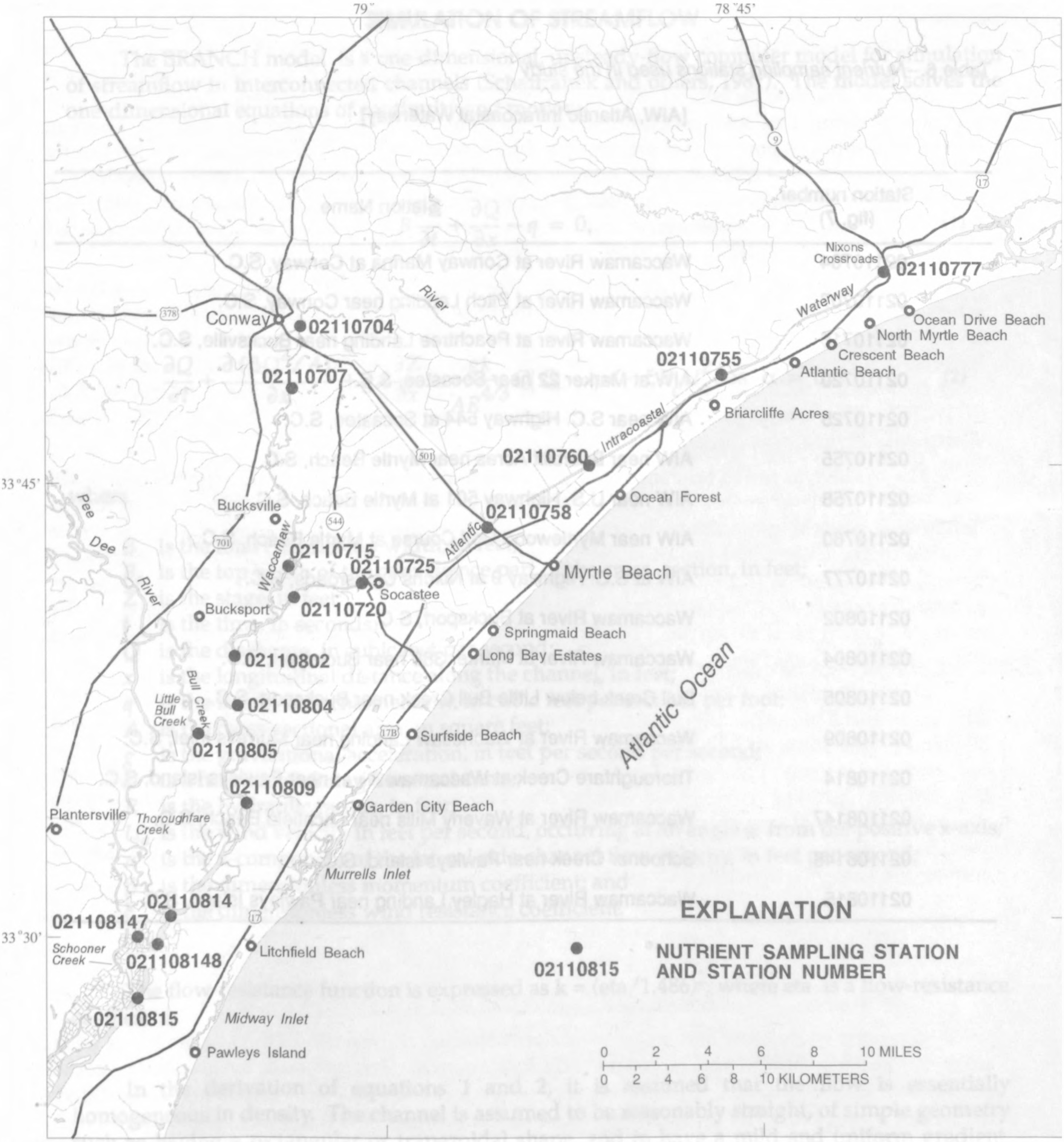

Figure 7.--Location of nutrient sampling stations.

Table 6.--*Nutrient sampling stations used in the study*

[AIW, Atlantic Intracoastal Waterway]

Station number (fig. 7)	Station Name
02110704	Waccamaw River at Conway Marina at Conway, S.C.
02110707	Waccamaw River at Pitch Landing near Conway, S.C.
02110715	Waccamaw River at Peachtree Landing near Bucksville, S.C.
02110720	AIW at Marker 22 near Socastee, S.C.
02110725	AIW near S.C. Highway 544 at Socastee, S.C.
02110755	AIW near Briarcliff Acres near Myrtle Beach, S.C.
02110758	AIW near U.S. Highway 501 at Myrtle Beach, S.C.
02110760	AIW near Myrtlewood Golf Course at Myrtle Beach, S.C.
02110777	AIW at S.C. Highway 9 at Nixons Crossroads, S.C.
02110802	Waccamaw River at Bucksport, S.C.
02110804	Waccamaw River at Marker 380 near Bucksport, S.C.
02110805	Bull Creek below Little Bull Creek near Bucksport, S.C.
02110809	Waccamaw River at Wachesaw Landing near Murrells Inlet, S.C.
02110814	Thoroughfare Creek at Waccamaw River near Pawleys Island, S.C.
021108147	Waccamaw River at Waverly Mills near Litchfield Beach, S.C.
021108148	Schooner Creek near Pawleys Island, S.C.
02110815	Waccamaw River at Hagley Landing near Pawleys Island, S.C.

SIMULATION OF STREAMFLOW

The BRANCH model is a one-dimensional, unsteady-flow computer model for simulation of streamflow in interconnected channels (Schaffranek and others, 1981). The model solves the one-dimensional equations of continuity and motion:

$$B\frac{\partial Z}{\partial t} + \frac{\partial Q}{\partial x} - q = 0, \tag{1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial (\beta Q^2/A)}{\partial x} + gA\frac{\partial Z}{\partial x} + \frac{gk}{AR^{4/3}}Q|Q| - qu' - \xi B_c U_a^2 \cos\ \alpha = 0, \tag{2}$$

where

B is the total channel top width, in feet;
B_c is the top width of the conveyance part of the cross section, in feet;
Z is the stage, in feet;
t is the time, in seconds;
Q is the discharge, in cubic feet per second;
x is the longitudinal distance along the channel, in feet;
q is the lateral side-channel flow, in cubic feet per second, per foot;
A is the cross-sectional area, in square feet;
g is the gravitational acceleration, in feet per second per second;
k is a function defining flow-resistance;
R is the hydraulic radius, in feet;
U_a is the wind velocity in feet per second, occurring at an angle α from the positive x-axis;
u' is the x-component of the lateral side-channel flow velocity, in feet per second;
β is the dimensionless momentum coefficient; and
ξ is the dimensionless wind resistance coefficient.

The flow-resistance function is expressed as $k = (eta/1.486)^2$, where eta is a flow-resistance coefficient.

In the derivation of equations 1 and 2, it is assumed that the flow is essentially homogeneous in density. The channel is assumed to be reasonably straight, of simple geometry such as having a rectangular or trapezoidal shape, and to have a mild and uniform gradient. These assumptions are appropriate for the system modeled in this study. Approximate solutions for the nonlinear partial-differential unsteady-flow equations can be obtained by finite-difference techniques. A weighted four-point finite-difference approximation is used in the BRANCH model. The finite-difference technique is described in detail by Schaffranek and others (1981).

In the model, rivers are presented as a series of cross sections and channel lengths, which define segments, junctions, and branches. Channel-geometry data that characterize the conveyance, area, width, and storage capacity at each cross section are input to the model. A segment is defined by an upstream and downstream cross section and the distance between them. A group of segments that are separated by junctions are called branches. The beginning or ending junctions of a branch with no continuing branches is known as an external boundary. Water level or streamflow data are input at the external boundaries as boundary conditions for the model. All other stages and streamflows are computed at cross sections. An idealized BRANCH network model schematization is shown in figure 8.

The model for the Waccamaw River, Pee Dee River, Bull Creek, and the AIW is schematicized using 23 branches, 15 internal junctions, and 5 external boundaries (fig. 9). Water levels used as the external boundaries during calibration of the flow model are: Waccamaw River at U.S. Highway 501 near Conway, S.C. (02110705), Pee Dee River aboveU.S. Highway 701 near Bucksport, S.C. (02135190), the AIW at S.C. Highway 9 at Nixons Crossroads, S.C. (02110777), Waccamaw River at Hagley Landing near Pawleys Island, S.C. (02110815), and Waccamaw River at Bucksport, S.C. (02110802).

The model was tested for convergence to determine the optimum simulation time-step and space-step (the distance between cross sections). A finite-difference solution to the partial differential governing equations is convergent if the numerical solution approaches the true solution of the differential equation as the numerical time-step and space-step are decreased (Smith, 1985). Convergence can be tested by repeated simulations of the model with a fixed set of boundary conditions for successively smaller computational time-steps and space-steps. The model is convergent if no further change in the model results is observed as the time-step and space-step are refined (Thompson, 1992).

Model simulations were generated for successively smaller computational time-steps of 60, 30, 15, 7.5, and 5 minutes. Significant differences in model results occurred between the 60- and 30-minute time-steps and between 30- and 15-minute time-steps. The differences between the 15- and 7.5-minute time-steps and the 7.5- and 5-minute time-steps were considered insignificant. Similar convergence testing was performed on the space-step. Cross sections defining the system were spaced at approximately 2.5 mile intervals and at 1 mile intervals. No significant differences in the model results were observed. The model was considered convergent using a time-step of 15 minutes and a space-step of 2.5 miles.

Flow-Model Calibration and Validation

Measured streamflow and water-level data collected during the 1989-91 water years were used to calibrate the BRANCH model. Calibration was accomplished by adjusting model parameters until simulated streamflows and water levels agreed with measured streamflows and water levels, primarily by modifying cross-sectional areas, flow resistance, gage datums, and storage volume.

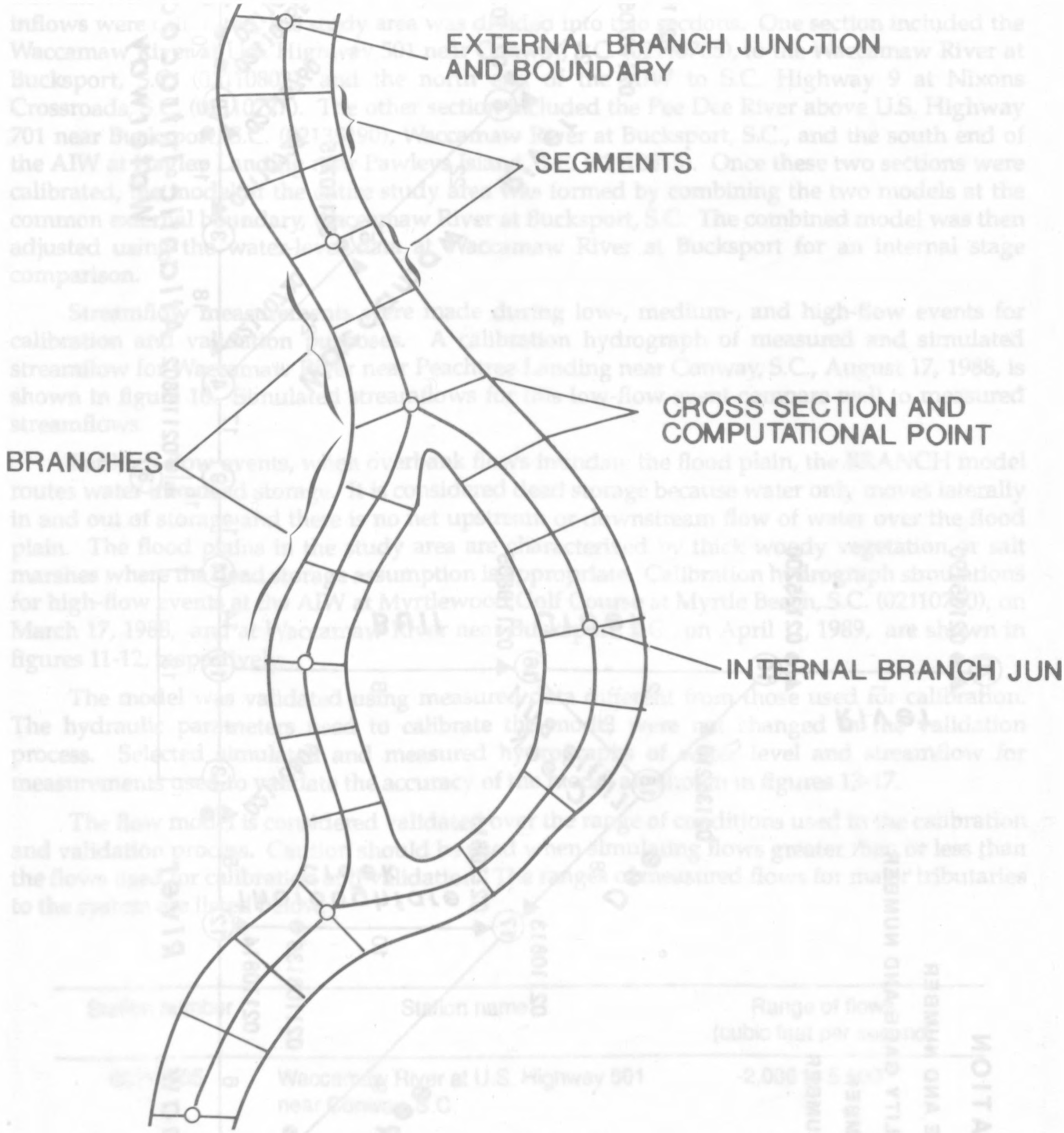

Figure 8.--Idealized BRANCH network model schematization.

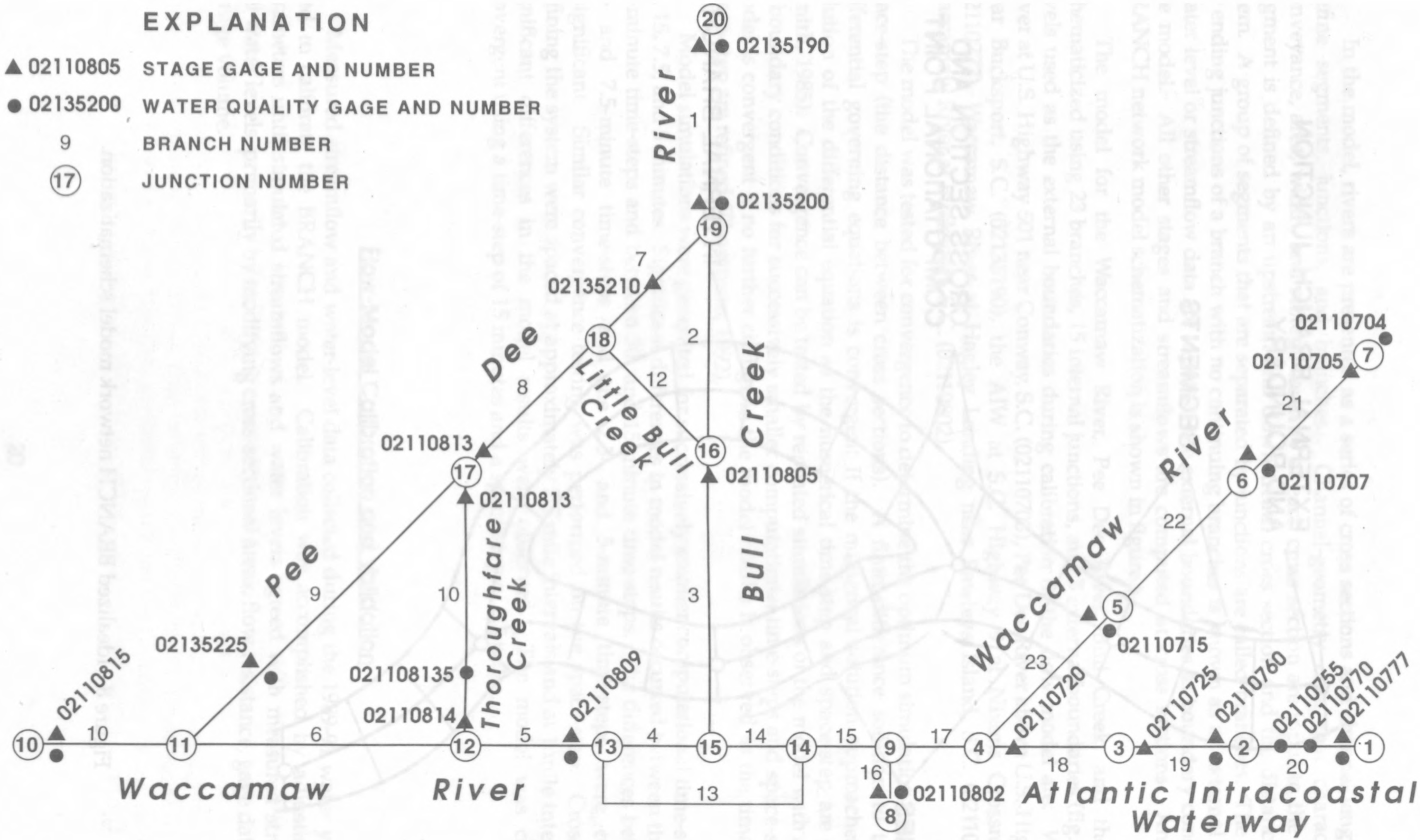

Figure 9.--BRANCH network model schematization for Atlantic Intracoastal Waterway and tributaries.

