DEVELOPMENT OF A WASTELOAD ALLOCATION MODEL FOR THE PIGEON RIVER BETWEEN CANTON AND HEPCO, NORTH CAROLINA

VOLUME I - TEXT

Versar INC.

DEVELOPMENT OF A WASTELOAD ALLOCATION MODEL FOR THE PIGEON RIVER BETWEEN CANTON AND HEPCO, NORTH CAROLINA

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Prepared for

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July 1989

ACKNOWLEDGEMENTS

We gratefully acknowledge the cooperation of Champion International Corporation during our study, including: Paul Wiegand, Bill Chapman, and Mary Lee Ransmeier. We also acknowledge Randy Dodd and Max Haner of NCNRCD for their helpful support and contributions to the study. Thanks are also due to Jim Greenfield, Tom Plouff, Forrest Leedy, and Kay Harris of EPA Region IV for their participation in the field collections. In addition, we appreciate the efforts of Gene Barker of the USGS for timely help in providing flow data from the Canton and Hepco gages.

EXECUTIVE SUMMARY

A QUAL2E-UNCAS wasteload allocation model was constructed to examine the relative impact of three point source inputs (Champion Paper Mill, Clyde WWTP, and Waynesville WWTP) on dissolved oxygen (DO) dynamics of the Pigeon River between Canton and Hepco, North Carolina. To calibrate the model, field measurements of dissolved oxygen, biochemical oxygen demand (BOD), sediment oxygen demand, (nitrogen, phosphorus, chlorophyll, flow, and light penetration were collected during a low flow period in September 1988. Sampling was conducted at 19 stations, including the three effluents and four tributaries entering the modeled region. The calibrated model was validated using two data sets -- the paper mill's riverwide self-monitoring data from September 1988, and data from a synoptic water quality survey of the Pigeon River conducted under higher flow conditions in July 1987. The validated model was then used to simulate five alternative loading scenarios to ascertain the impact of these alternatives on Pigeon River DO dynamics.

The field studies identified a pattern of DO in the river that was similar to patterns observed during previous summer monitoring by the paper mill. Water entered the upstream border of the study area near saturation, passed through the Champion Mill, and exited 15 °C warmer and supersaturated by means of artificial oxygenation. Proceeding downstream, DO levels alternately increased and declined in response to two sidestream oxygenation units and the associated rapid deaeration below them. Downstream of the oxygenators, DO levels steadily declined, reaching the lowest value near the river's confluence with Richland Creek, about halfway through the modeled region. Results of both the field study and the modeling efforts demonstrated that the effluent from the Champion Paper Mill, which has more than ten times the volume of the two WWTP's combined, was the most important of the three point sources in regulating Pigeon River DO dynamics. Simulated reduction of the mill effluent by 55% increased DO at the low point in the river by more than 1 ppm. In contrast, simulated removal of the WWTP's from the river resulted in no measurable change in river DO.

The sidestream oxygenation units maintained by the Champion Mill were found to maintain state water quality standards in the river during the time of our study, as no DO values less than 6 ppm were measured. However, violations in state water quality standards for DO have been historically detected, suggesting that conditions during our study did not represent worst case. Simulated removal of these units led to a 2 ppm decline in DO upstream of Richland Creek. However, the diluting effect of

Richland Creek was found to be more important in regulating DO in the river downstream of Richland Creek, as simulated removal of the oxygenation units was found to have no effect on DO downstream of Richland Creek.

Although ultimate carbonaceous BOD exceeded 50 mg/l from the Champion Mill effluent and 25 mg/l from the two WWTPs, these outputs did not have a major impact on DO dynamics in the river, primarily because of the short travel time (~ 2 days) through the study area. Presumably these high BOD loads are degraded within Walter's Lake, which forms the downstream border of our study area. Instead, nitrogenous demand, in the form of oxidation from ammonia, appeared to be the dominant source of impact on the river from the three effluent sources. Despite abundant nitrate concentrations, photosynthetic effects on DO were found to be negligible, presumably due to high light extinction coefficients within the river.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

TABLE OF CONTENTS (CONTINUED)

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I. INTRODUCTION

During low flow periods in summer, portions of the Pigeon River between Canton and Hepco, North Carolina have historically experienced depressed dissolved oxygen (DO) levels. The severity of the DO depression is such that on 21 occasions between 1985 and 1987, DO levels were below the minimum DO standard (4 ppm minimum) established by the State of North Carolina (Randall Dodd, North Carolina Department of Natural Resources and Community Development, Raliegh, NC, pers. comm.). These violations have occurred despite the presence of oxygenation systems at several locations in the river. At present, three point source dischargers are thought to be primarily responsible for the DO depletion: Champion International's Canton Mill, Waynesville Wastewater Treatment Plant (WWTP), and Clyde WWTP. However, the relative contribution of each of the facilities to the low DO events is not well documented.

Several studies have been conducted to describe factors affecting DO in the Pigeon River, but attempts to verify existing models have met with limited success (North Carolina Division of Environmental Management (NCDEM) 1984). The goal of this study is to develop a Qual2E-UNCAS wasteload allocation model for the Pigeon River that can be used to document the relative importance of various inputs to the river on DO levels, and to evaluate the consequences of several water quality management options. A four-step approach is used to achieve the study goal.

- Conduct field studies to quantify factors that affect oxygen content of the Pigeon River
- Calibrate and validate a QUAL2E model for the designated portion of the Pigeon River using new and/or existing data
- Gauge model uncertainty
- Run the model to examine effects of alternative management strategies on water quality in the Pigeon River

II. DESCRIPTION OF THE PIGEON RIVER WATERSHED

The Pigeon River originates in a mountainous area of western North Carolina and flows in a northwesterly direction to its confluence with the French Broad River near Newport, Tennessee (Fig. II-1). Elevation gradients in the watershed vary substantially from reach to reach, with elevations ranging from nearly 2,000 m at the headwaters to 306 m at the French Broad River confluence. From its headwaters to the confluence of its East and West Forks, the Pigeon River descends nearly 1200 m. For the remaining 111 km of its length, river descent is less rapid, with an average drop of 4.6 m/km. In the river reach between Canton and Crabtree Creek, the gradient is 1.9 m/km. In the reach below Crabtree Creek, the gradient increases to 3.4 m/km until Jonathans Creek. Below Jonathans Creek, the gradient is 4.9 m/km until the Pigeon River enters Walters Lake, just below Hepco.

Physically, the Pigeon River between Canton and Hepco is a rocky, shallow, warmwater stream, predominated by short riffles and long runs. River substrates are generally cobble/boulder, with exposed bedrock in high gradient areas, and combinations of sand and organic matter overlying rocks in slower depositional areas. During low flows, most of the river is less than 1 m in depth, with a maximum river depth of approximately 3 m recorded at River Mile 61.5 (Nisely and Tysland 1983). At Canton (River Mile 64.6), North Carolina's classification of the Pigeon River shifts from coldwater trout stream to warmwater fishery/non-contact recreation stream, with water temperatures in excess of 30' C recorded below the Champion Mill outfall during summer.

The Pigeon River watershed encompasses a total of 1725 km^2, more than one-half of which is above Hepco, North Carolina. Four tributaries: Richland Creek (177 km2), Crabtree Creek (69 km2), Jonathans Creek (175 km2), and Fines Creek (66 km2) contribute more than 85% of the areal increase in watershed size between Canton and Hepco. Six smaller tributaries account for the remaining increase in watershed size: Beaverdam Creek, Thickety Creek, Murray Branch, Bowen Branch, Chambers Branch, and Mill Branch.

Mean annual flows in the Pigeon River increase from 319 cfs at the Canton USGS gauge to 669 cfs at the Hepco USGS gauge, with recorded minimum flows of 27 cfs at Canton and 81 cfs at Hepco. In contrast, maximum flood flows at Hepco have been estimated at 42,000 cfs. Two reservoirs regulate flows on the Pigeon River between Canton and Hepco -- Lake Logan on the West Fork of the Pigeon River, and Lake Junaluska on Richland Creek. Lake Logan