Initially, the upper reaches of the Waccamaw and Pee Dee Rivers were calibrated to ensure that the freshwater inflow into the system was accurately simulated. Once the freshwater inflows were calibrated, the study area was divided into two sections. One section included the Waccamaw River at U.S. Highway 501 near Conway, S.C. (02110705), to the Waccamaw River at Bucksport, S.C. (02110802), and the north end of the AIW to S.C. Highway 9 at Nixons Crossroads, S.C. (02110777). The other section included the Pee Dee River above U.S. Highway 701 near Bucksport, S.C. (02135190), Waccamaw River at Bucksport, S.C., and the south end of the AIW at Hagley Landing near Pawleys Island, S.C. (02110815). Once these two sections were calibrated, the model of the entire study area was formed by combining the two models at the common external boundary, Waccamaw River at Bucksport, S.C. The combined model was then adjusted using the water-level data at Waccamaw River at Bucksport for an internal stage comparison.

Streamflow measurements were made during low-, medium-, and high-flow events for calibration and validation purposes. A calibration hydrograph of measured and simulated streamflow for Waccamaw River near Peachtree Landing near Conway, S.C., August 17, 1988, is shown in figure 10. Simulated streamflows for this low-flow event compare well to measured streamflows.

For high-flow events, when overbank flows inundate the flood plain, the BRANCH model routes water into dead storage. It is considered dead storage because water only moves laterally in and out of storage and there is no net upstream or downstream flow of water over the flood plain. The flood plains in the study area are characterized by thick woody vegetation or salt marshes where the dead storage assumption is appropriate. Calibration hydrograph simulations for high-flow events at the AIW at Myrtlewood Golf Course at Myrtle Beach, S.C. (02110760), on March 17, 1988, and at Waccamaw River near Bucksport, S.C., on April 11, 1989, are shown in figures 11-12, respectively.

The model was validated using measured data different from those used for calibration. The hydraulic parameters used to calibrate the model were not changed in the validation process. Selected simulated and measured hydrographs of water level and streamflow for measurements used to validate the accuracy of the model are shown in figures 13-17.

The flow model is considered validated over the range of conditions used in the calibration and validation process. Caution should be used when simulating flows greater than or less than the flows used for calibration and validation. The ranges of measured flows for major tributaries to the system are listed below.

Station number	Station name	Range of flows (cubic feet per second)
02110705	Waccamaw River at U.S. Highway 501 near Conway, S.C.	-2,000 to 5,000
02110760	AIW at Myrtlewood Golf Course at Myrtle Beach, S.C.	-3,000 to 3,000
02110802	Waccamaw River at Bucksport, S.C.	-5,000 to 13,000
02135200	Pee Dee River at U.S. Highway 701 near Bucksport, S.C.	-1,500 to 70,000

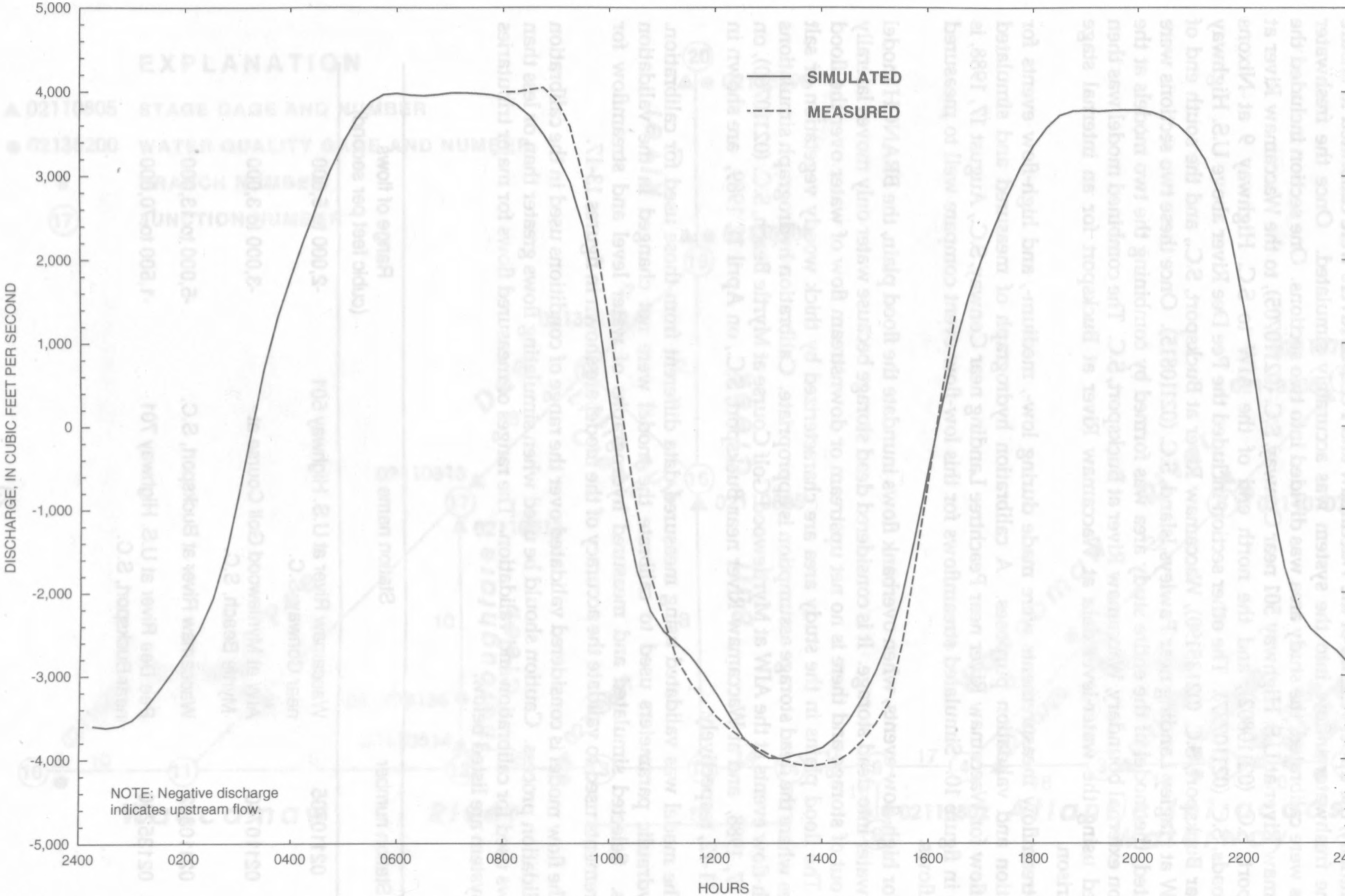

Figure 10.--Simulated and measured streamflows used in flow model calibration for the Waccamaw River at Peachtree Landing near Bucksville, S.C., August 17, 1988.

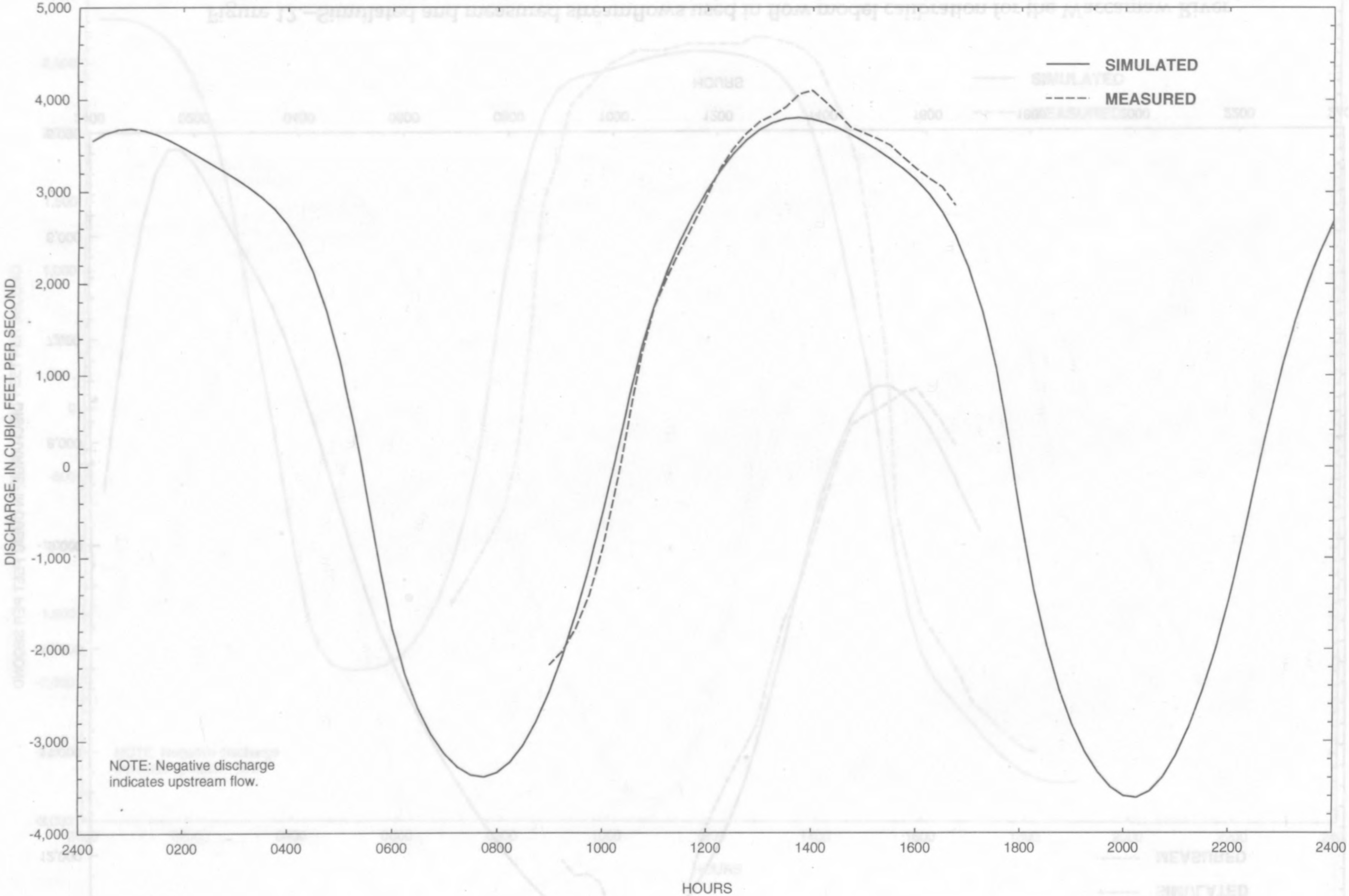

Figure 11.--Simulated and measured streamflows used in flow model calibration for the Atlantic Intracoastal Waterway at Myrtlewood Golf Course at Myrtle Beach, S.C., March 17, 1988.

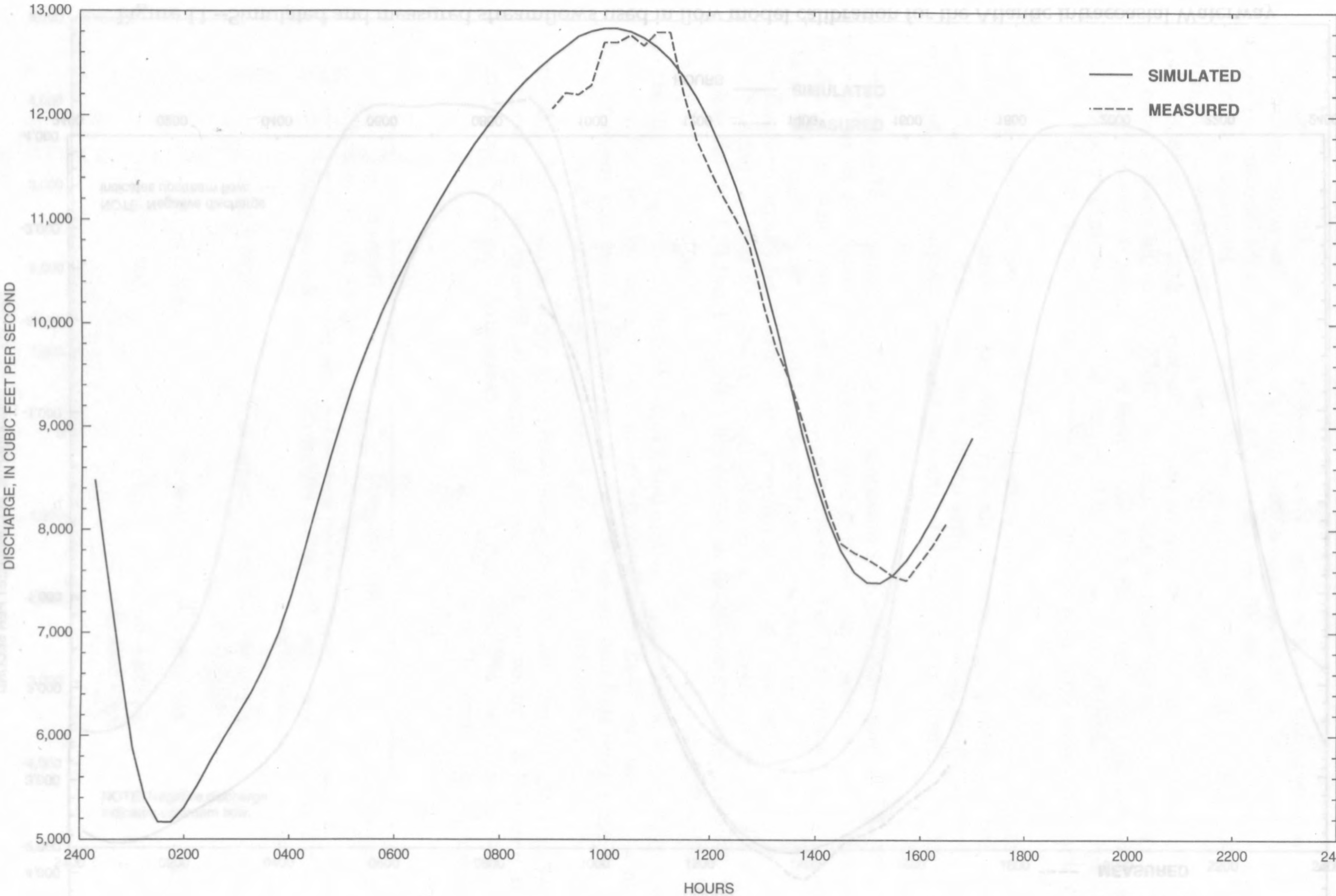

Figure 12.--Simulated and measured streamflows used in flow model calibration for the Waccamaw River near Bucksport, S.C., April 11, 1989.

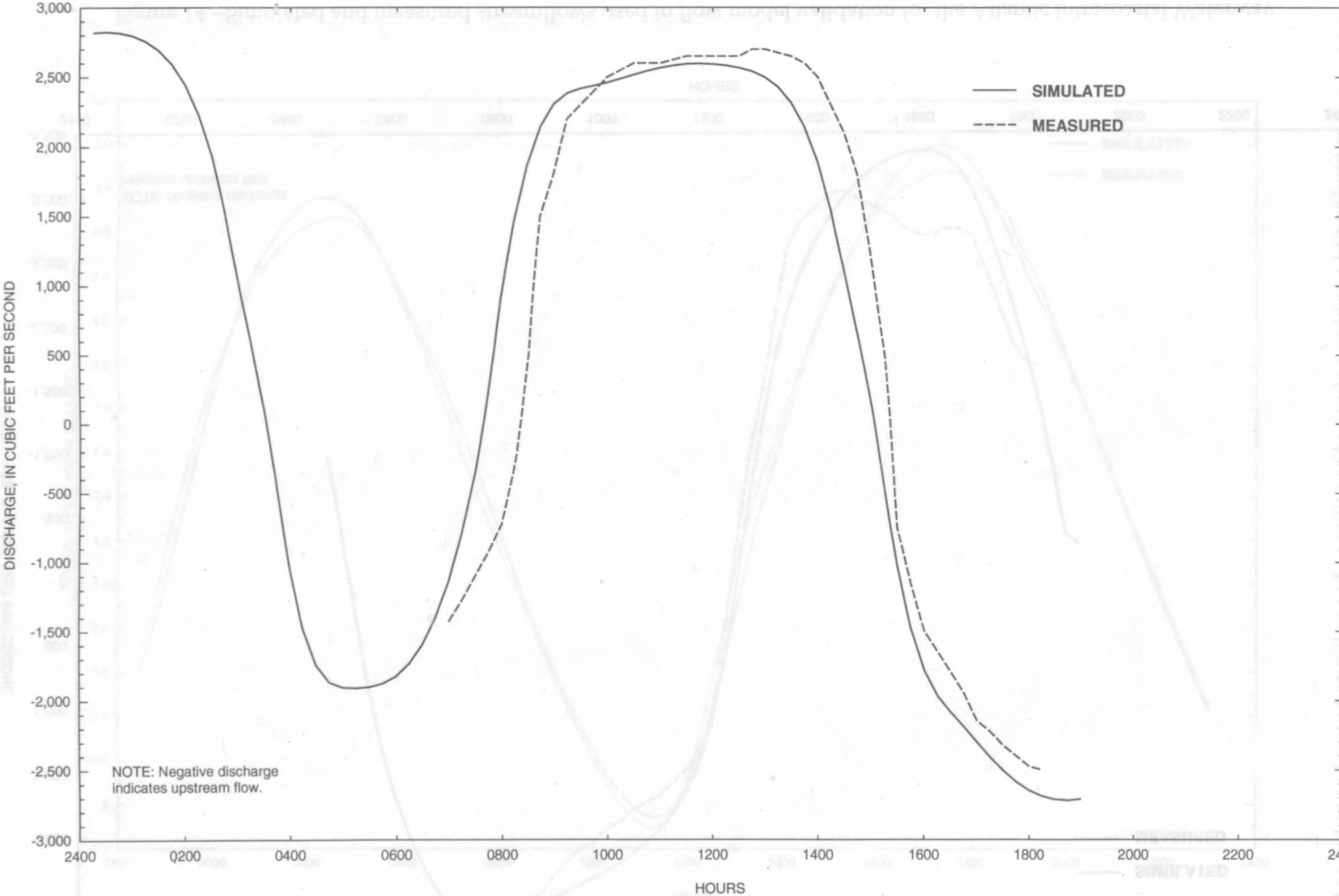

Figure 13.--Simulated and measured streamflows used in flow model validation for the Waccamaw River at Toddville Landing near Conway, S.C., August 15, 1990.

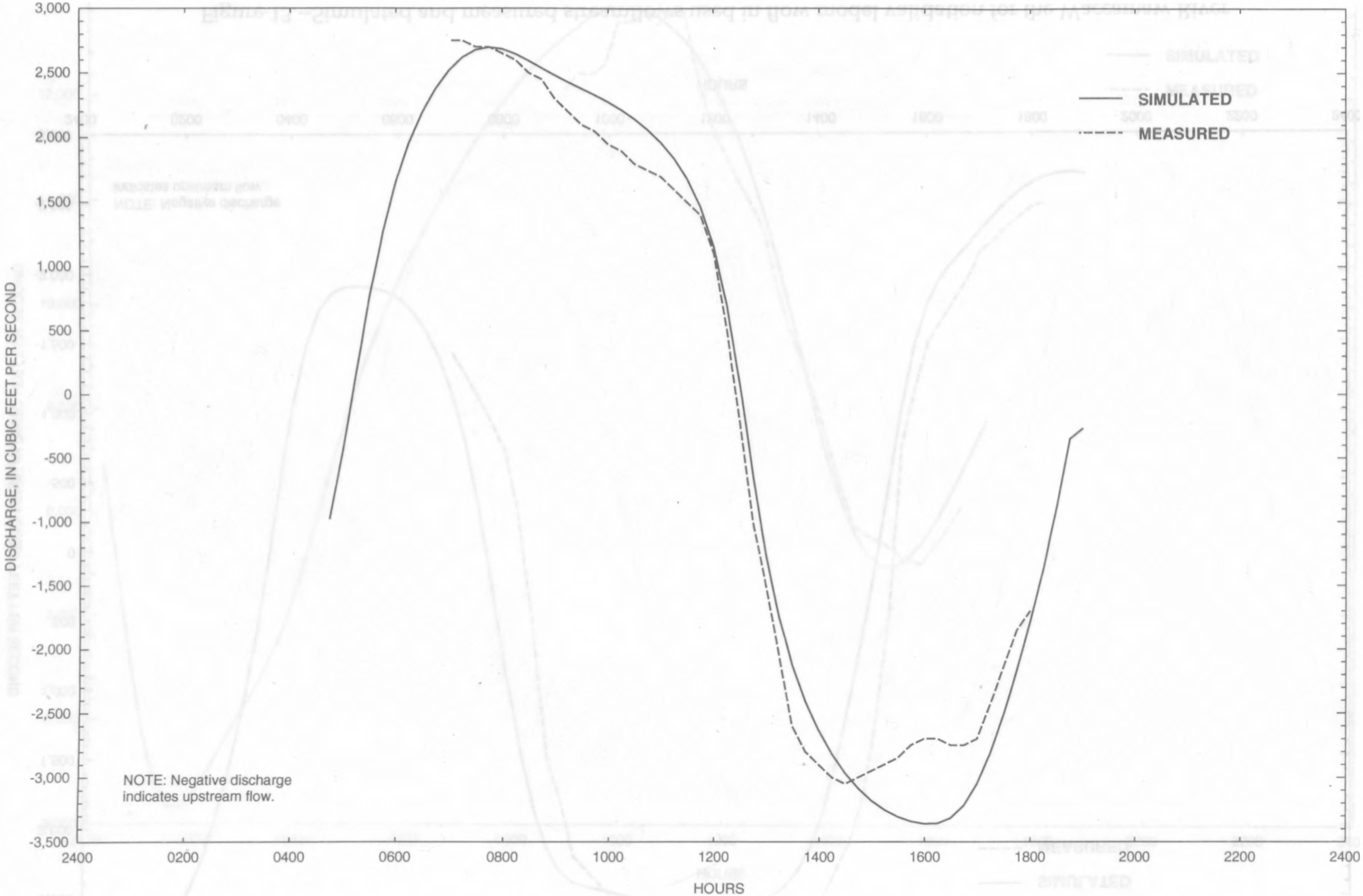

Figure 14.--Simulated and measured streamflows used in flow model validation for the Atlantic Intracoastal Waterway at Myrtlewood Golf Course at Myrtle Beach, S.C., August 15, 1990.

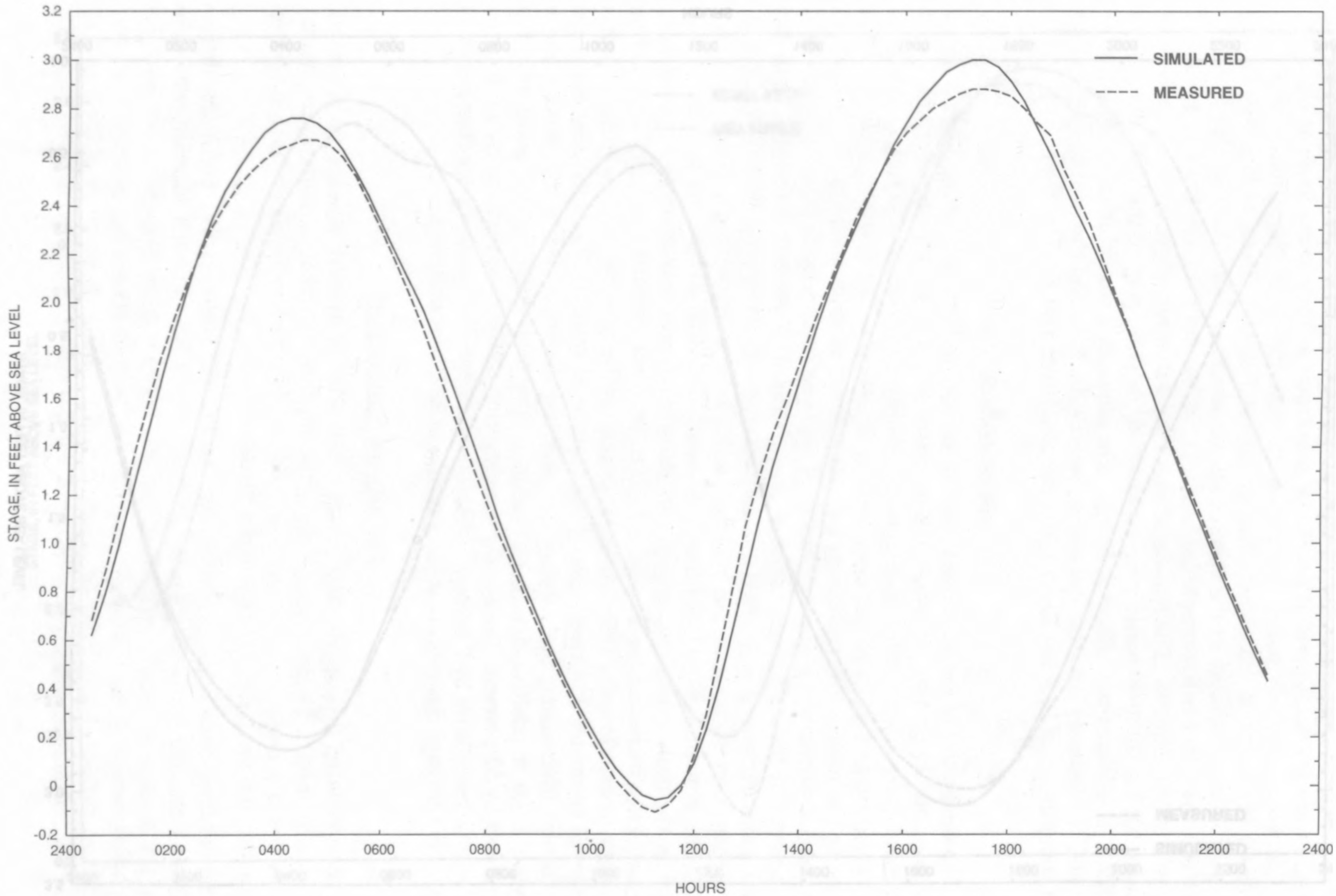

Figure 15.--Simulated and measured stages used in flow model validation for the Waccamaw River at Wachesaw Landing near Murrells Inlet, S.C., September 4, 1988.

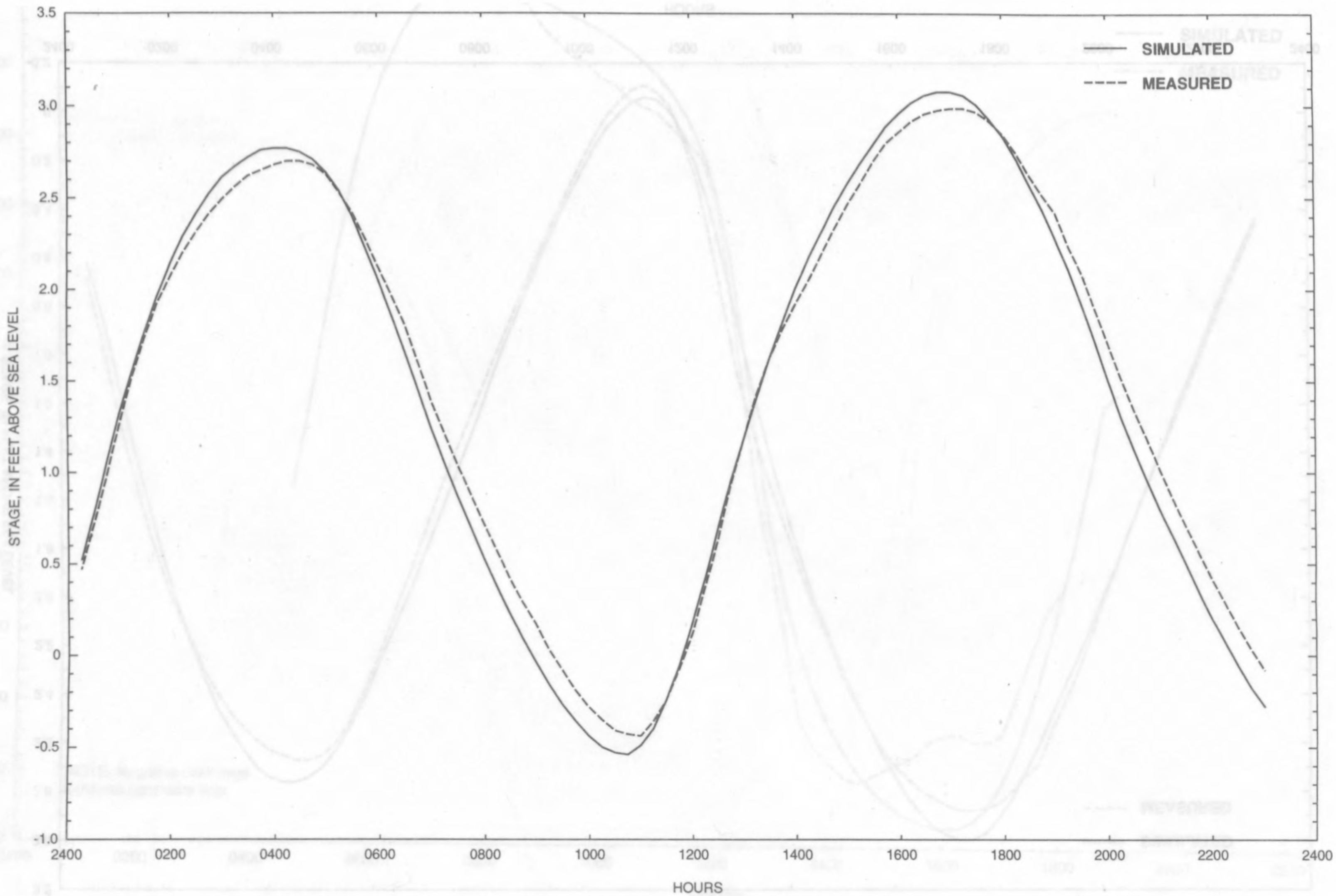

Figure 16.--Simulated and measured stages used in flow model validation for Thoroughfare Creek at the Waccamaw River near Pawleys Island, S.C., September 4, 1988.

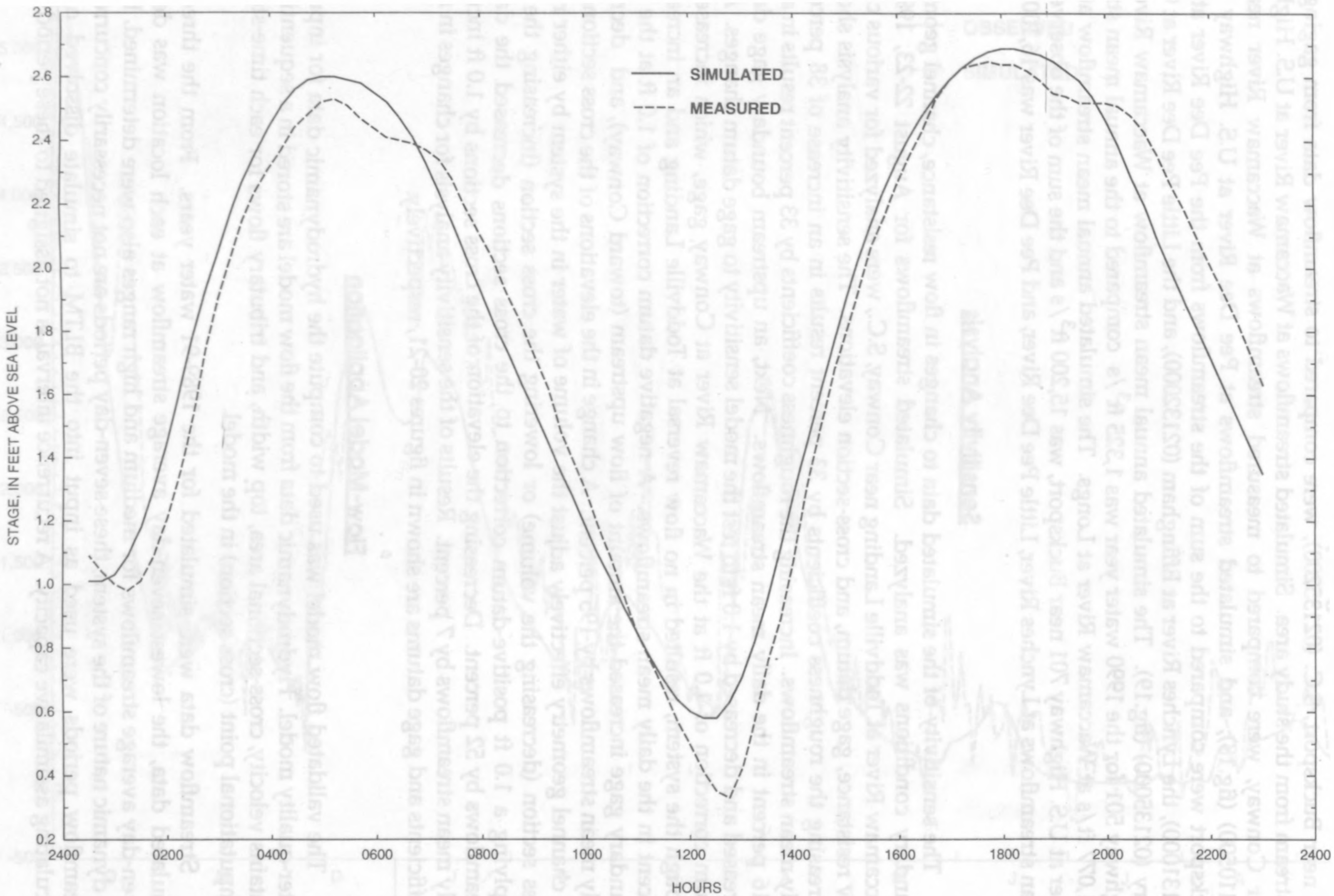

Figure 17.--Simulated and measured stages used in flow model validation for the Atlantic Intracoastal Waterway at S.C. Highway 544 near Socastee, S.C., September 4, 1988.