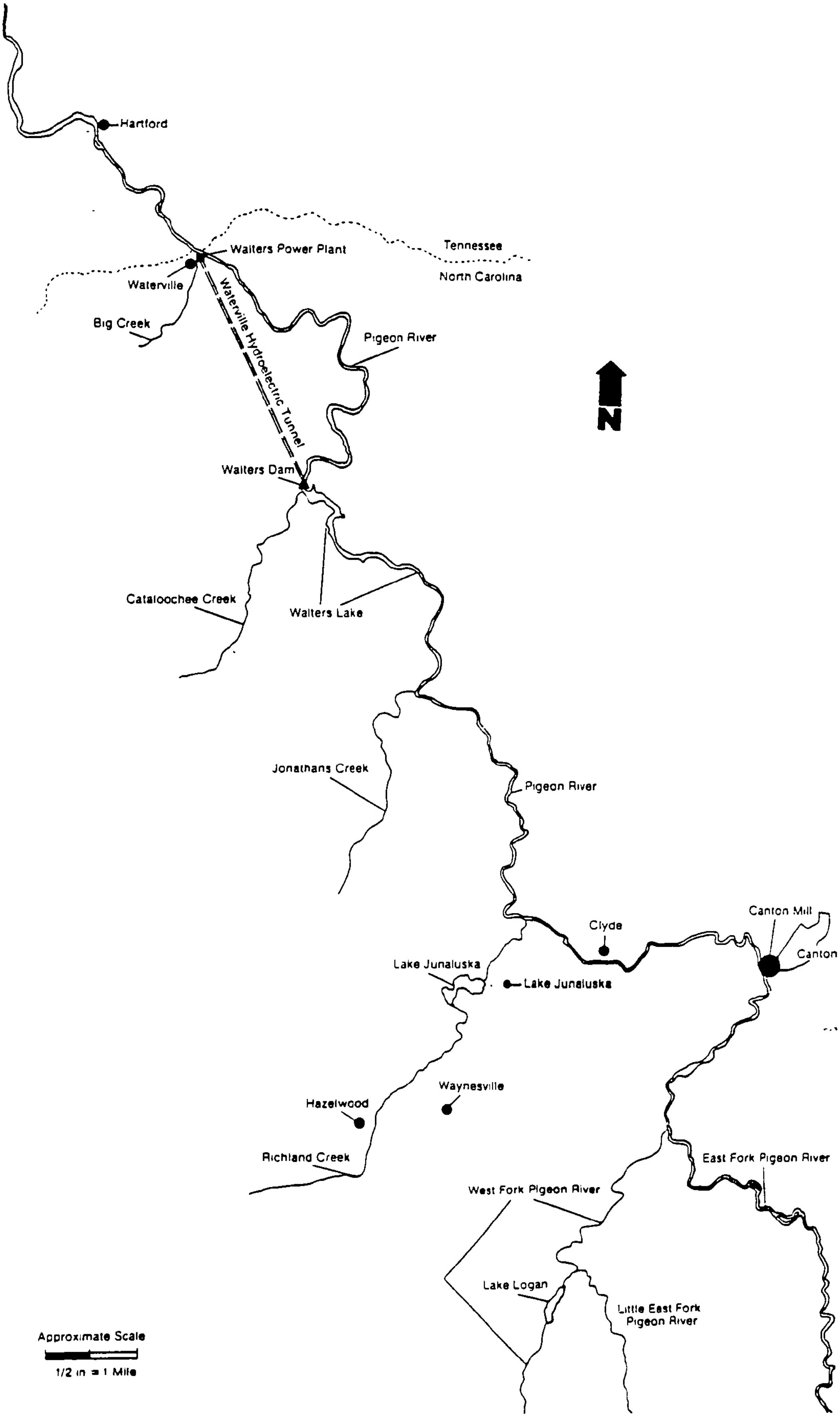


Figure II-1. Map of the Pigeon River, North Carolina (from Weston 1983) is owned by Champion International. Discharge from the lake is regulated to provide sufficient water to operate the Canton Mill throughout the year. Lake Junaluska is owned by a non-profit religous organization and discharge is apparently run-of-river (Max Haner, North Carolina Department of Natural Resources and Community Development, Asheville, NC, pers. comm.).

Land use in the Pigeon River watershed above Hepco is predominately agricultural or undeveloped; approximately 72% of the area is forested and 18% is crop/pasture land. Other areas comprise only 10% of the watershed, the largest fraction being urban (7.7%). Drainage from the upper watershed (above Canton) is used as a public water supply by the town of Canton, and is also used by the Champion paper mill. Withdrawals from the river for public water are on the order of 2 cfs, while withdrawals during full mill production are approximately 70 cfs at the paper mill. There are a total of 60 discharge permits issued by the State of North Carolina for the Pigeon River watershed above Hepco, but only four facilities (Champion Mill, Waynesville WWTP, Clyde WWTP, and Maggie Valley WWTP are required to comply with federal NPDES regulations. Smaller dischargers are primarily located in developed areas within the Jonathans Creek and Richland Creek subbasins.

Dissolved oxygen (DO) is artificially introduced to the Pigeon River at three locations: Champion Mill effluent, and also at sites 0.9 and 2.1 miles downstream of the Mill discharge. Champion's Mill effluent is oxygenated by means of a domed aeration cascade which introduces pure oxygen to Mill effluent just prior to its discharge into the river. At the downstream locations, DO is added to the river via sidestream oxygenation units. At each unit, gaseous oxygen is mixed with river water under 60-70 lbs of pressure. Eductors mix the highly oxygenated water with upstream water at a 1:3 ratio, and the mixture is returned to the river. The total volume of water withdrawn and returned to the stream at each sidestream location is approximately 18.3 cfs.

III. EMPIRICAL STUDY METHODS

Sampling in the Pigeon River was conducted September 27-28, 1988 between Canton and Hepco, North Carolina (Fig. III-1, Table III-1). Samples were collected at 18 stations to provide the following categories of data needs for the Qual2E-UNCAS model: modeled variables, process rates, physical driving functions, input loads, and conservative tracers.

The 18 sampling locations were selected to measure all major inputs to the river within the study area. Stations were located upstream of the confluence, and downstream of all major tributaries and discharges (Fig. III-1). Tributaries were sampled as close to their confluence with the Pigeon River as access allowed, and effluent samples were collected at or near the end of each discharge pipe. Mainstem stations located below inputs were sited approximately 0.5 miles downstream to ensure mixing of inputs with river water. An exception was the station downstream of Fines Creek (S11), where the Pigeon River enters Walters Lake before complete mixing of water from Fines Creek occurs. Water samples for chemical analysis were collected from the middle of the channel just below the surface. Dissolved oxygen concentration (DO) and temperature were measured near the middle of the channel at the surface and bottom, and near the river margin (shoal) at a midwater depth.

The 18 sampling stations were separated into 14 nominal stations, at which most parameters were measured, and four intensive stations which were sampled for the same array of parameters as nominal stations, but also included measurement of process rates and diurnal variability (Fig. III-1). Locations of intensive stations were sited to provide:

- A site above all effluents to define "background" diurnal variability (S1)
- A site downstream of the last Champion Mill aerator unit to document diurnal variation associated with the paper mill effluent (S4)
- A site downstream of the Clyde and Waynesville WWTPs to establish diurnal variation due to combined effluent loadings (S6)
- A site several miles downstream of the DO sag zone to identify diurnal patterns in water entering Walters Lake (S10).

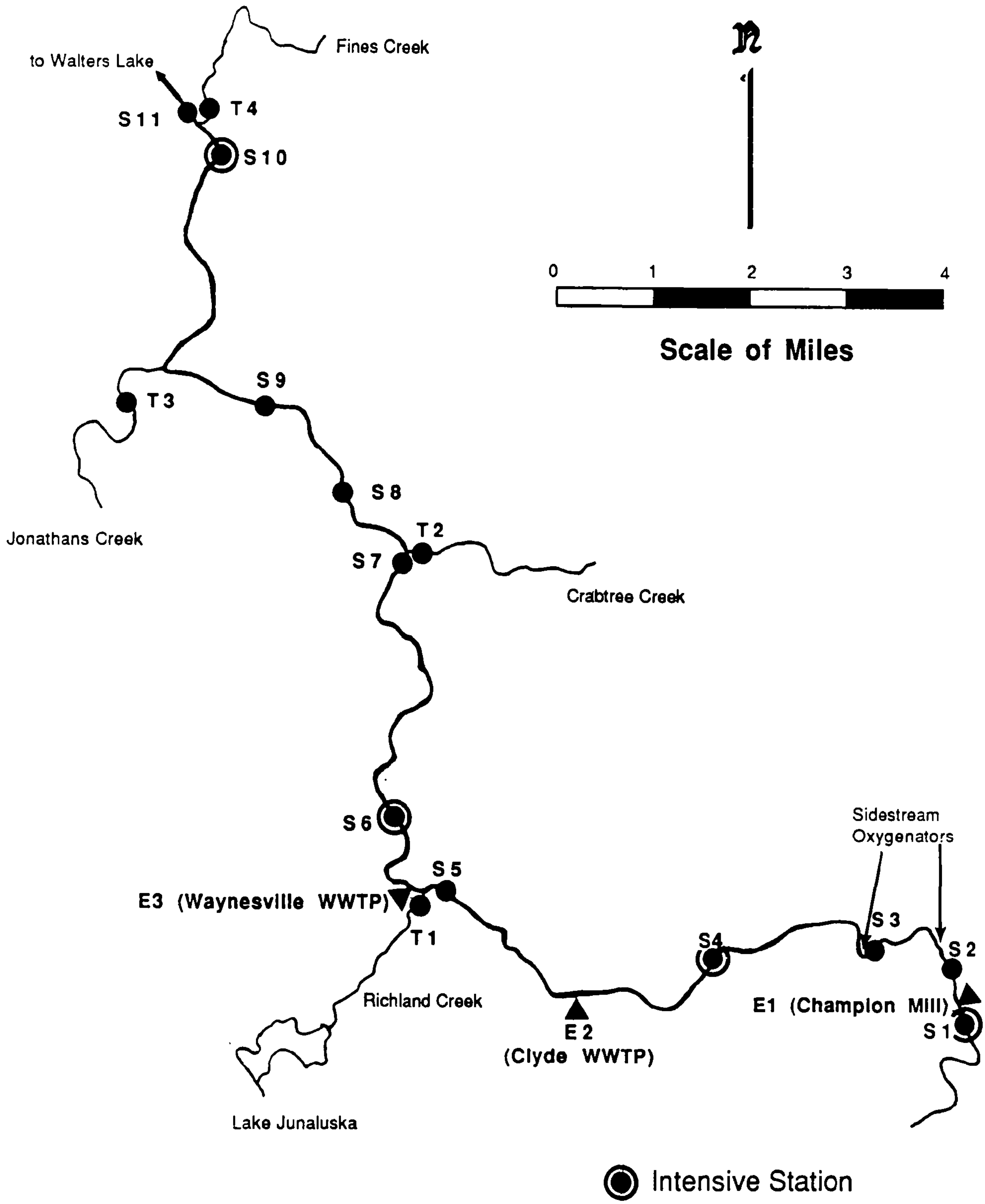


Figure III-1. Nominal and intensive sampling stations in the Pigeon River, North Carolina study area

Table III-1. Description of station locations within the Pigeon River, North Carolina study area

Station	River Mile	Description
S1*	63.5	Headwater, at Champion Mill intake
S2	62.8	Downstream of Champion effluent, at Fiberville bridge
S3	61.5	Between first and second sidestream oxygenators, just upstream of second oxygenator
S4*	59.2	Between second oxygenator and Clyde WWTP effluent, at Thickety Road divergence from river
S5	55.2	Upstream of Richland Creek, at pollution control project site
S6*	53.8	Downstream of Waynesville effluent and Richland Creek, at bridge off Rt. 209
S7	49.8	Upstream of Crabtree Creek, on Riverside Road
S8	48.7	Downstream of Crabtree Creek, on Riverside Road
S9	47.6	Upstream of Jonathans Creek, on Riverside Road
S10*	43.0	Upstream of Fines Creek at I-40 bridge, access from I-40
S11	42.6	Downstream of Fines Creek, access from dead end road on west bank
T1	54.9	Richland Creek, on Hyder Mountain Road bridge, creek mile 0.2
T2	49.8	Crabtree Creek, off Riverside Road, creek mile 0.05

*Indicates intensive sampling station

Table III-1. Continued

Station	River Mile	Description
T3	46.0	Jonathans Creek, on White Oak Road below Dark Hollow Road, creek mile 0.8
T4	42.7	Fines Creek, at bridge at Panther Creek Road, creek mile 0.3
E1	63.3	Champion paper mill effluent
E2	57.1	Clyde WWTP effluent
E3	54.8	Waynesville WWTP effluent

Sampling Parameters

Nominal stations were sampled twice on 27 September; once between 0800 and 1130 and once between 1330 and 1530. Nominal stations were sampled for temperature, flow rate, dissolved oxygen, nutrients, chloride, five-day biochemical oxygen demand (BOD), ultimate carbonaceous biochemical oxygen demand (UCBOD) and chlorophyll during the morning sampling period (Table III-2). In the afternoon, nominal stations were sampled for 5-day BOD, dissolved oxygen, temperature, and flow. Flow measurements at mainstem and tributary stations were made prior to and after the main portion of the study on 27 September. During the main portion of the study, staff gauge readings were recorded each time a station was sampled to document constancy in flows during the study.

Intensive stations were sampled five times throughout the day to determine diurnal patterns in the various parameters. Intensive stations were sampled for temperature, flow rate, dissolved oxygen, nutrients (NO_2-N, NO_3-N, Total Kjeldal nitrogen, total phosphorus, ortho-phosphate), 5-day BOD, and chlorophyll on a diurnal basis (0700, 1300, 1700, 2030, and 2400) (Table III-2). Chloride and UCBOD were sampled only at 0700.

Water column photosynthesis and sediment oxygen demand (SOD) were also measured on 27 September at three of the four intensive stations (S4, S6, S10). SOD and photosynthesis were not measured at S1 because process rates at the upstream boundary of the model (S1) are not incorporated into the model. Instead, process rates were measured at S2, immediately below the Champion discharge. Water column photosynthesis was measured between 1300 and 1800 and SOD was measured in three consecutive tests between 1300 and 2400. Two additional SOD measurements (one light and one dark chamber) were taken simultaneously from 1200 to 1600 on 28 September at station S1 to document differences in SOD due to photosynthesis at the upstream study area boundary.

Light attenuation measurements were made at all mainstem stations (S1-S11) on 27 September between 1330 and 1930. In addition, percent shading was visually estimated at mainstem stations on 28 September.

In addition to dissolved oxygen (DO) and temperature data collected as part of the main study on 27 September, a longitudinal DO/temperature survey was conducted on 28 September at all stations along the mainstem. In conjunction with the longitudinal survey on 28 September, deaeration measurements were made from 1300 to 1500 below the sidestream oxygenator at RM 61.5.

Table III-2 Parameters/sampling times for intensive nominal and special study locations sampled in the Pigeon River study area during September 1988

	Intensive Stations						Nominal Stations		
	27 Sept					28 Sep	27 Sept		28 Sep
Parameter	0700	1300	1700	2030	2400		0800-1130	1330-1530	
Flow	√	√	√	√	√	√			
Dissolved Oxygen	√	√	√	√	√	√	√	√	√
Temperature	√	√	√	√	√	√	√	√	√
BOD_5	√	√	√	√	√		√	√	
Ultimate BOD	√						√		
SOD		√	√	√			√		
Atmospheric Exchange						√			√
Light Attenuation		√*						√*	
Percent Shading						√			√
Chlorophyll a	√						√		
Photosynthesis		√						√	
Total Kjeldahl Nitrogen	√	√	√	√	√		√		
Ammonia-nitrogen	√	√	√	√	√		√		
Nitrate-nitrogen	√	√	√	√	√		√		
Nitrite-nitrogen	√	√	√	√	√		√		
Total Phosphorus	√	√	√	√	√		√		
Ortho-phosphate	√	√	√	√	√		√		
Chloride	√						√		

*Mainstem stations only.

Measurement Methods

Flow

Flow at mainstem and tributary stations was measured using standard USGS techniques (Buchanan and Somers 1969). At each station, a transect was established across the stream. Depth and velocity measurements were made at intervals of 0.5-3.0 m, depending on stream width. Velocity measurments were taken at each point on the transect with a Pygmy-Price current meter at a depth below the surface equal to 0.6 times the total stream depth. Staff gauges were installed at mainstem and tributary stations and corrected with stream flow measurements. Stream heights were recorded each time a station was sampled as a means of monitoring changes in flow throughout the study. Gauging station data from seven USGS sites within the study area were also obtained. Paper mill plant intake and effluent discharge rates were obtained from data reported to the NCDEM by the Champion Mill and the WWTPs at Clyde and Waynesville. Additionally, withdrawal rates for the town of Canton's water supply were obtained from the town of Canton.

Dissolved Oxygen/Temperature

Dissolved oxygen concentration and temperature were measured using a series of electronic meters, including Yellow Springs Instruments (YSI) models 55, 56, 57, and 58, and Hydrolab Surveyor II. To insure validity of DO and temperature measurements, each meter was calibrated with Winkler titrations prior to the sampling day, checked or recalibrated before the afternoon sampling, and checked again after the 2400 sampling. Additional calibration checks were performed at intermediate times by a mobile quality assurance team that compared measurements taken with a calibrated meter with those made with the meters assigned to specific stations. Whenever measurements from two meters differed by more than 0.4 ppm, an air calibration check was performed on each meter. Meters which differed from air saturation by more than 0.4 ppm were removed from use until they could be recalibrated.

Biochemical Oxygen Demand

Two types of biochemical oxygen demand (BOD) samples were collected during the study, five-day and ultimate carbonaceous. Five-day BOD was measured using EPA standard method 405.1 (EPA

1983) and UCBOD was calculated according to procedures established by North Carolina Department of Environmental Monitoring (NCDEM).

Sediment Oxygen Demand

Sediment Oxygen Demand (SOD) was measured in recirculating chambers similar to the design used by Hickey (1988) (Figure III-2). At each station sampled, chambers were placed at a location with substrate composition and bottom topography which were representative of the reach. An exception was S10, where swift, deep water and a highly irregular bottom limited chamber locations to a shallow pool area. After installation, sandbags were positioned around the periphery of the chamber to provide a watertight seal. Chambers were cleared of trapped air and disturbed sediments by running the circulation pump with the chamber ports opened. Chambers were then sealed and water within the chamber was recirculated at a constant velocity with a 13,240 l/h pump for 1.5 to 4.5 h. Temperature and DO were measured at approximately 15 min intervals with a YSI DO probe installed in the chamber. Total oxygen consumption rates were calculated by linear regression of DO vs. time for each experiment. When regressions were non-significant at the α = 0.05 level, oxygen consumption was assumed equal to zero. Water column respiration, as measured by 5-day BOD at each site, was subtracted from total oxygen consumption to calculate SOD.