To validate annual volumes of freshwater entering the system, simulated daily mean streamflows were compared to measured data. Simulated daily mean streamflow hydrographs at Waccamaw River at U.S. Highway 501 near Conway, S.C., and Pee Dee River at U.S. Highway 701 near Bucksport, S.C. (02135200), were compared to streamflow data from gaging stations upstream from the study area. Simulated streamflows at Waccamaw River at U.S. Highway 501 near Conway, were compared to measured streamflows at Waccamaw River near Longs (02110500) (fig.18), and simulated streamflows at Pee Dee River at U.S. Highway 701 near Bucksport were compared to the sum of the streamflows from the Pee Dee River at Pee Dee (02131000), the Lynches River at Effingham (02132000), and the Little Pee Dee River at Galivants Ferry (02135000) (fig.19). The simulated annual mean streamflow at Waccamaw River at U.S. Highway 501 for the 1990 water year was 1,325 ft^3/s compared to the annual mean streamflow of 1,077 ft/s at Waccamaw River at Longs. The simulated annual mean streamflow at Pee Dee River at U.S. Highway 701 near Bucksport, was 15,200 ft^3/s and the sum of the observed annual mean streamflows at Lynches River, Little Pee Dee River, and Pee Dee River was 16,100 ft^3/s.

Sensitivity Analysis

The sensitivity of the simulated data to changes in flow resistance, channel geometry, and boundary conditions was analyzed. Simulated streamflows for August 22-23, 1990, at the Waccamaw River at Toddville Landing near Conway, S.C., were analyzed for various changes in flow resistance, gage datum, and cross-section elevations. The sensitivity analysis showed that decreasing the roughness coefficients by 33 percent results in an increase of 38 percent in the daily mean streamflows. Increasing the roughness coefficients by 33 percent results in a decrease of 16 percent in the daily mean streamflows. Next, an upstream boundary gage datum was increased and decreased by 1.0 ft to test the model sensitivity to gage datum changes. A positive datum correction of 1.0 ft at the Waccamaw River at Conway gage, which increases the fall through the system, resulted in no flow reversal at Toddville Landing and an increase of 288 percent in the daily mean streamflows. A negative datum correction of 1.0 ft at the upstream boundary gage increased the amount of flow upstream (toward Conway), and decreased the daily mean streamflows by 195 percent. A change in the elevations of the cross sections defining the channel geometry effectively adjust the volume of water in the system by either raising the cross section (decreasing the volume) or lowering the cross section (increasing the volume). Applying a 1.0 ft positive-datum correction to the cross sections decreased the daily mean streamflows by 52 percent. Decreasing the elevation of the cross sections by 1.0 ft increased the daily mean streamflows by 7 percent. Results of the sensitivity analysis for changes in roughness coefficients and gage datums are shown in figures 20-21, respectively.

Flow-Model Application

The validated flow model was used to compute the hydrodynamic data for input into the water-quality model. Hydrodynamic data from the flow model are stored in a sequential file that contains velocity, cross-sectional area, top width, and tributary flows for each time-step at each computational point (cross section) in the model.

Streamflow data were simulated for the 1989-91 water years. From the three years of simulated data, the lowest seven-day average streamflow at each location was determined. Seven-day average streamflows for medium and high ranges also were determined. Because of the dynamic nature of the system, these seven-day periods are not necessarily concurrent. These streamflow periods were used as input into the BLTM to simulate dissolved oxygen for calculating assimilative capacity. A recurrence interval is not assigned to these periods.

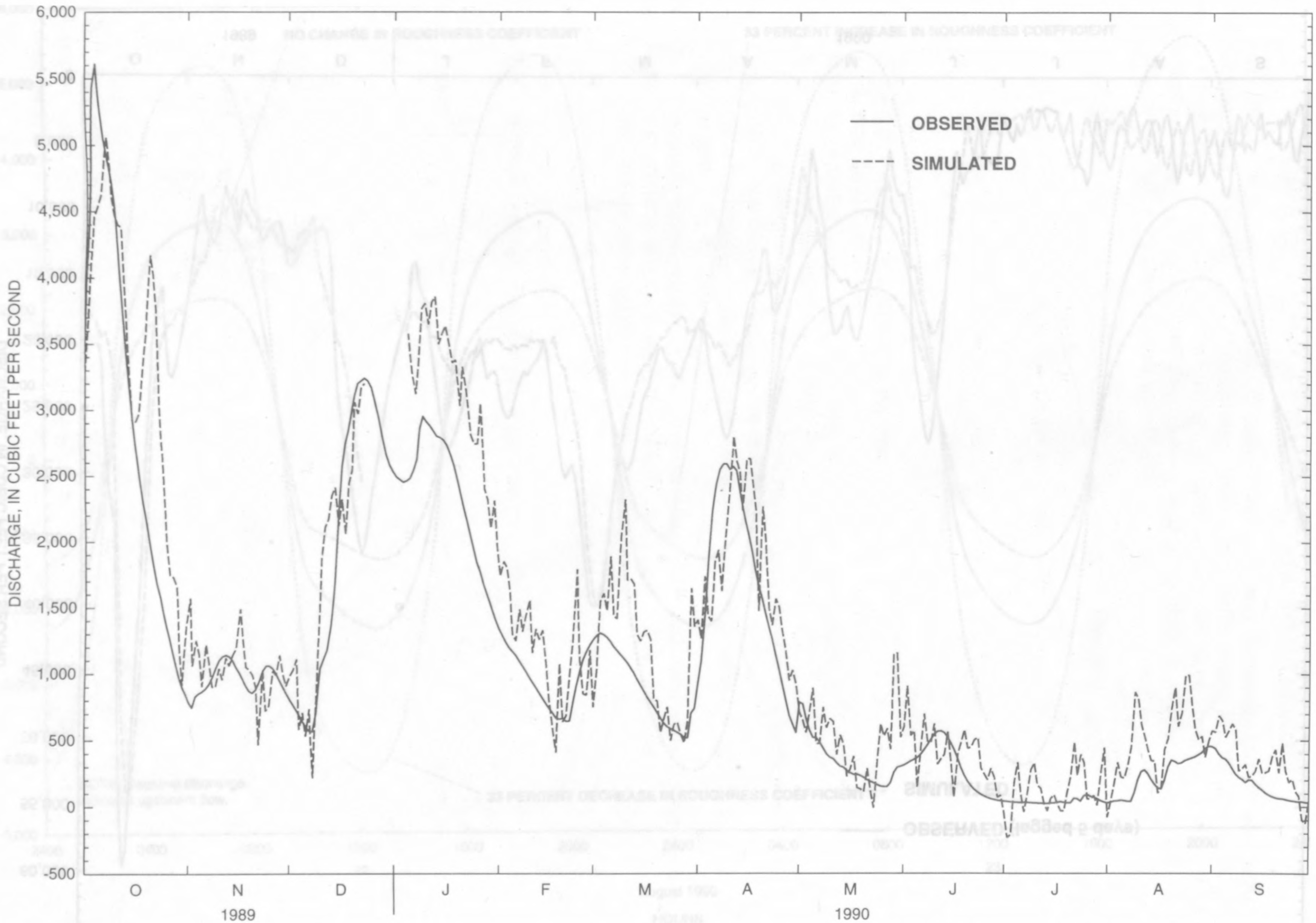

Figure 18.--Simulated daily mean discharge for Waccamaw River at U.S. Highway 501 near Conway, S.C., and observed daily mean discharge for Waccamaw River at Longs, S.C.

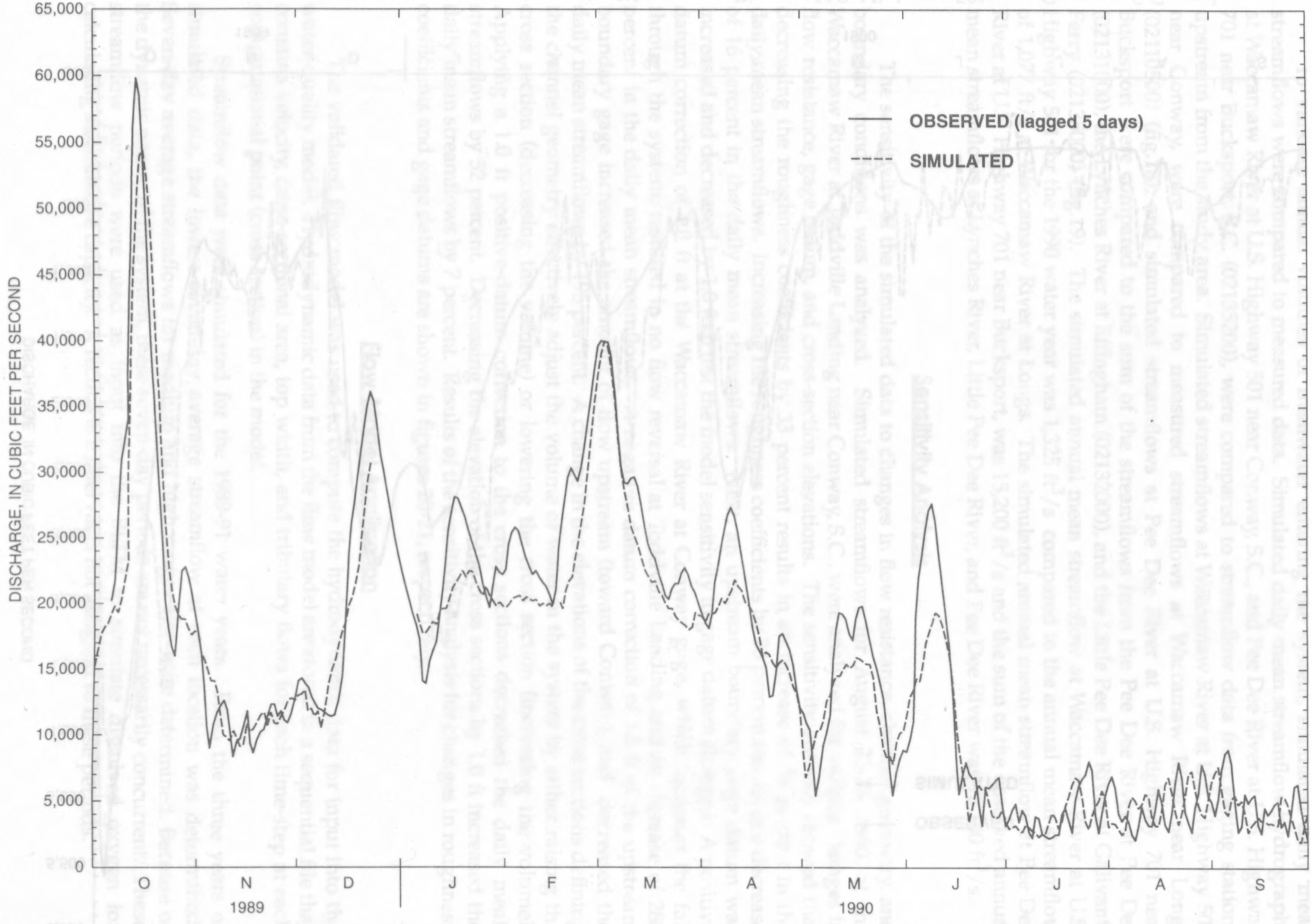

Figure 19.--Simulated daily mean discharge for Pee Dee River at U.S. Highway 701 near Bucksville, S.C., and sum of observed daily mean discharge of three upstream tributaries lagged 5 days.

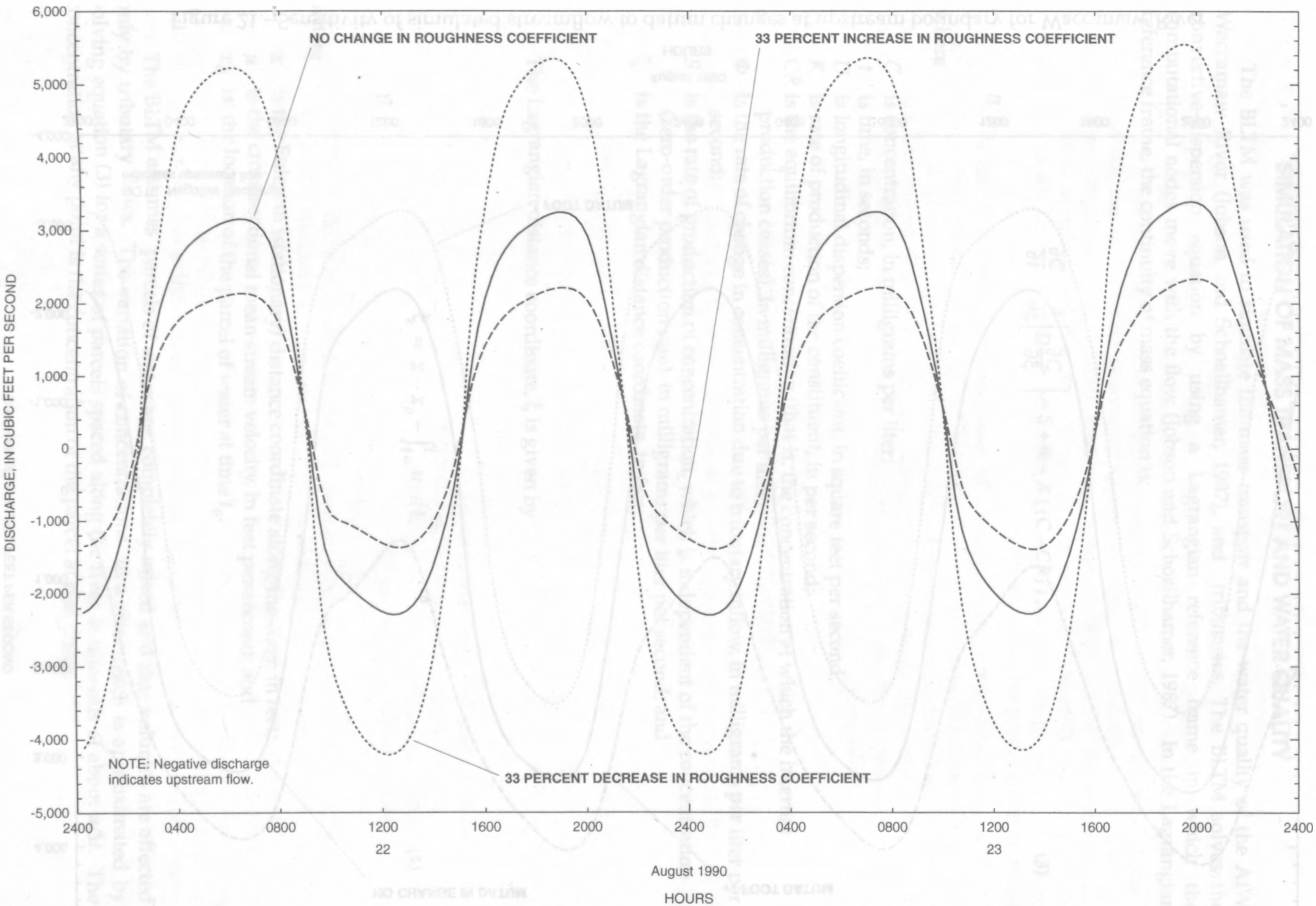

Figure 20.--Sensitivity of simulated streamflow to changes in roughness coefficient values for Waccamaw River near Toddville Landing near Conway, S.C., August 22-23, 1990.

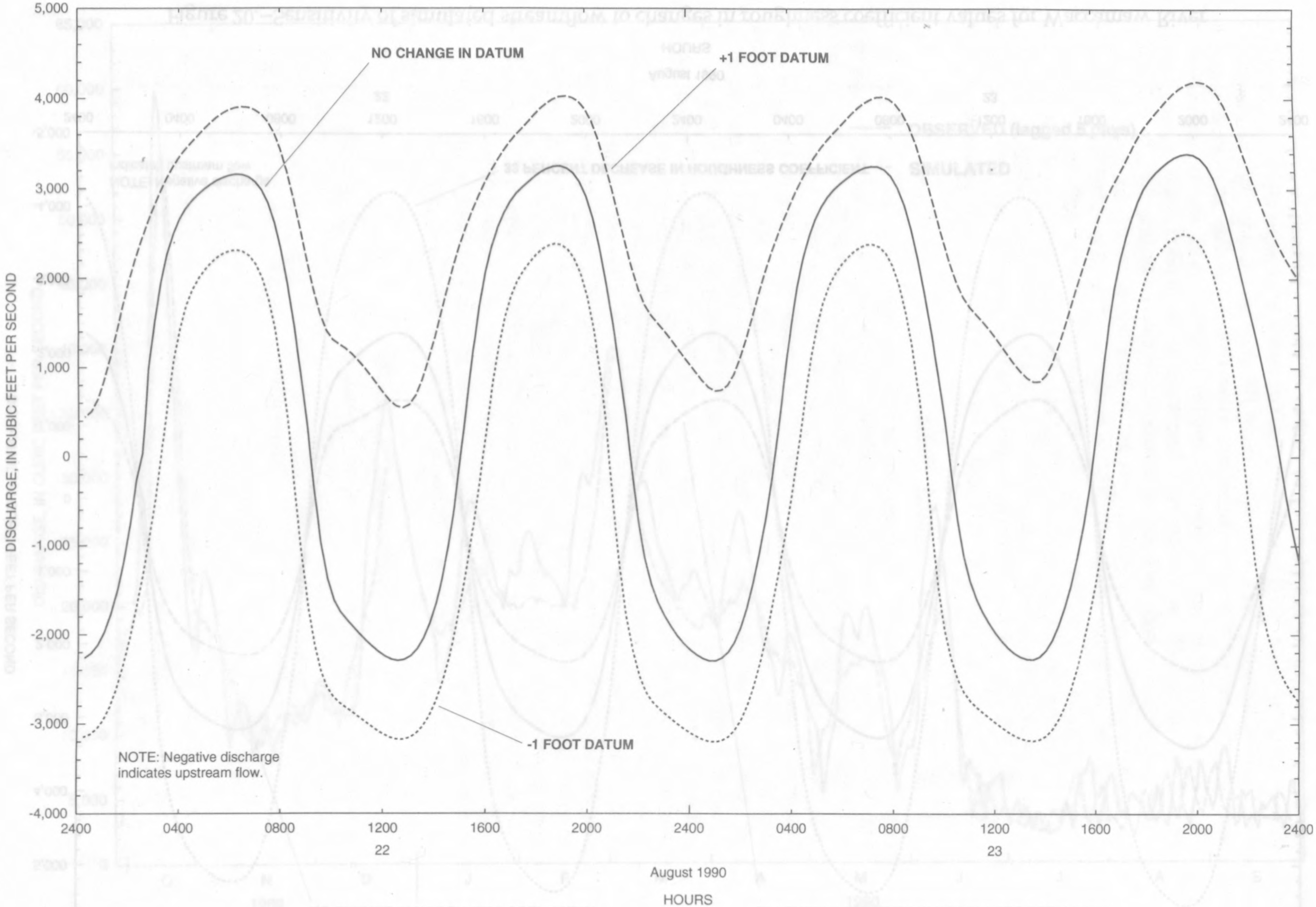

Figure 21.--Sensitivity of simulated streamflow to datum changes at upstream boundary for Waccamaw River near Toddville Landing near Conway, S.C., August 22-23, 1990.

SIMULATION OF MASS TRANSPORT AND WATER QUALITY

The BLTM was used to simulate the mass transport and the water quality of the AIW, Waccamaw River (Jobson and Schoellhamer, 1987), and tributaries. The BLTM solves the convective-dispersion equation by using a Lagrangian reference frame in which the computational nodes move with the flow (Jobson and Schoellhamer, 1987). In the Lagrangian reference frame, the continuity of mass equation is:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial \xi}\left[D\frac{\partial C}{\partial \xi}\right] + S + \Phi + K((C - CR)) \quad (3)$$

where

C is concentration, in milligrams per liter;
t is time, in seconds;
D is longitudinal dispersion coefficient, in square feet per second;
K is rate of production of the constituent, in per second;
CR is the equilibrium concentration (that is, the concentration at which the internal production ceases), in milligrams per liter;
Φ is the rate of change in concentration due to tributary inflow, in milligrams per liter per second;
S is the rate of production of concentration, which is independent of the concentration (zero-order production rate), in milligrams per liter per second; and
ξ is the Lagrangian distance coordinate, in feet.

The Lagrangian distance coordinate, ξ is given by

$$\xi = x - x_o - \int_{to}^{t} u \; dt, \quad (4)$$

where

x is the Eulerian (stationary) distance coordinate along the river, in feet;
u is the cross-sectional mean stream velocity, in feet per second; and
x_o is the location of the parcel of water at time t_o.

The BLTM assumes parcels of water are completely mixed and that volumes are affected only by tributary flows. The variation of concentrations in a river reach is approximated by solving equation (3) for a series of parcels spaced along the river at intervals of about $u\Delta t$. The concentration at any point is the concentration of the parcel at that point.

The assumption of completely mixed parcels may cause interpolation errors when determining the concentration of a given point. The accuracy of a Lagrangian model, as compared to an Eulerian model, is that this interpolation error applies only to the output computations; the grid concentration is not used in further computations, and therefore, the error is not compounded. In an Eulerian model, similar interpolation errors are made for every time step and grid point, but the interpolated values are used as the basis of all further computations (Jobson, 1981). The advantages of the Lagrangian approach are (1) the scheme is very accurate in modeling the convection and dispersion terms in comparison to the usual Eulerian approach (Jobson, 1980; Thomson and others, 1984), (2) the Lagrangian model is stable for any time step (Jobson, 1981), (3) the computer code for the algorithms is short, (4) the conceptual model directly represents the actual transport processes, and (5) the model does not require extensive computer resources to run.

The water-quality subroutine of the BLTM uses the reaction kinetics found in the QUAL2 water-quality model (Roesner and others, 1977a, 1977b). The model can simulate up to 10 major constituents that affect dissolved-oxygen concentration dynamics. The model has the ability to allow for multiple waste discharges, withdrawals, tributary flows, and incremental inflow and outflow. A conceptualization of the constituents and their interaction in the QUAL2 model are shown in figure 22.

Mass Transport Model Calibration and Validation

The mass transport model was calibrated with measured specific conductance data from the gaging stations located along the AIW to determine dispersion factors. The dimensionless dispersion factor is used in the Lagrangian Transport solution. The factor is defined as:

$$D_f = \frac{D}{\Delta t \mu^2}, \qquad (5)$$

where

D_f is dispersion factor, (dimensionless);
D is dispersion rate, in square feet per second;
Δt is simulation time step, in seconds; and
μ is mean velocity, in feet per second.

Specific conductance, an indirect measure of dissolved solids, is a conservative constituent and is an effective natural tracer for calibrating mass transport. Concentrations of conservative constituents are not affected by biological degradation, but are changed by increases or decreases of that constituent in the subreach or by dilution in response to changing streamflow conditions. Specific conductance values were input to the model at the external boundaries of the AIW at S.C. Highway 9 at Nixons Crossroads, S.C., and at Waccamaw River at Hagley Landing near Pawleys Island, S.C. Specific conductance simulations were calibrated by adjustment of the dispersion factor. A dispersion factor of 0.03 (for an hourly time step) was used for the entire model. Simulated and measured specific conductances for the AIW at Grand Strand Airport, North Myrtle Beach, S.C., October 2-5, 1990, are compared in figure 23.

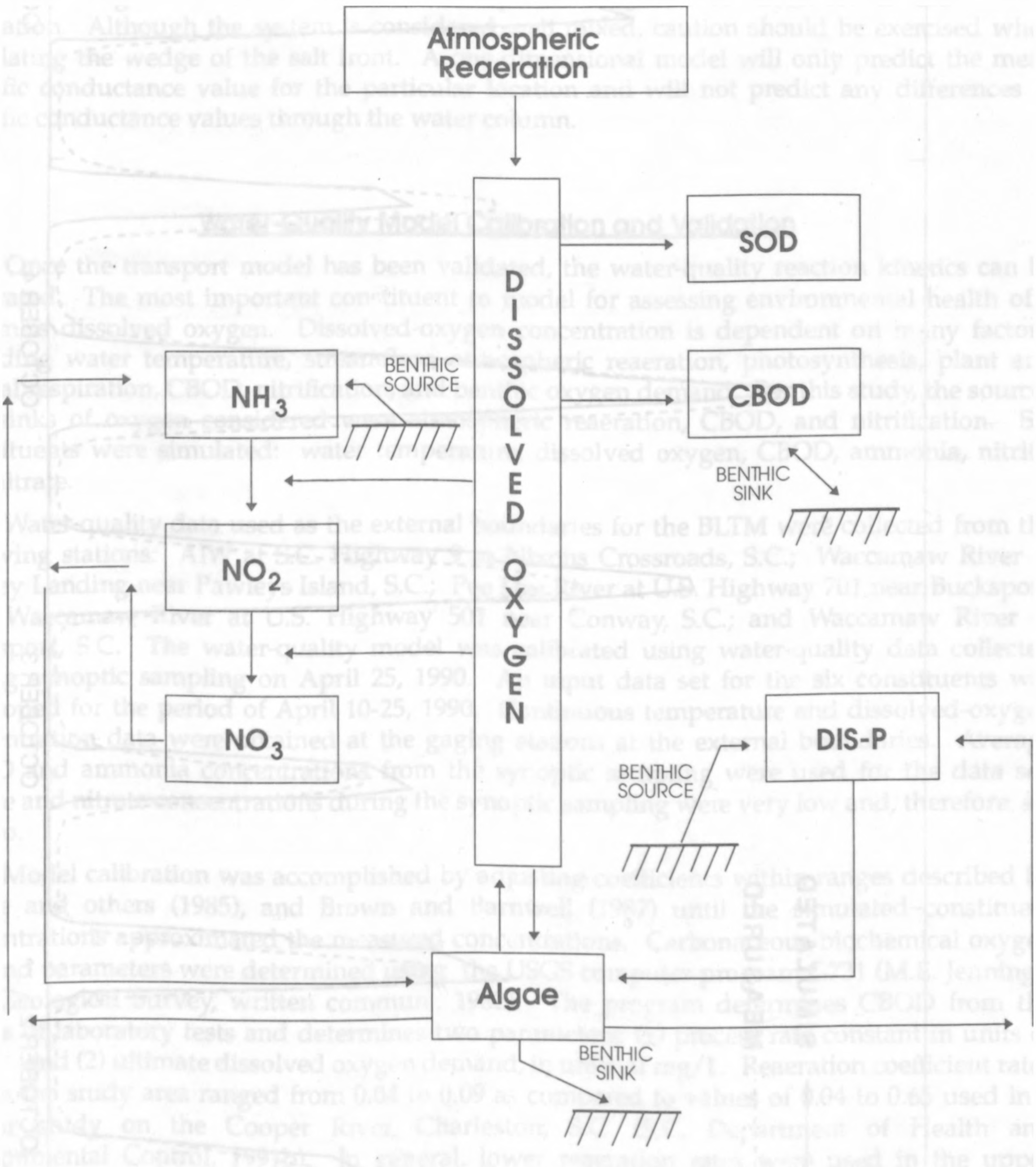

Figure 22.--Major constituents interaction in the QUAL2 model.

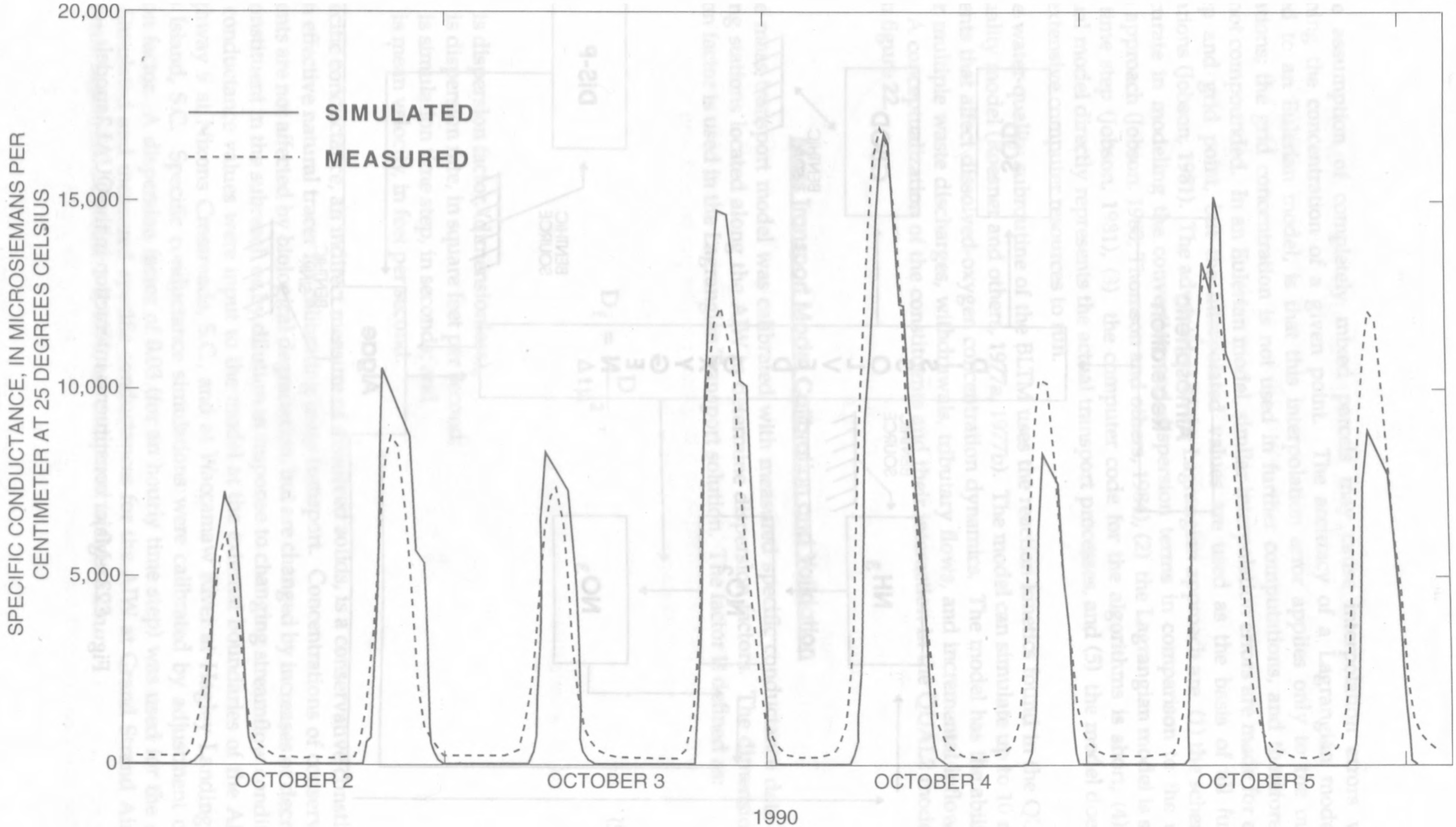

Figure 23.--Simulated and measured specific conductance used in calibration of the mass transport model in the Atlantic Intracoastal Waterway at Grand Strand Airport, North Myrtle Beach, S.C., October 2-5, 1990.

For validation of the transport model, specific conductance data for the period July 7-12, 1990, at the AIW at Grand Strand Airport, North Myrtle Beach, S.C., (02110770) were used. Simulated values corresponded favorably to measured specific conductances (fig. 24).

The transport model is considered validated over the range of conditions used in the calibration and validation process. Caution should be used when simulating specific conductances greater than or less than the specific conductances used for calibration and validation. Although the system is considered well mixed, caution should be exercised when simulating the wedge of the salt front. A one-dimensional model will only predict the mean specific conductance value for the particular location and will not predict any differences in specific conductance values through the water column.

Water-Quality Model Calibration and Validation

Once the transport model has been validated, the water-quality reaction kinetics can be calibrated. The most important constituent to model for assessing environmental health of a stream is dissolved oxygen. Dissolved-oxygen concentration is dependent on many factors, including water temperature, streamflow, atmospheric reaeration, photosynthesis, plant and animal respiration, CBOD, nitrification, and benthic oxygen demand. For this study, the sources and sinks of oxygen considered were atmospheric reaeration, CBOD, and nitrification. Six constituents were simulated: water temperature, dissolved oxygen, CBOD, ammonia, nitrite, and nitrate.

Water-quality data used as the external boundaries for the BLTM were collected from the following stations: AIW at S.C. Highway 9 at Nixons Crossroads, S.C.; Waccamaw River at Hagley Landing near Pawleys Island, S.C.; Pee Dee River at U.S. Highway 701 near Bucksport, S.C.; Waccamaw River at U.S. Highway 501 near Conway, S.C.; and Waccamaw River at Bucksport, S.C. The water-quality model was calibrated using water-quality data collected during synoptic sampling on April 25, 1990. An input data set for the six constituents was developed for the period of April 10-25, 1990. Continuous temperature and dissolved-oxygen concentration data were obtained at the gaging stations at the external boundaries. Average CBOD and ammonia concentrations from the synoptic sampling were used for the data set. Nitrite and nitrate concentrations during the synoptic sampling were very low and, therefore, set to zero.

Model calibration was accomplished by adjusting coefficients within ranges described by Bowie and others (1985), and Brown and Barnwell (1987) until the simulated constituent concentrations approximated the measured concentrations. Carbonaceous biochemical oxygen demand parameters were determined using the USGS computer program G731 (M.E. Jennings, U.S. Geological Survey, written commun., 1982). The program determines CBOD from the results of laboratory tests and determines two parameters: (1) process rate constant in units of days $^{-1}$ and (2) ultimate dissolved oxygen demand, in units of mg/L. Reaeration coefficient rates within the study area ranged from 0.04 to 0.09 as compared to values of 0.04 to 0.65 used in a similar study on the Cooper River, Charleston, S.C. (S.C. Department of Health and Environmental Control, 1991b). In general, lower reaeration rates were used in the upper reaches of the model and increased towards the lower boundaries. Rate constants used in the model and recommended values are listed in table 7. A calibration hydrograph of simulated and measured dissolved-oxygen concentrations for April 10-25, 1990, at AIW at S.C. Highway 544, are shown in figure 25. Similar hydrograph comparisons were made at three other internal stations. Additional comparisons were made between simulated and measured concentrations of dissolved oxygen, CBOD, and ammonia for the day of synoptic sampling.