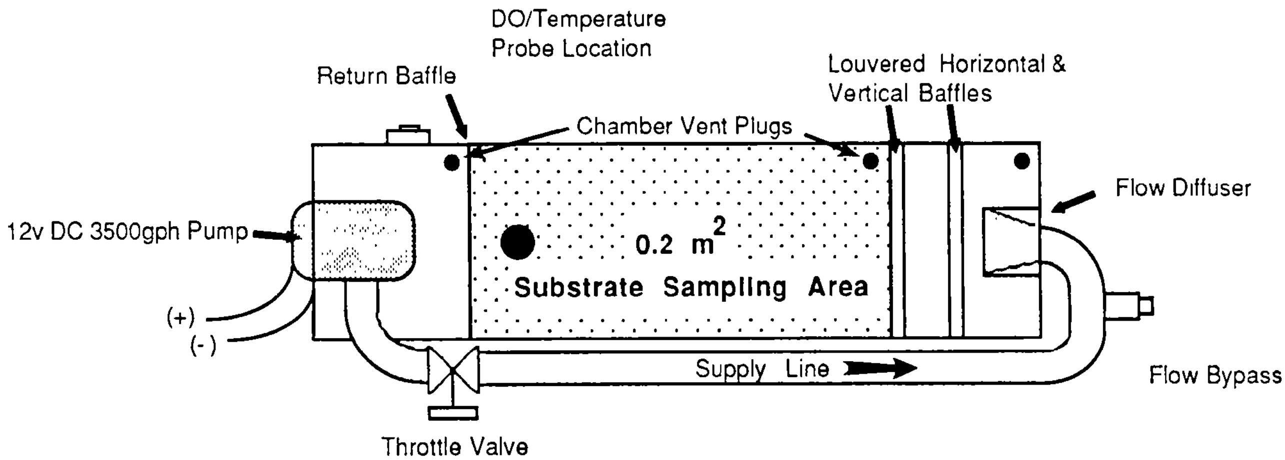
Photosynthesis

Photosynthesis rates were estimated empirically by direct measure of oxygen production and consumption rates, and were also estimated indirectly from other parameters measured. Empirical measurements were made by measuring DO levels in replicate light and dark bottles which were incubated *in situ* for 3-4 h. DO measurements were made with a YSI DO meter equipped with a BOD probe.

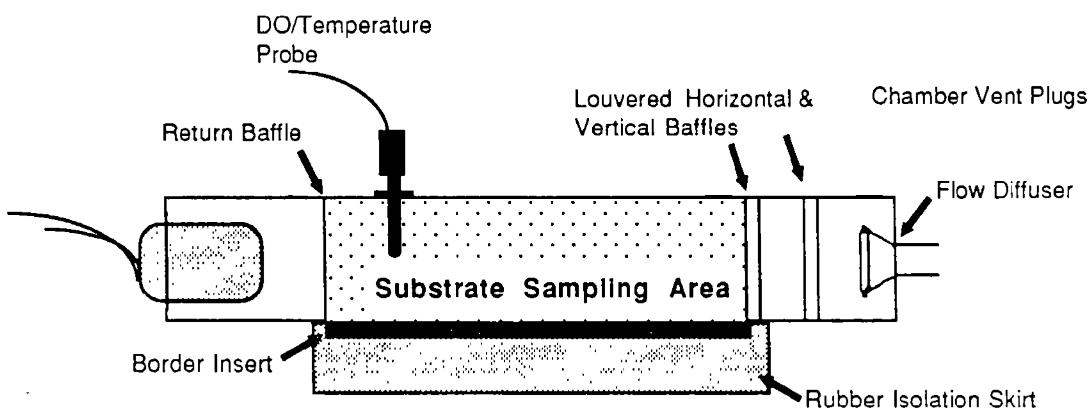
Chlorophyll *a* was collected by filtering 100-200 ml of sample and freezing the filters in the field. In the laboratory, frozen filters were ground in acetone and examined fluorometrically (Loftus and Carpenter 1971).

Light attenuation measurements were made at approximately 10 cm intervals with a Li-Cor model LI-185A photometer mounted on a meter stick. Light extinction curves were then constructed based on percent of available light at depth.

Sediment Oxygen Demand (SOD) Chamber



Top View



Side View

Figure III-2. *In situ* recirculating SOD chamber used on the Pigeon River, North Carolina (modified from Hickey 1988)

Nutrients

Total Kjeldahl nitrogen, nitrate as nitrogen, nitrite as nitrogen, and ammonia nitrogen, and total phosphorus and ortho-phosphate as phosphorus were collected and analyzed using standard EPA protocols (Table III-3) (EPA 1983). Quality control procedures in the laboratory followed standard EPA protocol, using complete chain-of-custody procedures, and including control, blank, spike, and duplicate samples in each batch processed.

Chloride

Chloride samples were collected at each station to serve as a conservative tracer for other constituents. Laboratory analysis followed EPA protocol 325.3.

Deaeration

The rate of deaeration of supersaturated river water below Champion's second sidestream oxygenation unit (RM 61.5) was measured by holding shallow pans of supersaturated river water in a floating apparatus. Water for these pans was collected from immediately below the oxygenation site. The rate of dissolved oxygen decline in each pan as measured with a YSI DO meter at approximately 15 minute intervals for 2 h. Three bottles were concurrently filled and placed within the pans to account for the changes in dissolved oxygen concentration associated with metabolic processes. The DO decline in these bottles was subtracted from the total decline in DO to calculate loss rates due to deaeration.

Table III-3. Analytical methods for Pigeon River water chemistry sampling

Parameter	Preservation	Analytical Method
Total Kjeldahl Nitrogen	$H_2SO/4°C$	Colormetric (EPA 351.3)
Ammonia^{-N}	$H_2SO/4°C$	Colormetric (EPA 350.2)
NO_2-N	$H_2SO/4°C$	Spectrophotometric (EPA 353.2)
NO_3-N	$H_2SO/4°C$	Spectrophotometric (EPA 353.2)
Total P/Ortho-P	$H_2SO/4°C$	Colorometric (EPA 365.2)
CBOD	Chill 4°C	5 day (EPA 405.1)
		150 day (NCDEM long term method)
NBOD	Chill 4°C	150 day (NCDEM long term method)
Chloride	Chill 4°C	Titrimetric (EPA 325.3)

IV. EMPIRICAL STUDY RESULTS

Flow

Flow in the Pigeon River study area was relatively constant for the several days up to and including the study period (Fig. IV-1). Flows ranged from approximately 72 cfs at Canton to 131 cfs at Hepco (Fig. IV-2). At Canton, nearly all of the water in the river was withdrawn by Champion Mill; only about 3 cfs of the total 70 cfs available spilled over the dam and was not used by the mill. Within the mill, evaporation and other losses accounted for an estimated reduction of about 3 cfs between intake flow and effluent flow. Downstream, two major tributaries, Richland Creek (T1), and Jonathans Creek (T3) constituted about 80% of the increase in flow between the Champion Mill outfall and Hepco. Effluent flows contributed by Clyde and Waynesville WWTPs (E2 and E3) were small relative to the Champion effluent; the combined total flow of Waynesville and Clyde WWTPs was 15 times less than flow from Champion (E1).

Temperature

During the study, mainstem temperatures were consistently lowest upstream of the mill and highest just downstream of the mill effluent (Figs. IV-3, IV-4, and IV-5). A similar longitudinal pattern was observed for all three sampling periods; temperatures rose from about 18 °C at the mill intake to about 33 °C below the mill outfall, and slowly declined to about 20 °C by Hepco. However, some warming was apparent from S7 to S9 (Crabtree Creek to Jonathans Creek), presumably due to an increase in solar insolation attributed to the shallow, wide stretches which are common in that reach.

Diurnal temperature variation measured at the four intensive stations (S1, S4, S6, and S10) was generally small and related to the proximity of the station to Champion Mill effluent (Fig. IV-6). Upstream of the papermill (S1), essentially no diurnal variation was observed. At the two intensive stations closest to the Champion effluent (S4 and S6), diurnal fluctuations of 3-4 °C were recorded, probably due to the greater temperature differential between air and water at these stations at night.

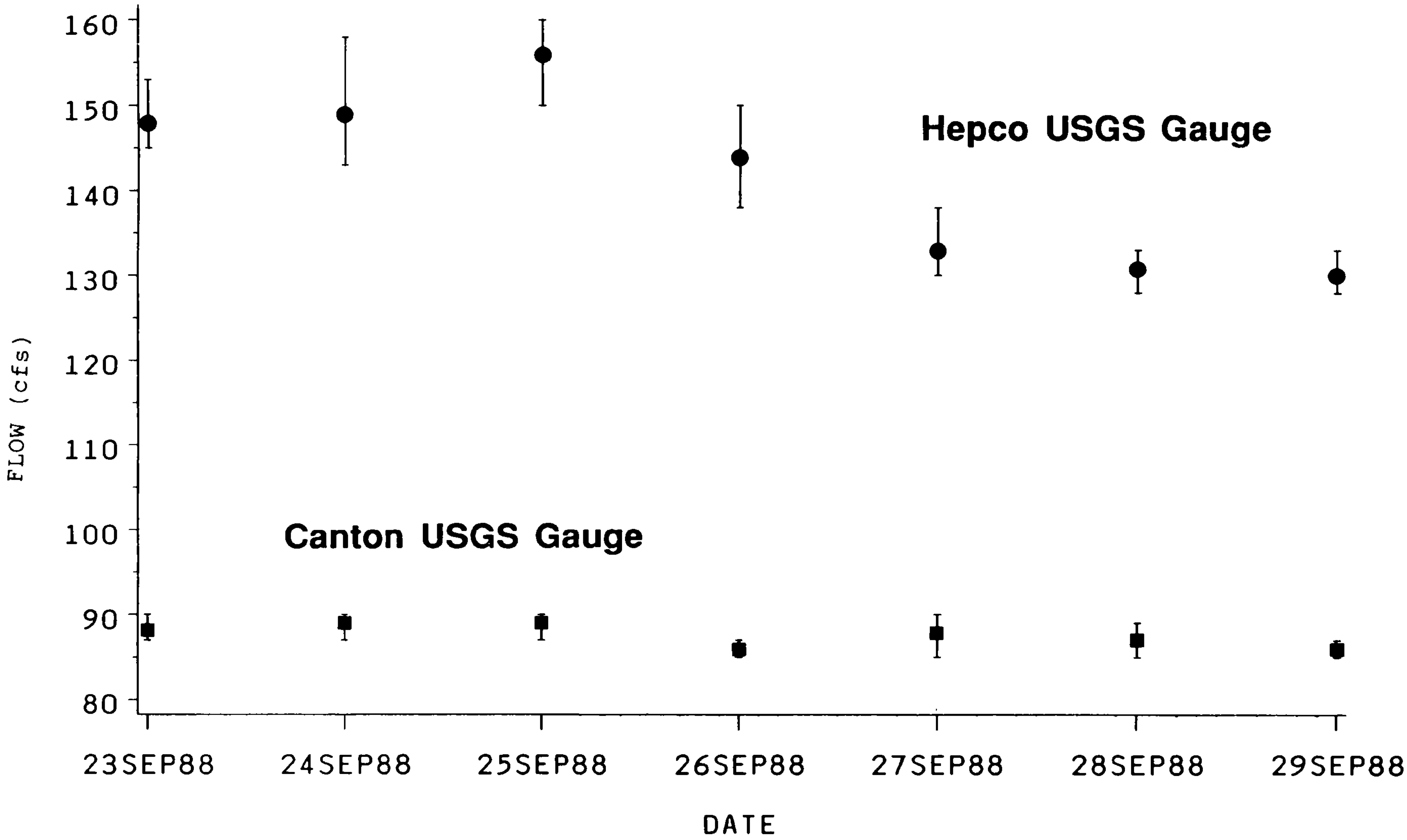


Figure IV-1. Flow data from continuous USGS gauges at canton and Hepco, North Carolina, during 23-29 September 1988

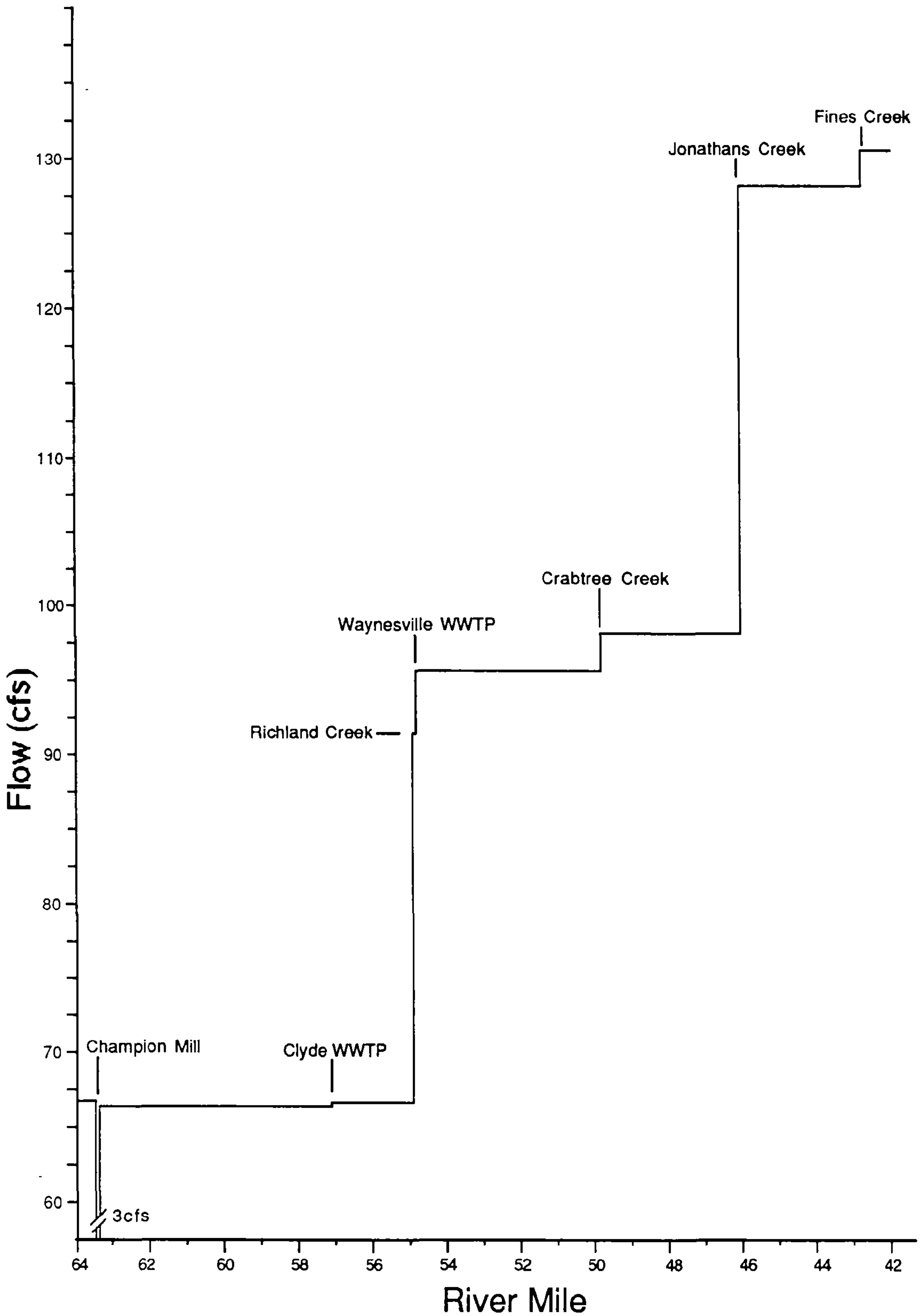


Figure IV-2. Flows in the Pigeon River, North Carolina between Canton and Hepco on 27 September 1988