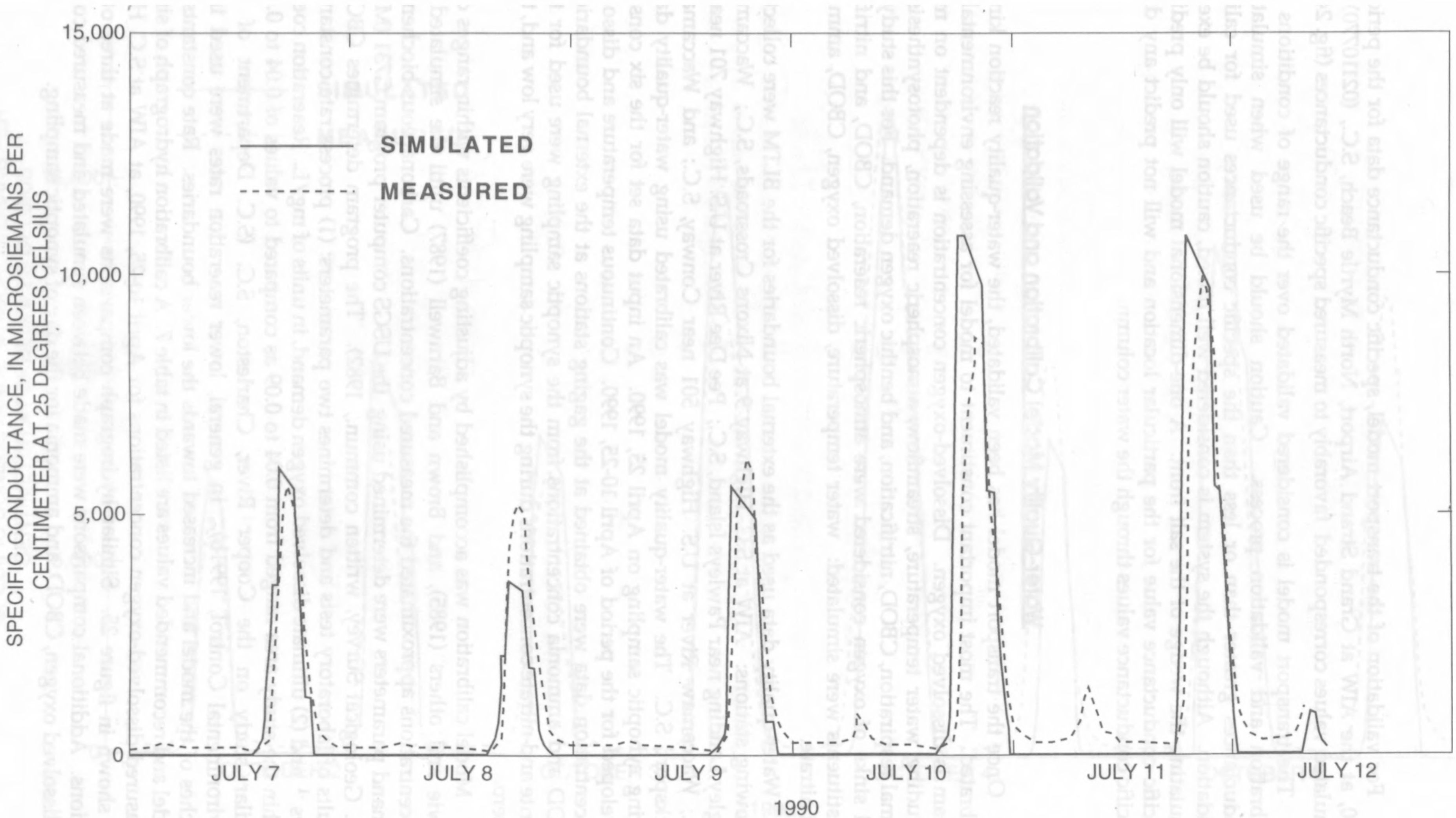

Figure 24.--Simulated and measured specific conductance used in validation of the mass transport model for the Atlantic Intracoastal Waterway at Grand Strand Airport, North Myrtle Beach, S.C., July 7-12, 1990.

Table 7.--*Recommended rate constant values and values used in the Branched Lagrangian Transport Model*

[mg, milligram; m, meter; NH_3, ammonia; NO_2, nitrite; NO_3, nitrate; ---, no recommended value]

Variable	Recommended values[1]	Value used
Carbonaceous biological oxygen demand decay rate in day^{-1} (30 day)	0.02 - 3.4	0.09
Atmospheric reaeration rate in day^{-1}	0 - 100	.07
Carbonaceous sink rate in day^{-1}	-.36 - .36	.01
Benthos consumption of oxygen in mg $day^{-1}m^{-1}$	---	.99
Rate constant for biological oxidation of NH_3 to NO_2 in day^{-1}	.1 - 1.0	.23
Benthos source rate for ammonia in mg of ^{-}N $day^{-1}m^{-1}$	---	1.50
Rate constant for biological oxidation of NO_2 to NO_3 day^{-1}	.2 - 2.0	.60
Oxygen used to oxidize ammonia $\frac{mg\text{-}O}{mg\ N}$	3 - 4	3.90

[1]Brown and Barnwell, 1987

The water-quality model for the AIW and Waccamaw River was validated using synoptic data collected on September 1, 1989, and August 25, 1990, respectively. Input data sets for the six constituents (water temperature, dissolved oxygen, CBOD, ammonia, nitrite, and nitrate) were developed for September 6-17, 1989, and August 10-18, 1990. These data sets were developed in the same manner as the data sets that were used in the calibration. A verification hydrograph of simulated and measured dissolved-oxygen concentrations for the Waccamaw River at Peachtree Landing near Conway, S.C., for September 6-16, 1989, are shown in figure 26. Similar hydrograph comparisons were made at three other internal stations. Additional comparisons were made between simulated and measured concentrations of dissolved oxygen, CBOD, and ammonia for the day of the synoptic sampling.

The water-quality model is considered validated over the range of conditions used in the calibration and validation process. Caution should be used when simulating physical water-quality properties, nutrient concentrations, and flows greater than or less than those used for calibration and validation.

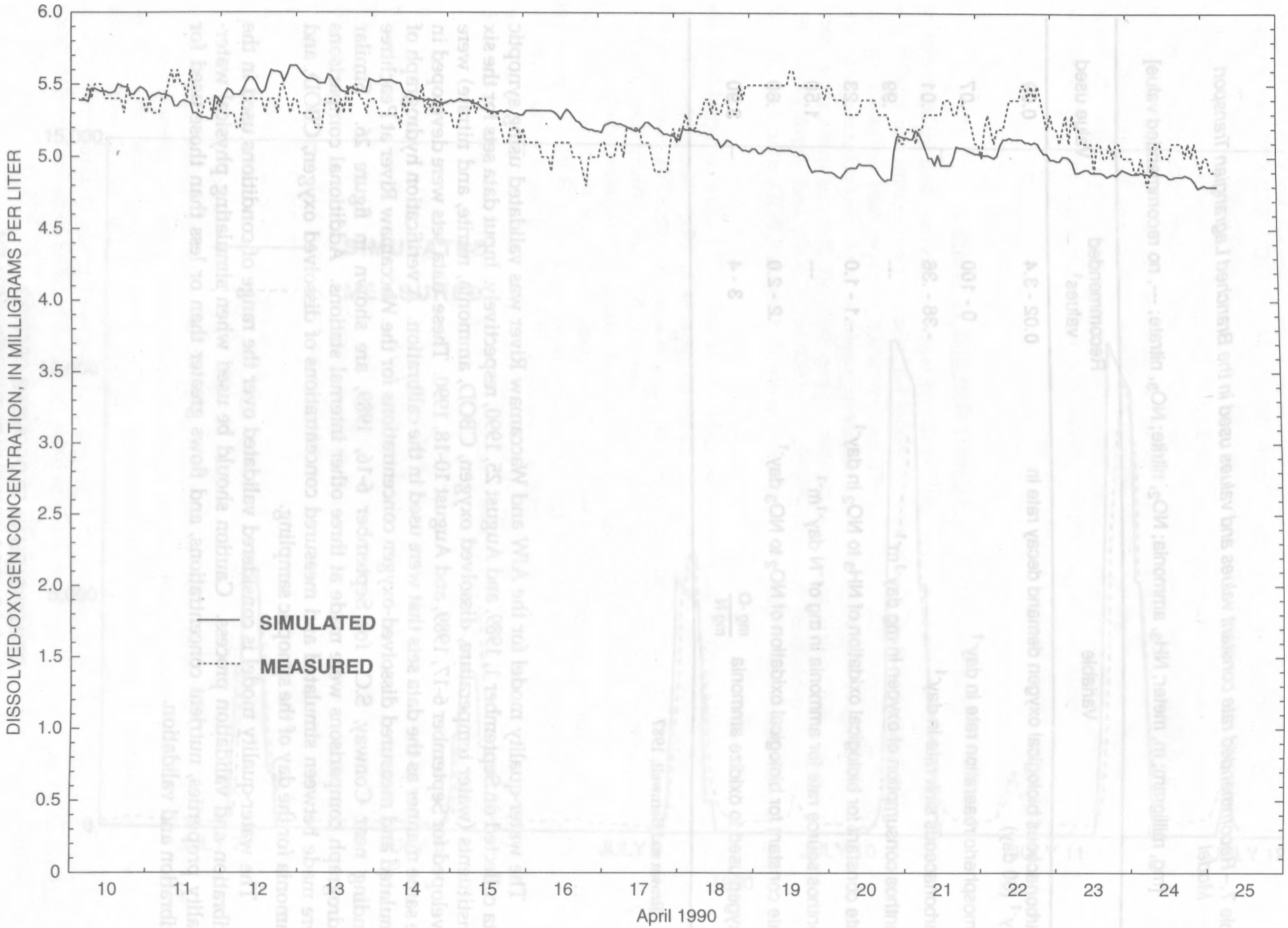

Figure 25.--Simulated and measured dissolved oxygen concentrations used in calibration of the water-quality model for the Atlantic Intracoastal Waterway at S.C. Highway 544 near Socastee, S.C., April 10-25, 1990.

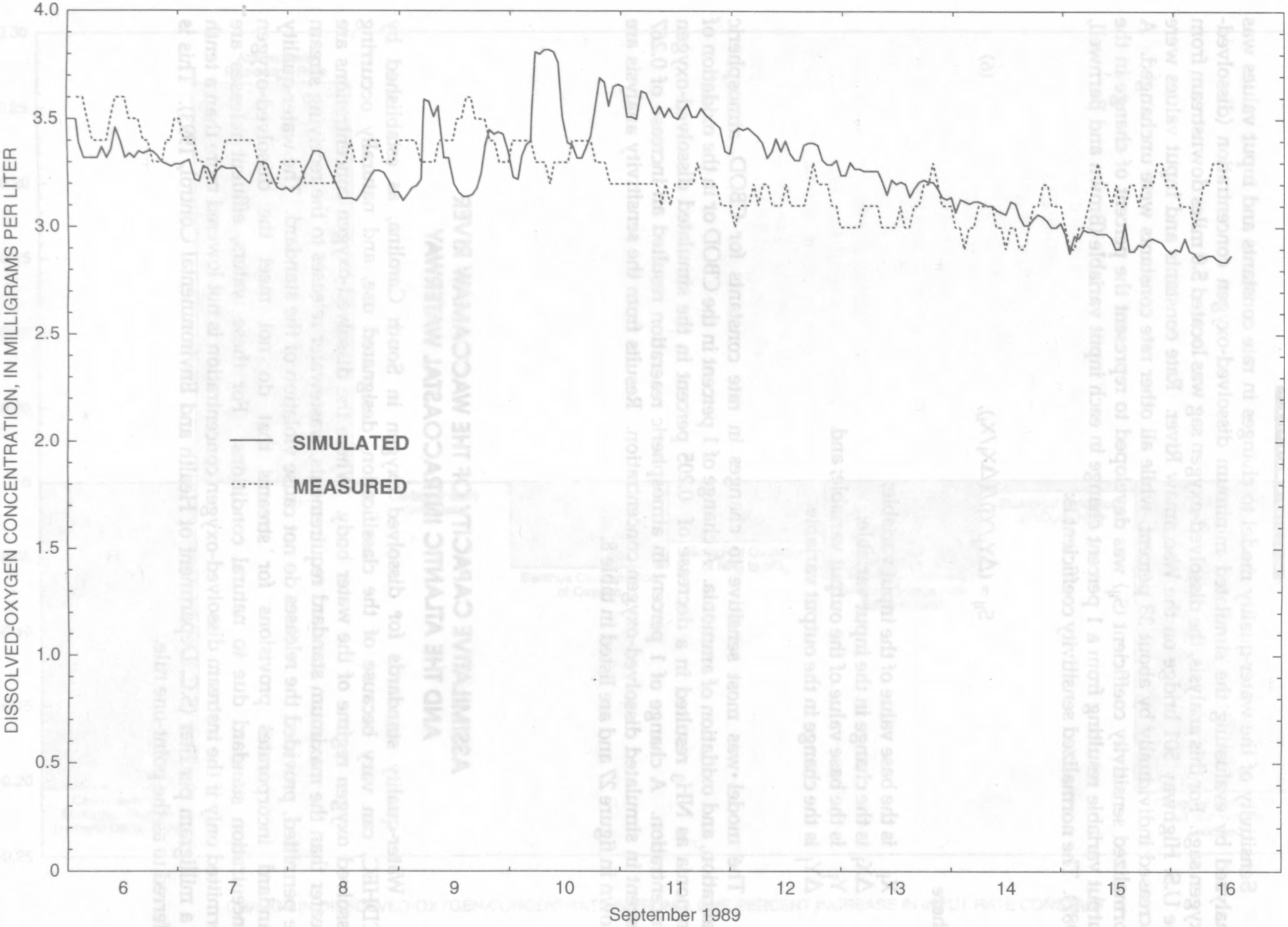

Figure 26.--Simulated and measured dissolved oxygen concentrations used in validation of the water-quality model for Waccamaw River at Peachtree Landing near Conway, S.C., September 6-16, 1989.

Sensitivity Analysis

Sensitivity of the water-quality model to changes in rate constants and input values was analyzed by evaluating the simulated minimum dissolved-oxygen concentration (dissolved-oxygen sag). For this analysis, the dissolved-oxygen sag was located 5.0 miles downstream from the U.S. Highway 501 bridge on the Waccamaw River. Rate constants and input values were increased individually by about 33 percent, while all other rate constants were unchanged. A normalized sensitivity coefficient (S_{ij}) was developed to represent the percent of change in the output variable resulting from a 1 percent change in each input variable (Brown and Barnwell, 1987). The normalized sensitivity coefficient is:

$$S_{ij} = (\Delta Y_j / Yj)/(\Delta X_i / X_i), \tag{6}$$

where

X_i is the base value of the input variable;
ΔX_i is the change in the input variable;
Y_j is the base value of the output variable; and
ΔY_j is the change in the output variable.

The model was most sensitive to changes in rate constants for CBOD, atmospheric reaeration, and oxidation of ammonia. A change of 1 percent in the CBOD or in the oxidation of ammonia as NH_3 resulted in a decrease of 0.205 percent in the simulated dissolved-oxygen concentration. A change of 1 percent in atmospheric reaeration resulted an increase of 0.267 percent in simulated dissolved-oxygen concentration. Results from the sensitivity analysis are shown in figure 27 and are listed in table 8.

ASSIMILATIVE CAPACITY OF THE WACCAMAW RIVER AND THE ATLANTIC INTRACOASTAL WATERWAY

Water-quality standards for dissolved oxygen in South Carolina, as established by SCDHEC, can vary because of the classification, designated use, and naturally occurring dissolved oxygen regime of the water body. Where the dissolved-oxygen concentrations are greater than the maximum standard requirements, wastewater releases to the receiving stream are permitted, provided the releases do not cause violation of the standard. The water-quality standard incorporates provisions for streams that do not meet the dissolved-oxygen concentration standard due to natural conditions. For these waters, effluent releases are permitted only if the instream dissolved-oxygen concentration is not lowered more than a tenth of a milligram per liter (S.C. Department of Health and Environmental Control, 1993). This is referred to as the point-one rule.

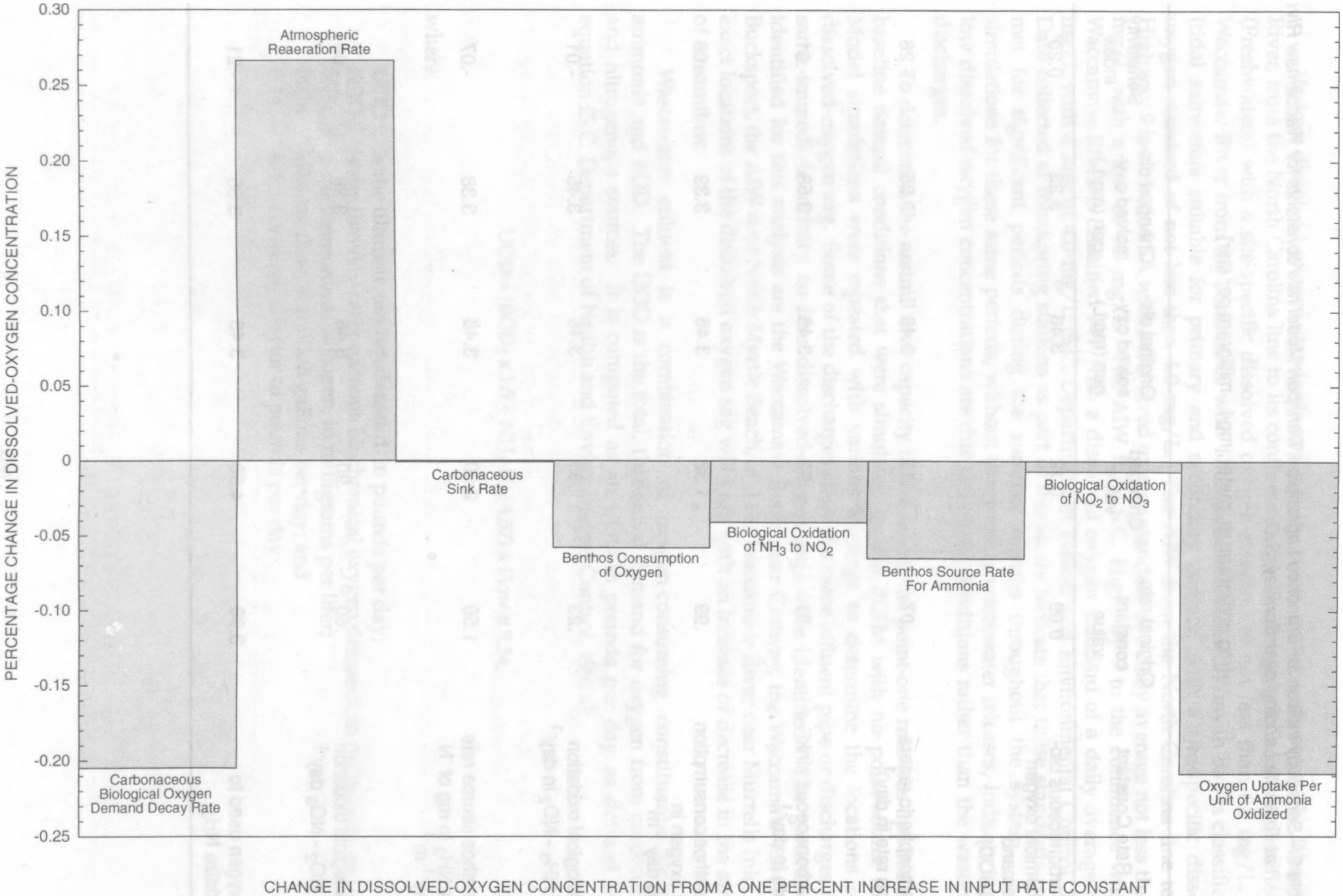

Figure 27.--Sensitivity indices for simulation of dissolved-oxygen concentration using the Branched Lagrangian Transport Model.

Table 8.--*Sensitivity indices for Branched Lagrangian Transport Model rate constants for Waccamaw River at Toddville Landing near Conway, S.C.*

[mg, milligram; m, meter; mg/L, milligram per liter]

Rate Constant	Original rate constant value	Changed value	Original dissolved oxygen (mg/L)	Changed dissolved oxygen (mg/L)	Sensitivity index
Carbonaceous biochemical oxygen demand (CBOD)	0.09	0.12	3.46	3.22	0.20
Atmospheric reaeration rate in day^{-1}	.07	.10	3.46	3.85	-.26
Carbonaceous sink rate in day^{-1}	-.01	.36	3.46	3.58	<-.01
Benthos consumption of oxygen in $mg\ day^{-1}\ m^{-1}$	.99	1.32	3.46	3.39	-.06
Biological oxidation of NH_3 - NO_2 in day^{-1}	.23	.33	3.46	3.45	-.01
Benthos source rate for NH_3 in mg of ^{-}N $day^{-1}\ m^{-1}$	1.50	2.00	3.46	3.38	-.07
Biological oxidation of NO_2 - NO_3 day^{-1}	.60	.90	3.46	3.39	-.04
Oxygen used to oxidize NH_3	3.90	4.50	3.46	3.35	-.21

Various dissolved-oxygen standards apply to the rivers in the study area. The Waccamaw River, from the North Carolina line to its confluence with Thoroughfare Creek, is classified FW (Freshwaters) with a site-specific dissolved oxygen standard of not less than 4.0 mg/L. The Waccamaw River from the confluence with Thoroughfare Creek to Winyah Bay is classified SA (tidal saltwaters suitable for primary and secondary contact) with a site-specific dissolved oxygen standard of not less than 4.0 mg/L. The AIW from the North Carolina line to S.C. Highway 9 is classified SA with a dissolved oxygen standard of a daily average not less than 5.0 mg/L with a low of 4.0 mg/L. The AIW from S.C. Highway 9 to the confluence with the Waccamaw River is classified FW with a dissolved oxygen standard of a daily average of 5.0 mg/L with a low of 4.0 mg/L (S.C. Department of Health and Environmental Control, 1993). Data collected at monitoring stations as part of this study indicate that these standards are not met for significant periods during the summer months throughout the system. Model simulations for these same periods, without the existing wastewater releases, indicate that the low dissolved-oxygen concentrations are due to natural conditions rather than the wastewater discharges.

To determine the assimil ıtive capacity of the rivers, the point-one rule was applied to the baseline natural conditions that were simulated by the BLTM with no point-source inputs. Model simulations were repeated with various loadings to determine the locations of the dissolved-oxygen sag. Some of the discharges share the same effluent pipe or discharges in the same immediate vicinity, so four dissolved-oxygen sags were identified. The general areas identified for this analysis are the Waccamaw River near Conway, the Waccamaw River near Bucksport, the AIW near North Myrtle Beach, and the Waccamaw River near Murrells Inlet. The exact locations of the dissolved oxygen sag will vary with an increase or decrease in the amount of streamflow.

Wastewater effluent is a combination of oxygen-consuming constituents, primarily ammonia and BOD. The UOD is the total, theoretical demand for oxygen from carbonaceous and nitrogenous sources. It is computed as an UOD in pounds per day, as defined by the equation (S.C. Department of Health and Environmental Control, 1991a):

$$UOD = (BOD_5 \times 1.5 + NH_3\text{-}N \times 4.57) \times Flow \times 8.34, \qquad (7)$$

where

UOD is the ultimate oxygen demand, in pounds per day;
BOD_5 is the five-day carbonaceous biochemical oxygen demand, in milligrams per liter;
NH_3-N is the ammonia as nitrogen, in milligrams per liter;
Flow is waste flow, in million gallons per day; and
8.34 is the conversion factor to pounds per day.

Assimilative capacities at Waccamaw River near Conway were determined for six different 7-day average streamflows, as listed in the following table. Results indicate the UOD ranged from 370 to 6,740 lbs/d for 7-day average streamflows of 17 to 1,500 ft^3/s, respectively. The location of the dissolved oxygen sag varied from 2 to 6 miles downstream of Toddville Landing at low and high flows, respectively. An assimilative capacity curve for the Waccamaw River near Conway is shown in figure 28.

7-day average streamflow (cubic feet per second)	Date	Ultimate oxygen demand (pounds per day)	Dissolved oxygen sag location in miles downstream from station 02110707 (fig. 1)
17	07-13-90 to 07-19-90	370	1.7
97	09-29-90 to 10-06-90	570	2.5
172	07-05-90 to 07-11-90	1,100	3.7
457	06-18-90 to 06-24-90	2,150	5.0
634	07-05-91 to 07-11-91	3,200	6.5
1,500	10-13-91 to 10-19-91	6,740	11.0

Assimilative capacities at Waccamaw River near Bucksport were determined for four different 7-day average streamflows, as listed below. Results indicate the UOD ranged from 580 to 7,300 lb/d for 7-day average streamflow from 62 to 1,180 ft^3/s, respectively. The location of the dissolved oxygen sag varies from 2 to 4 miles downstream from the confluence of the AIW and Waccamaw River at low and high flows, respectively. An assimilative capacity curve for the Waccamaw River near Bucksport is shown in figure 29.

7-day average streamflow (cubic feet per second)	Date	Ultimate oxygen demand (pounds per day)	Dissolved oxygen sag location in miles downstream from station 02110802 (fig. 6)
62	07-05-90 to 07-11-90	580	0.2
183	07-05-91 to 07-11-91	910	1.0
640	01-16-90 to 01-22-90	4,200	1.5
1,180	10-11-92 to 10-17-92	7,300	2.3

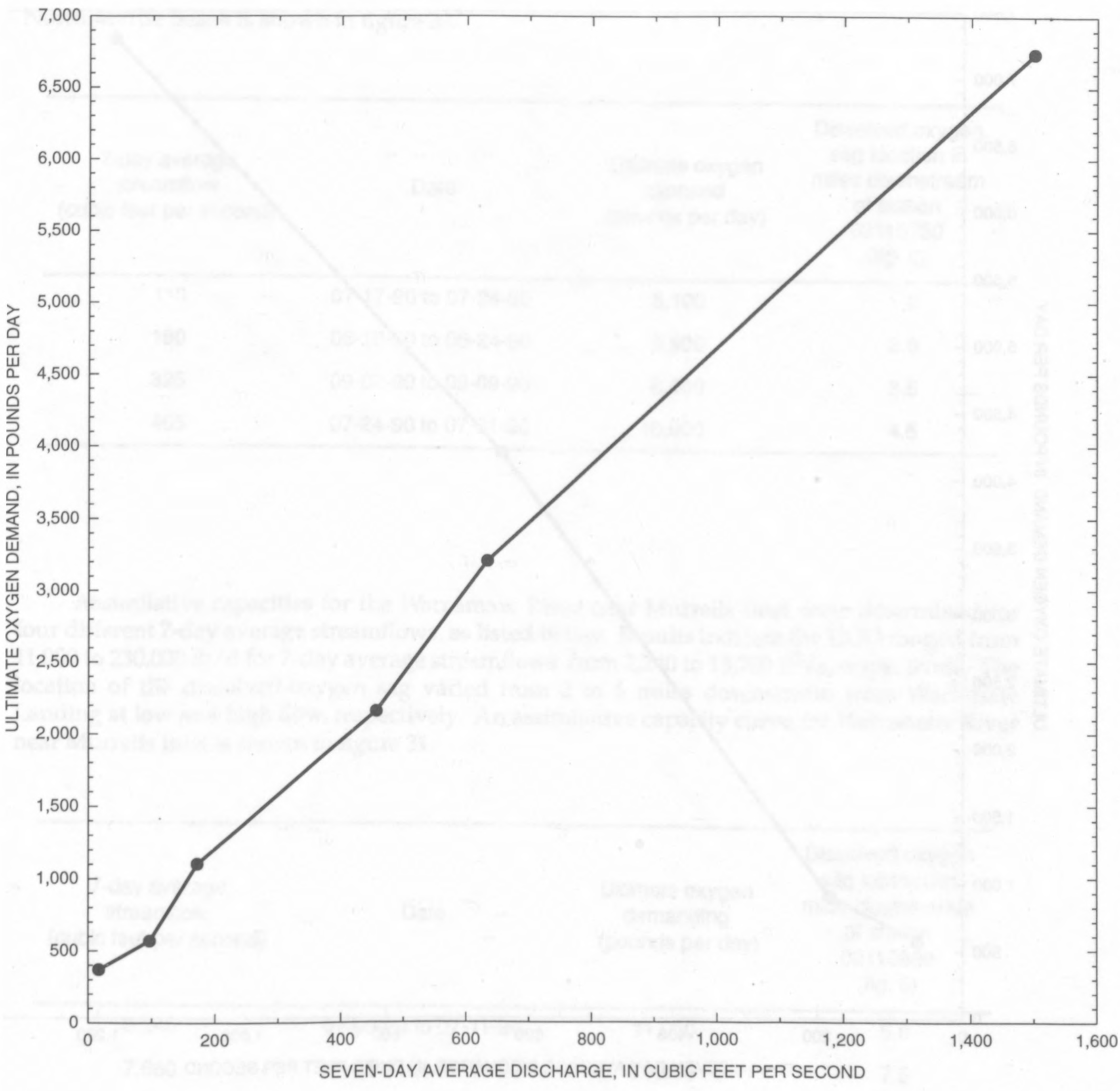

Figure 28.--Assimilative capacity curve for Waccamaw River near Conway, S.C.

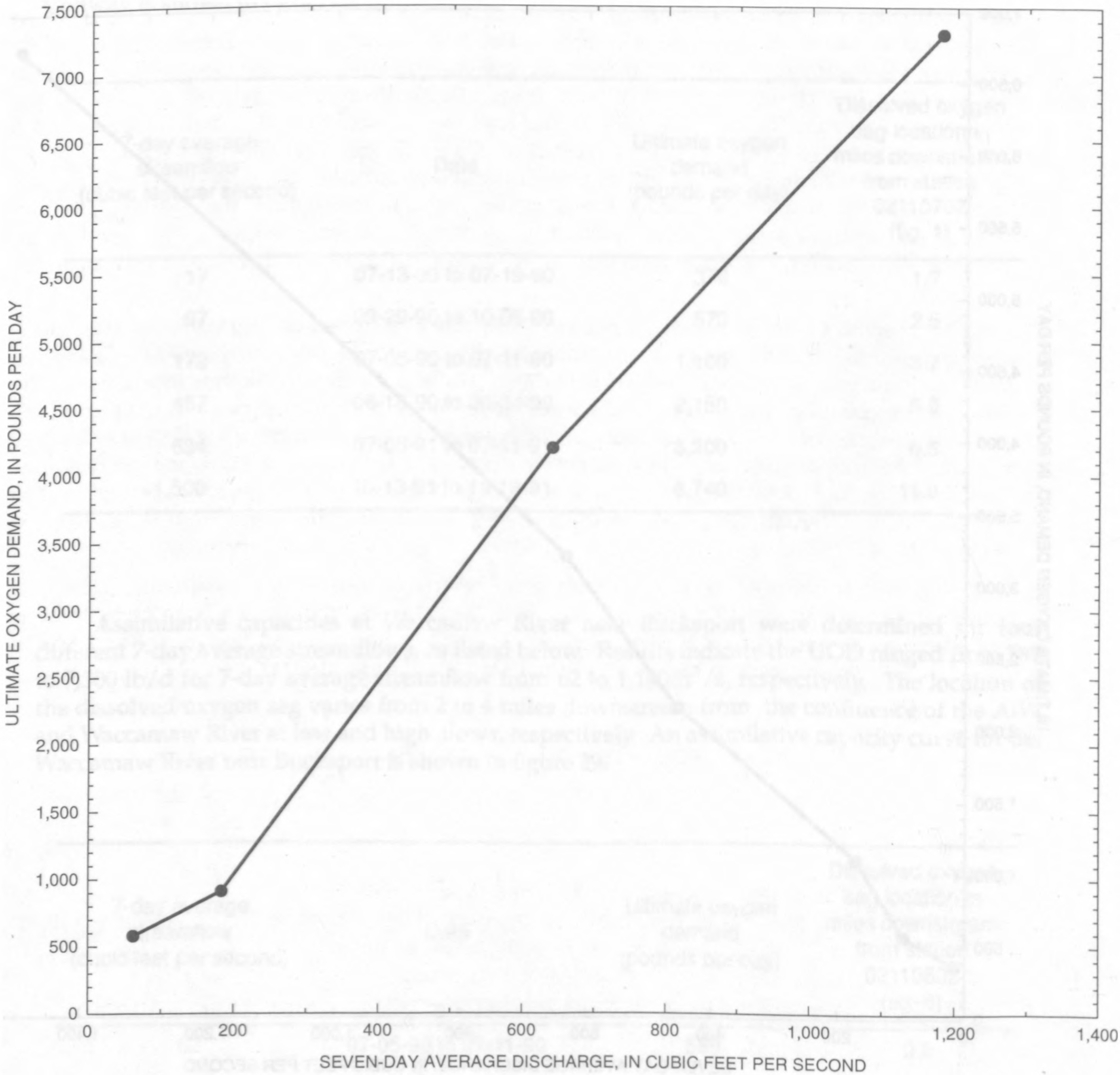

Figure 29.--Assimilative capacity curve for Waccamaw River near Bucksport, S.C.

Assimilative capacities for the AIW near North Myrtle Beach were determined for four different 7-day average streamflows, as listed below. Results indicate the UOD ranged from 5,100 to 10,000 lb/d for 7-day average streamflows from 110 to 465 ft^3/s, respectively. The location of the dissolved oxygen sag varies from 1 to 4.5 miles from the North Myrtle Beach Airport at low and high flows, respectively. An assimilative capacity curve for the AIW near North Myrtle Beach is shown in figure 30.