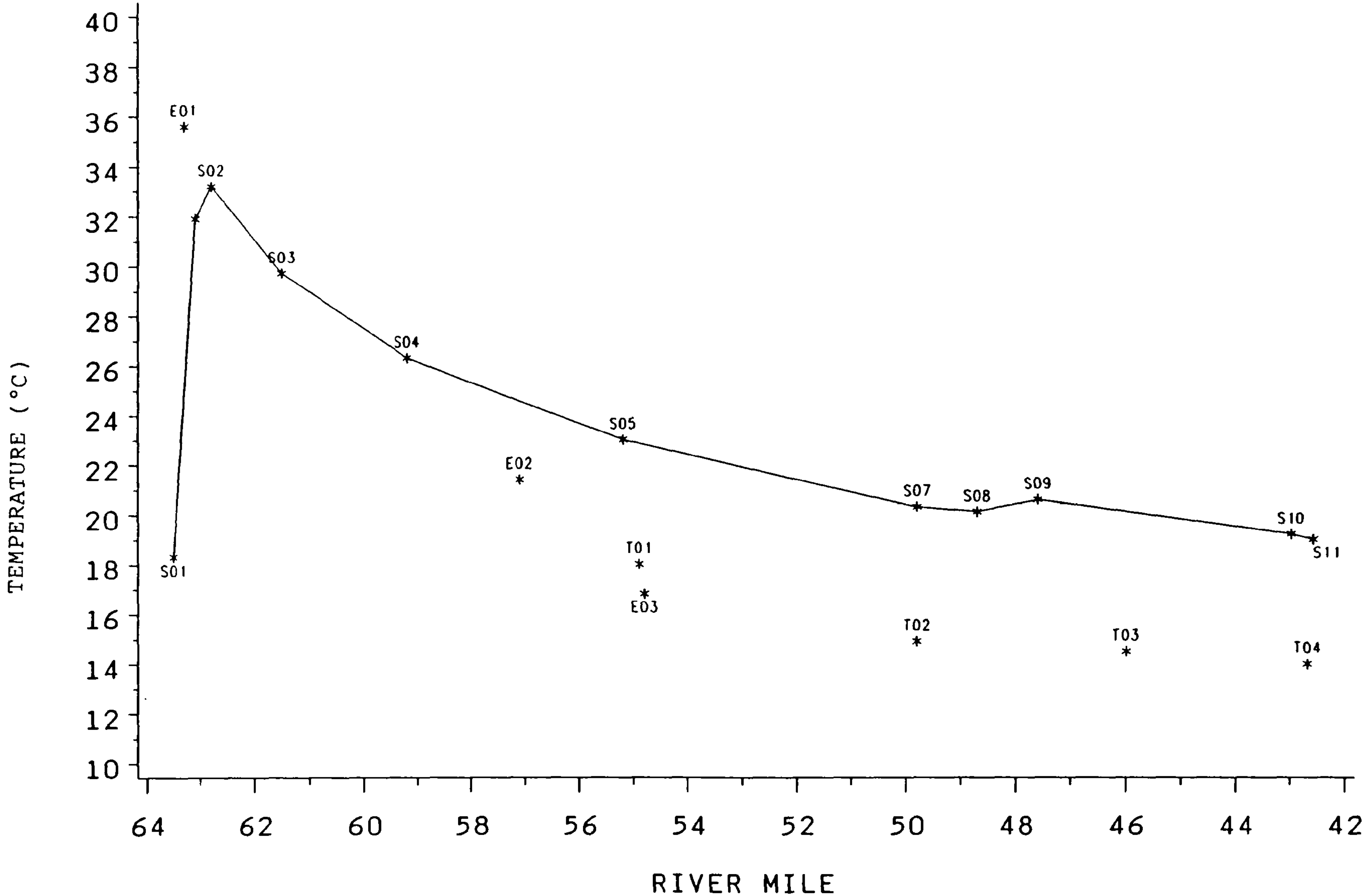


Figure IV-3. Water temperatures (°C) at mainstem and input sampling stations within the Pigeon River, North Carolina study area between 0700 and 1100 on 27 September 1988

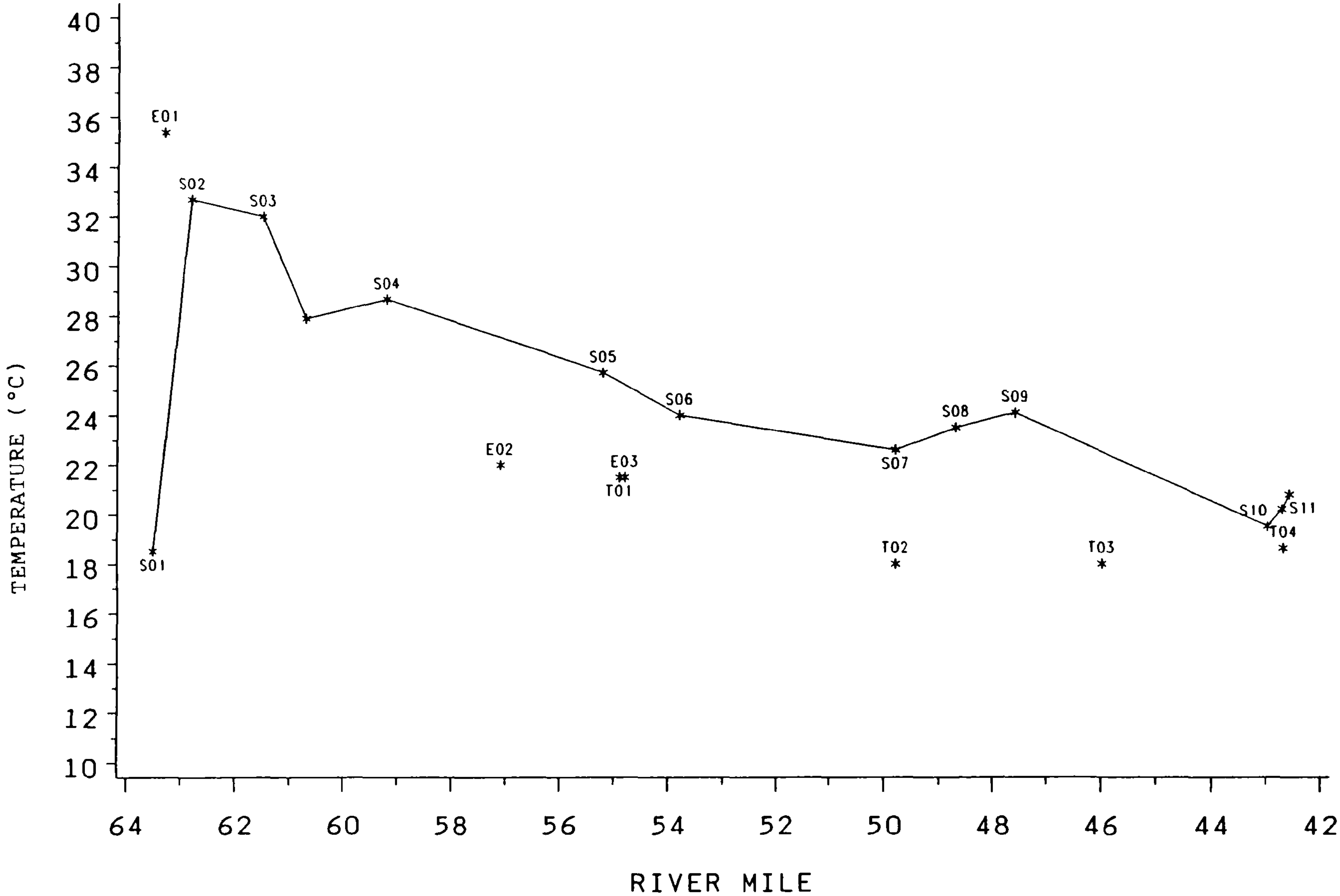


Figure IV-4. Water temperatures (^{O}C) at mainstem and input sampling stations within Pigeon River, North Carolina study area between 1300 and 1700 on 27 September 1988

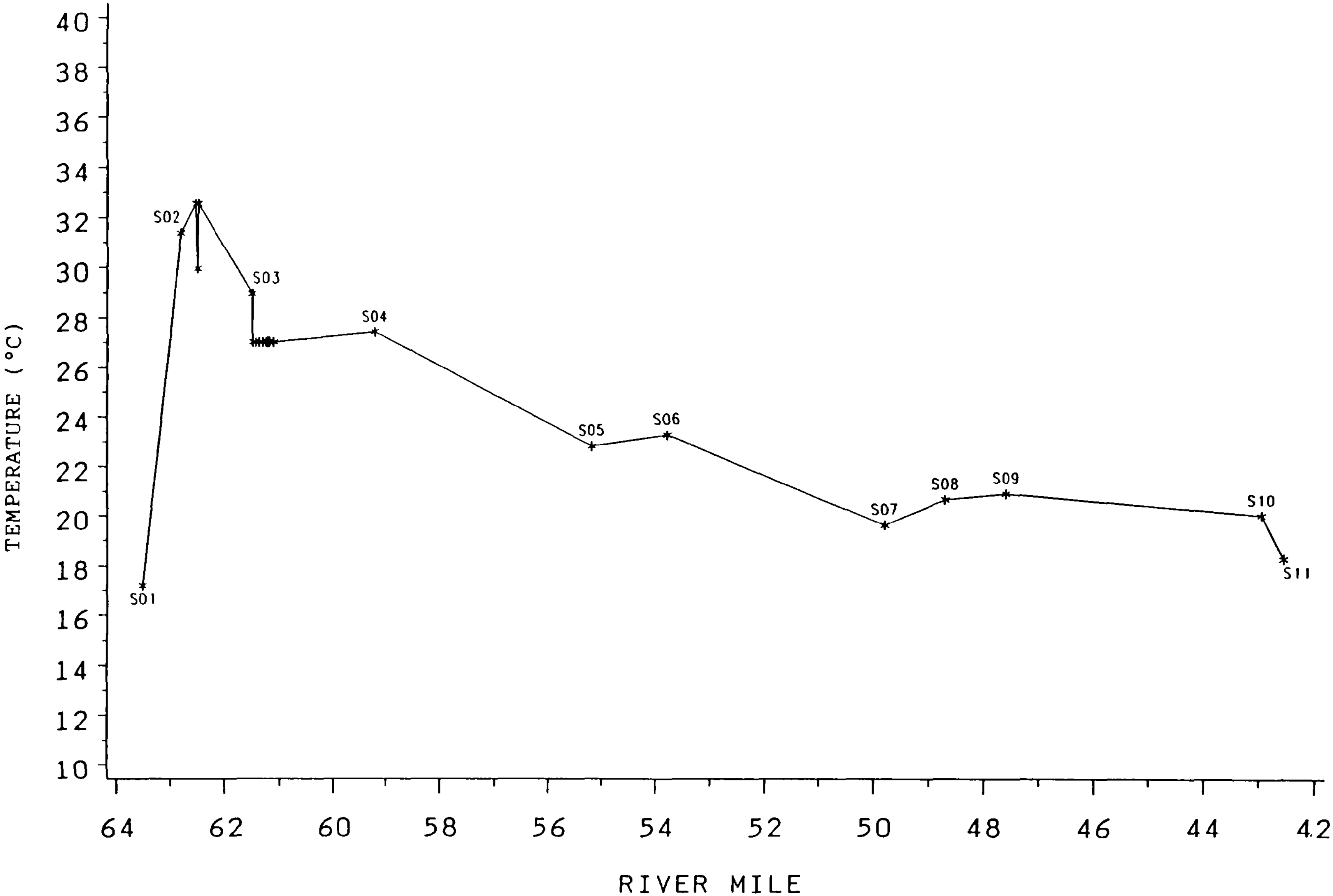


Figure IV-5. Water temperatures (^{o}C) at mainstem and input sampling stations within Pigeon River, North Carolina study area between 1000 and 1530 on 28 September 1988

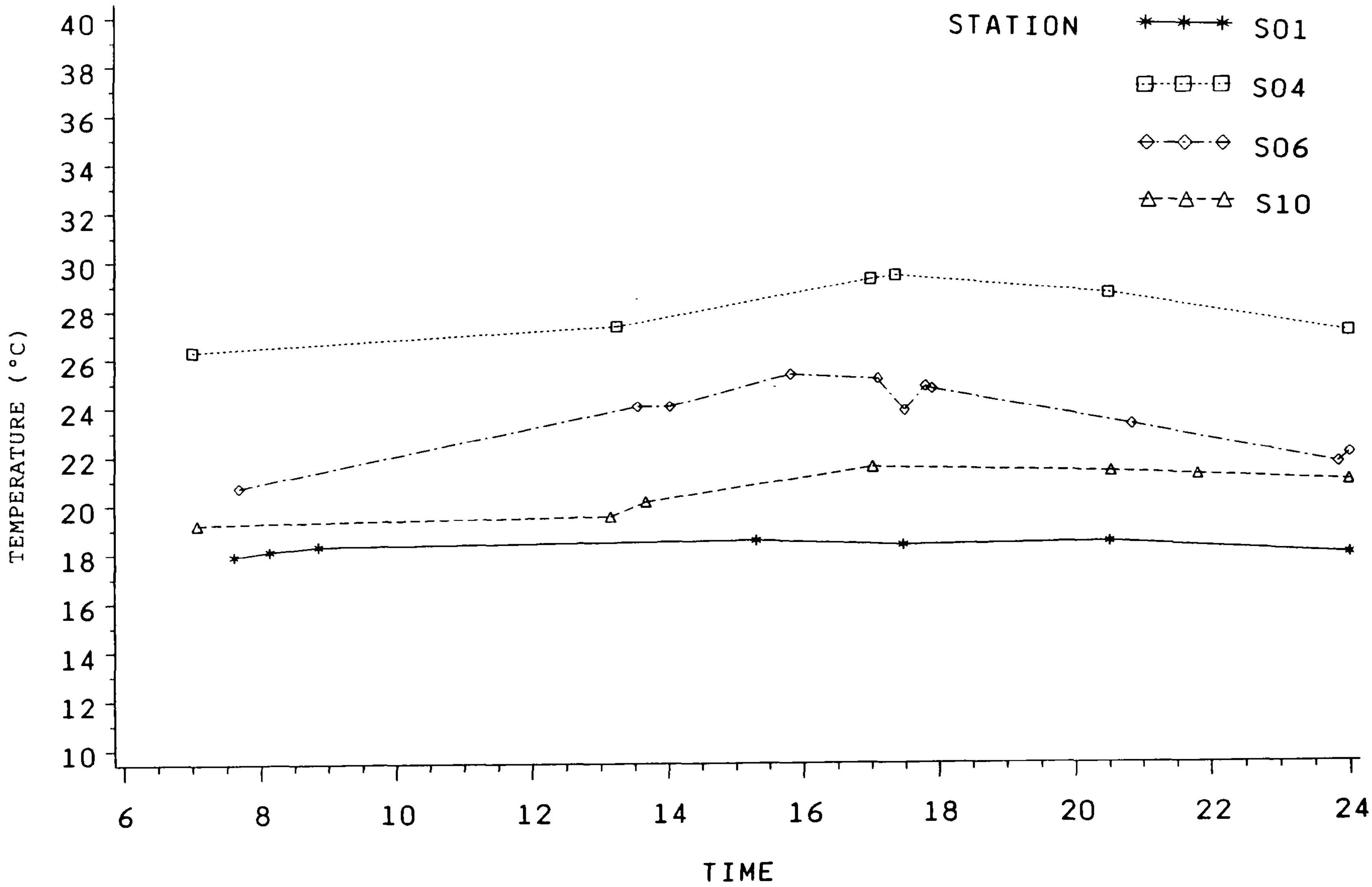


Figure IV-6. Diurnal temperature variation measured at four intensive stations in the Pigeon River, North Carolina on 27 September 1988

Dissolved Oxygen (DO)

Longitudinal dissolved oxygen (DO) patterns in the mainstem were similar among sample periods; a decline in DO to almost 2 ppm below saturation was evident near Richland Creek (S5), and recovery to values near saturation was apparent by Hepco (S11) (Figs. IV-7, IV-8, and IV-9). However, even with the decline below saturation, no DO values below 6 ppm were observed during the study.

On 28 September, additional DO monitoring conducted near Champion's two sidestream oxygenation units revealed DO peaks greater than 20 ppm immediately downstream of each unit, with rapid declines observed slightly downstream (Fig. IV-9). These declines were attributed to dissolution of supersaturated oxygen from the water column, as measured in the deaeration of supersaturated river water held in shallow pans (Fig. IV-10).

Diurnal DO variation measured at the intensive sampling stations was relatively small (less than 2 ppm), and inconsistent among stations (Fig. IV-11). Diurnal fluctuation was greatest upstream of the mill at S1, with the highest DO recorded in late afternoon and lowest values observed in the early morning. Dirunal variation in DO at the three stations below the Champion outfall did not exceed 1 ppm.

BOD

Both five-day (BOD_5) and UCBOD results followed similar longitudinal patterns in the study area; BOD_5 was highest near Champion's outfall and declined with distance downstream (Figs. IV-12, IV-13, and IV-14). In addition, the diluting effect of the combined addition of Richland Creek at RM 54.9 and Waynesville WWTP at RM 54.8 was evident in all three sets of samples.

As with DO and water temperature, diurnal variation in BOD_5 was smallest at S1, above the Champion Mill outfall (Fig. IV-15). At S4, S6, and S10, BOD_5 was lowest at 0700 and highest between 1300 and 1700. Conversely, BOD_5 at S1 was near zero at all sample times, but the highest value of 0.5 mg/l occurred in the 0700 samples.

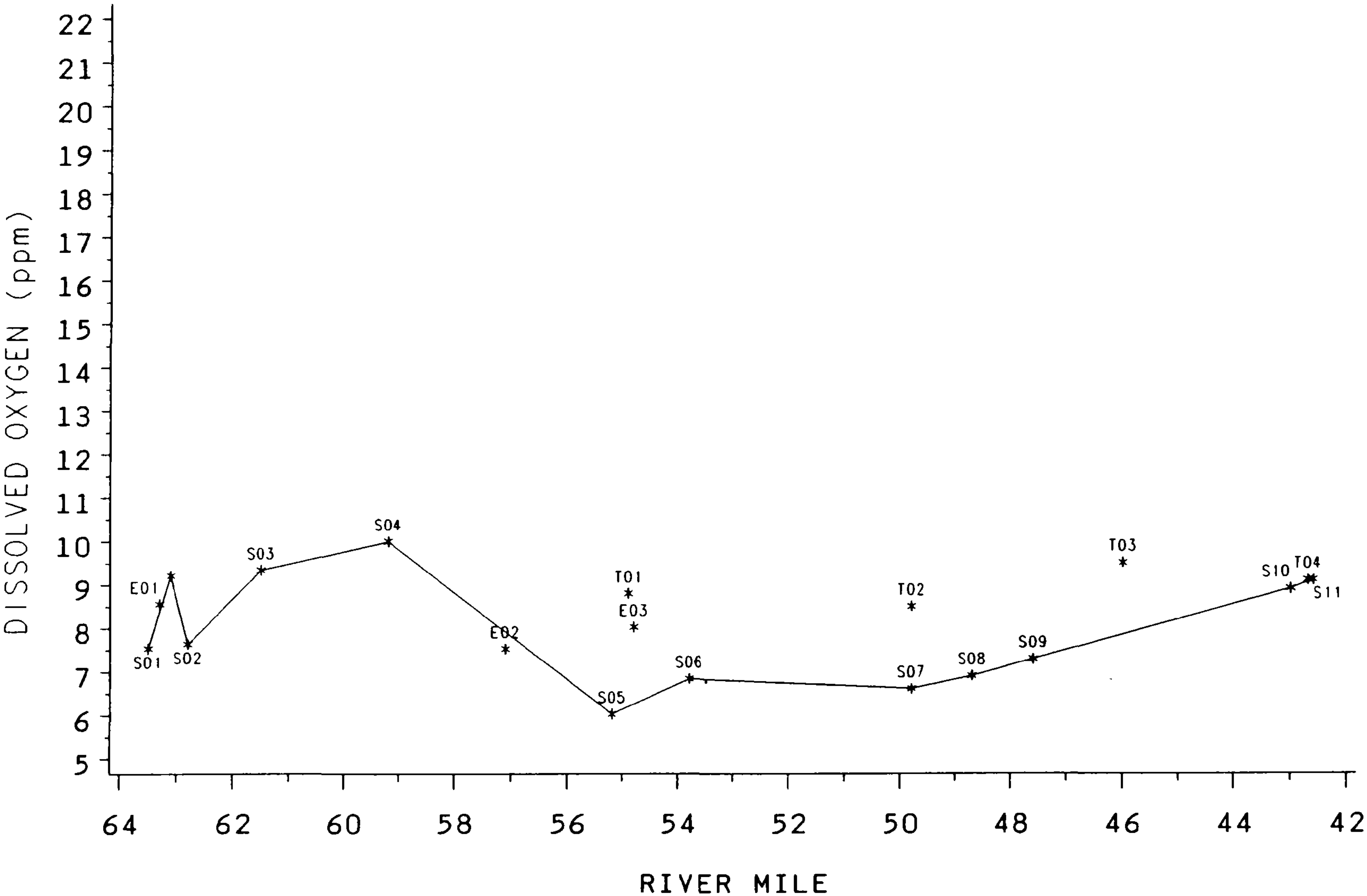


Figure IV-7. Dissolved oxygen (ppm) levels at mainstem and input sampling stations within the Pigeon River, North Carolina study area between 0700 and 1100 on 27 September 1988