7-day average streamflow (cubic feet per second)	Date	Ultimate oxygen demand (pounds per day)	Dissolved oxygen sag location in miles downstream of station 02110730 (fig. 6)
110	07-17-90 to 07-24-90	5,100	1.0
180	06-18-90 to 06-24-90	5,900	2.0
325	09-02-90 to 09-09-90	8,000	3.5
465	07-24-90 to 07-31-90	10,000	4.5

Assimilative capacities for the Waccamaw River near Murrells Inlet were determined for four different 7-day average streamflows, as listed below. Results indicate the UOD ranged from 11,000 to 230,000 lb/d for 7-day average streamflows from 2,240 to 13,700 ft^3/s, respectively. The location of the dissolved-oxygen sag varied from 2 to 6 miles downstream from Wachesaw Landing at low and high flow, respectively. An assimilative capacity curve for Waccamaw River near Murrells Inlet is shown in figure 31.

7-day average streamflow (cubic feet per second)	Date	Ultimate oxygen demanding (pounds per day)	Dissolved oxygen sag location in miles downstream of station 02110809 (fig. 6)
2,240	07-05-90 to 07-11-90	11,000	5.0
7,660	07-05-91 to 07-11-91	71,200	7.5
12,000	10-11-92 to 10-16-72	191,000	9.0
13,700	08-20-91 to 08-27-91	230,000	9.5

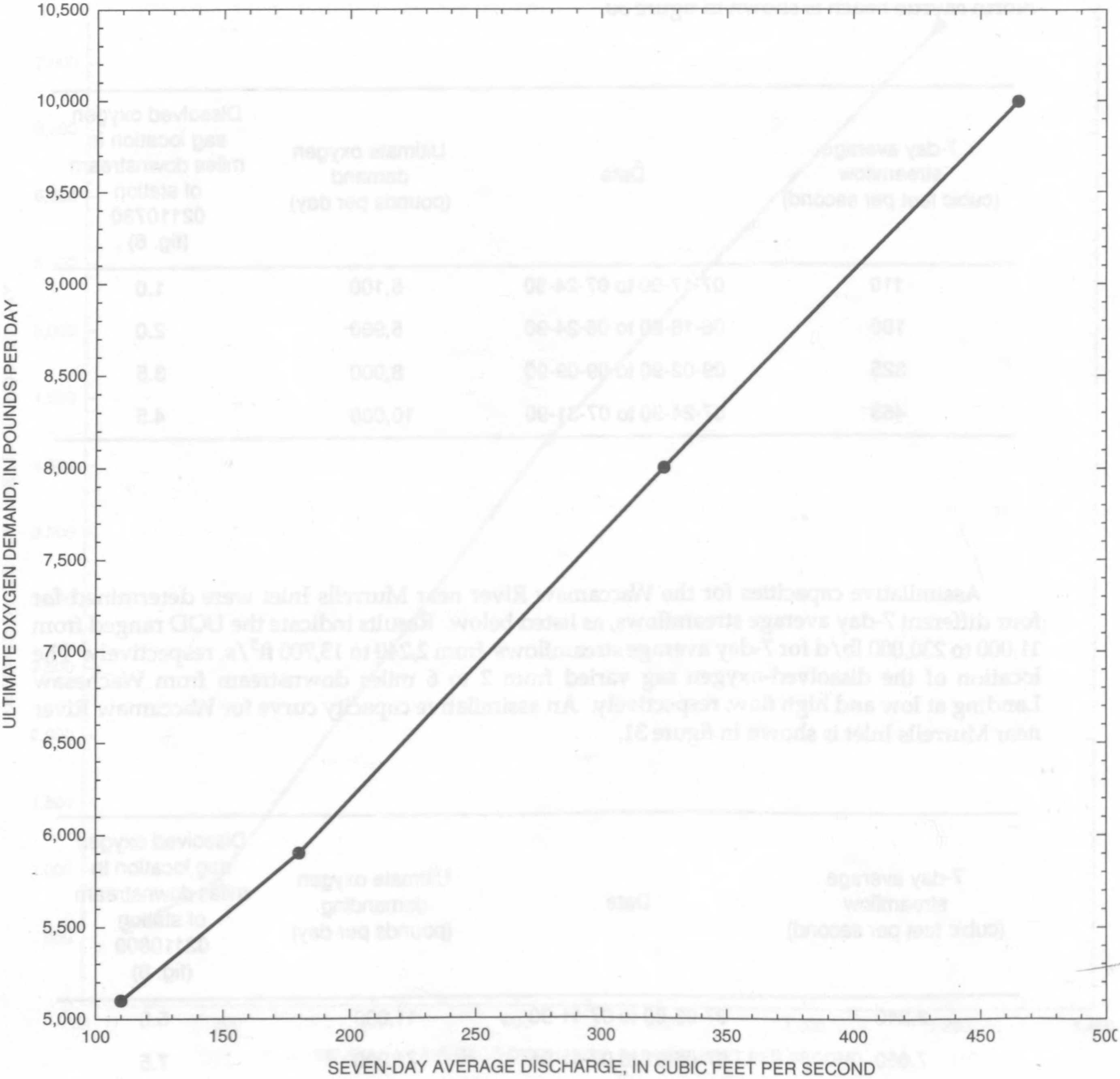

Figure 30.--Assimilative capacity curve for Atlantic Intracoastal Waterway near North Myrtle Beach, S.C.

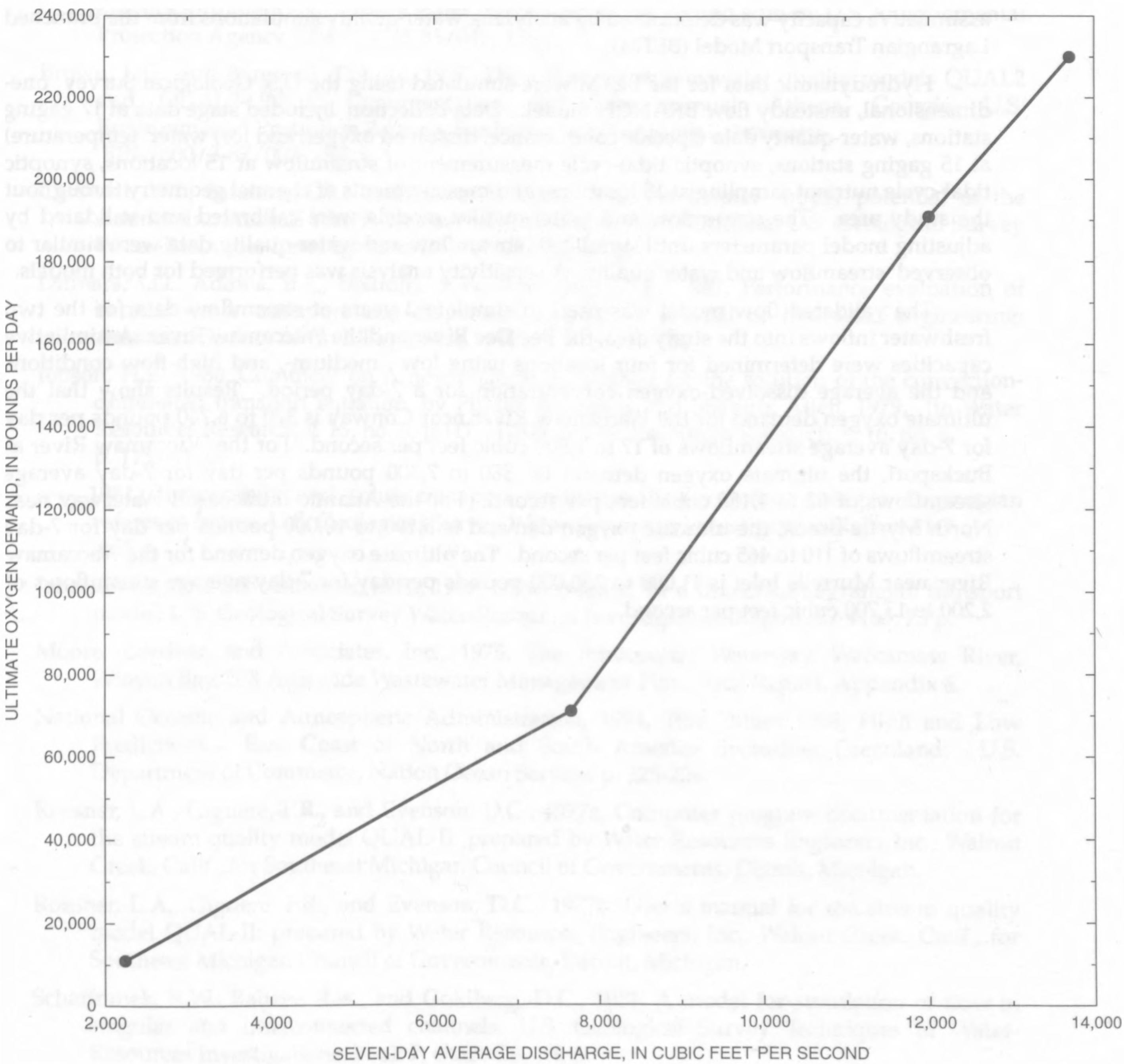

Figure 31.--Assimilative capacity curve for Waccamaw River near Murrells Inlet, S.C.

SUMMARY

The assimilative capacity was determined for tidally affected reaches of the Waccamaw River and the Atlantic Intracoastal Waterway (AIW) near Myrtle Beach, S.C. The study area included the Pee Dee River south of U.S. Highway 701 bridge, the Waccamaw River south of the U.S. Highway 501 bridge, and the AIW south from S.C. Highway 9 to Pawleys Island. The assimilative capacity was determined by analyzing water-quality simulations from the Branched Lagrangian Transport Model (BLTM).

Hydrodynamic data for the BLTM were simulated using the U.S. Geological Survey one-dimensional, unsteady flow BRANCH model. Data-collection included stage data at 17 gaging stations, water-quality data (specific conductance, dissolved oxygen and (or) water temperature) at 15 gaging stations, synoptic tidal-cycle measurement of streamflow at 15 locations, synoptic tidal-cycle nutrient sampling at 15 locations, and measurements of channel geometry throughout the study area. The streamflow and water-quality models were calibrated and validated by adjusting model parameters until simulated streamflow and water-quality data were similar to observed streamflow and water quality. A sensitivity analysis was performed for both models.

The validated flow model was used to simulate 3 years of streamflow data for the two freshwater inflows into the study area, the Pee Dee River and the Waccamaw River. Assimilative capacities were determined for four locations using low-, medium-, and high-flow conditions and the average dissolved-oxygen concentration for a 7-day period. Results show that the ultimate oxygen demand for the Waccamaw River near Conway is 370 to 6,740 pounds per day for 7-day average streamflows of 17 to 1,500 cubic feet per second. For the Waccamaw River at Bucksport, the ultimate oxygen demand is 580 to 7,300 pounds per day for 7-day average streamflows of 62 to 1,180 cubic feet per second. For the Atlantic Intracoastal Waterway near North Myrtle Beach, the ultimate oxygen demand is 5,100 to 10,000 pounds per day for 7-day streamflows of 110 to 465 cubic feet per second. The ultimate oxygen demand for the Waccamaw River near Murrells Inlet is 11,000 to 230,000 pounds per day for 7-day average streamflows of 2,200 to 13,700 cubic feet per second.

SELECTED REFERENCES

Bowie, G.L., Mills, W.B., Porcella, D.B., Campbell, C.L., Pagenkopf, J.R., Rupp, G.L., Johnson, K.M., Chan, P.W.H., Gherini, S.A., and Chamberlin, C.E., 1985, Rates, constants, and kinetics formulation in surface water quality modeling, second edition: U.S. Environmental Protection Agency, EPA/600/3-85/040, 455 p.

Brown, L.C., and Barnwell, T.O., Jr., 1987, The enhanced stream water quality models QUAL2 and QUAL2-UNCAS--Documentation and user manual: Athens, Georgia, U.S. Environmental Protection Agency, Environmental Research Laboratory, EPA/600/3-87/007, 189 p.

Carswell, W.J., Sanders,. C.L., and Johnson, D.M., 1988, Freshwater supply potential of the Atlantic Intracoastal Waterway near Myrtle Beach, South Carolina: U.S. Geological Survey Water-Resources Investigations Report 88-4066, 45 p.

Ditmars, J.D., Adams, E.E., Bedford, K.W., and Ford, D.E., 1987, Performance evaluation of surface water transport and dispersion models, *in* Journal of hydraulic engineering: American Society of Civil Engineers, v. 113, n. 8, p. 961-980.

Jobson, H.E., 1980, Comment on A new collocation method for the solution of the convection-dominated transport equation, by Pinder, George E.,and Shapiro, Allen, 1979, (in Water Resources Research, v. 15, no. 5, p 1177-1182): Water Resources Research, v. 16, no. 6, p. 1135-1136.

----- 1981, Temperature and solute-transport simulation in streamflow using a Lagrangian reference frame: U.S. Geological Survey Water-Resources Investigations Report 81-2, 165 p.

Jobson, H.E., and Schoellhamer, D.H., 1987, Users manual for a Branched Lagrangian transport model: U.S. Geological Survey Water-Resources Investigations Report, 87-4163, 73 p.

Moore, Gardner, and Associates, Inc., 1975, The Intracoastal Waterway, Waccamaw River, Winyah Bay, 208 Areawide Wastewater Management Plan, Final Report, Appendix 6.

National Oceanic and Atmospheric Administration, 1994, Tide Tables 1994, High and Low Predictions - East Coast of North and South America, Including Greenland: U.S. Department of Commerce, Nation Ocean Service, p. 225-226.

Roesner, L.A., Giguere, P.R., and Evenson, D.C., 1977a, Computer program documentation for the stream quality model QUAL-II: prepared by Water Resources Engineers Inc., Walnut Creek, Calif., for Southeast Michigan Council of Governments, Detroit, Michigan.

Roesner, L.A., Giguere, P.R., and Evenson, D.C., 1977b, User's manual for the stream quality model QUAL-II: prepared by Water Resources Engineers, Inc., Walnut Creek, Calif., for Southeast Michigan Council of Governments, Detroit, Michigan.

Schaffranek, R.W., Baltzer, R.A., and Goldberg, D.C., 1981, A model for simulation of flow in singular and interconnected channels: U.S. Geological Survey Techniques of Water-Resources Investigations, book 7, chap. C3, 110 p.

Schaffranek, R.W., 1989, Evolution and operational status of the BRANCH-Network unsteady flow model: Proceedings of the Advanced Seminar on One-Dimensional, Open-Channel Flow and Transport Modeling: U.S. Geological Survey Water-Resources Investigations Report 89-4061, p. 99.

S.C. Department of Health and Environmental Control, 1991a, Agreement on the development of wasteload allocations/total maximum daily loads and NPDES permit limitations, 43 p.

S.C. Department of Health and Environmental Control, 1991b, Water Quality Modeling of the Cooper River: S.C. Department of Health and Environmental Control Technical Report 005-91, p. 12.

S.C. Department of Health and Environmental Control, 1993, Water Classifications and Standards (Reg. 61-68) and Classified Waters (Reg. 61-69) for the State of South Carolina, 18-34 p.

Smith, G.D., 1985, Numerical solution of partial differential equations, finite difference methods, Third Edition: Brunel University, p. 43-45

Thompson, D.B., 1992, Numerical methods 101-convergence of numerical models, *in* Jennings, M., and Bhowmik, N.G., eds., Hydraulic engineering; saving a threatened resource--in search of solutions: New York, American Society of Civil Engineers, p. 398-403.

Thomson, N.R., Sykes, J.F., and Lennox, W.C., 1984, A lagrangian porous media mass transport model: Water Resources Research, v. 20, no. 3, p. 391-399.

U.S. Geological Survey, 1973, Brookgreen, S.C., quadrangle: 7.5-minute series topographic map, scale 1:24,000, contour interval 20 feet.

-----1973, Bucksville, S.C., quadrangle: 7.5-minute series topographic map, scale 1:24,000, contour interval 20 feet.

-----1973, Conway, S.C., quadrangle: 7.5-minute series topographic map, scale 1:24,000, contour interval 20 feet.

-----1973, Plantersville, S.C., quadrangle: 7.5-minute series topographic map, scale 1:24,000, contour interval 20 feet.

-----1973, Waverly Mills, S.C., quadrangle: 7.5-minute series topographic map, scale 1:24,000, contour interval 20 feet.

-----1973, Yauhannah, S.C., quadrangle: 7.5-minute series topographic map, scale 1:24,000, contour interval 20 feet.

----1984, Hand, S.C., quadrangle: 7.5-minute series topographic map, scale 1:24,000, contour interval 2 meter.

-----1984, Myrtle Beach, S.C., quadrangle: 7.5-minute series topographic map, scale 1:24,000, contour interval 2 meter.

-----1984, Ocean Forest, S.C., quadrangle: 7.5-minute series topographic map, scale 1:24,000, contour interval 2 meter.

----1984, Surfside Beach, S.C., quadrangle: 7.5-minute series topographic map, scale 1:24,000, contour interval 2 meter.

☆ U.S. Government Printing Office: 1995–642-068/20003