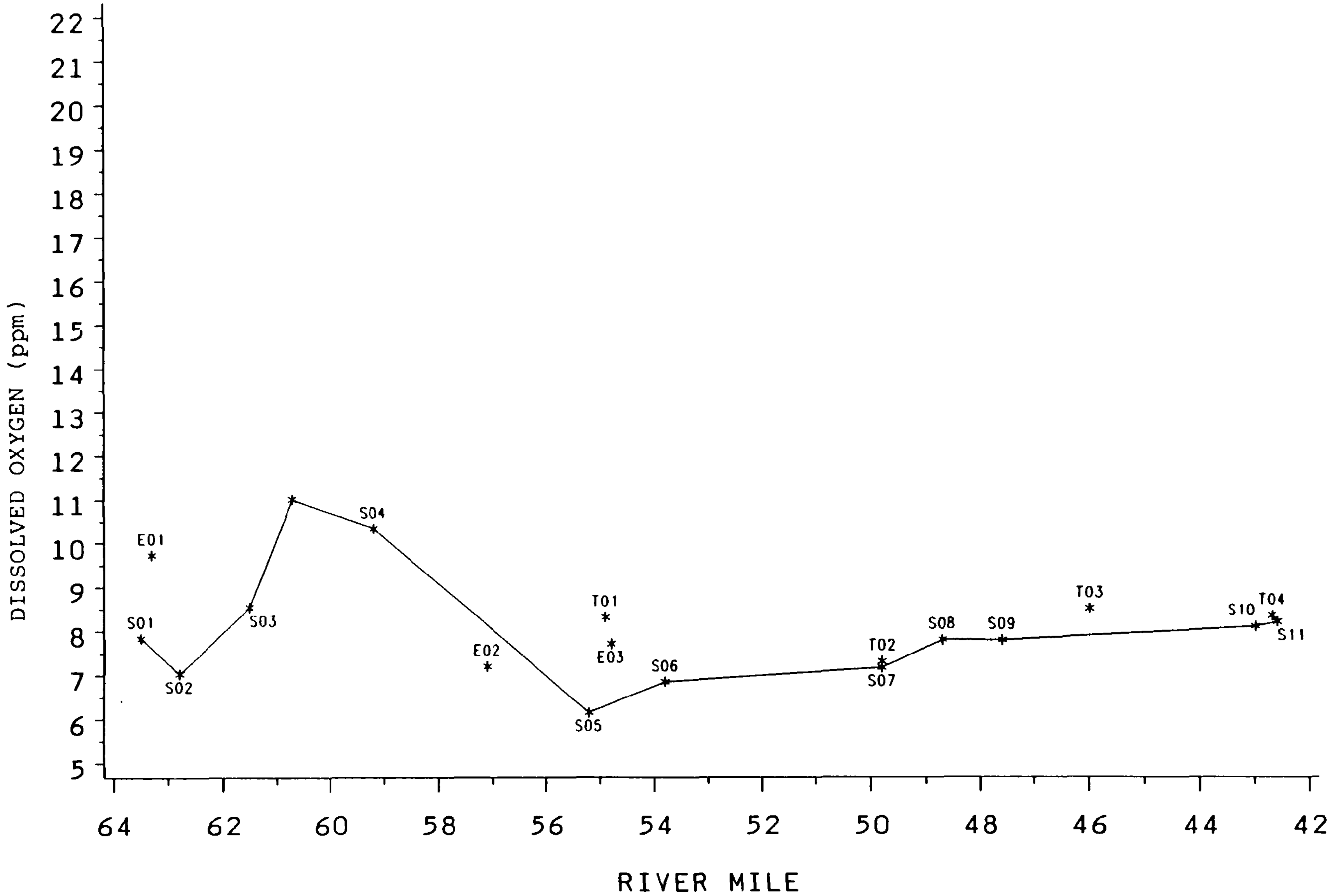


Figure IV-8. Dissolved oxygen (ppm) levels at mainstem and input sampling stations within the Pigeon River, North Carolina study area between 1300 and 1700 on 27 September 1988

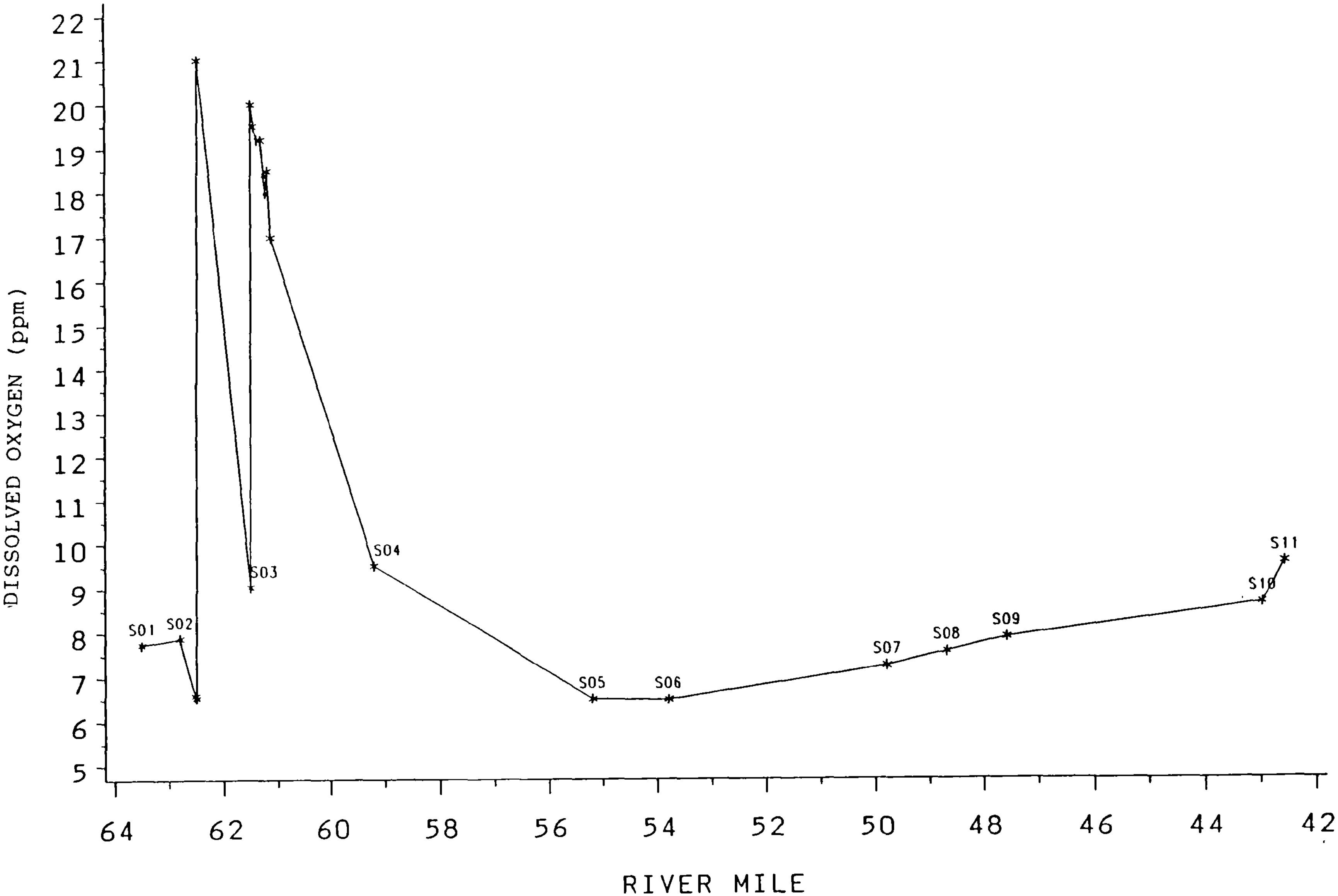


Figure IV-9. Dissolved oxygen (ppm) levels at mainstem and input sampling stations within the Pigeon River, North Carolina study area between 1000 and 1530 on 28 September 1988

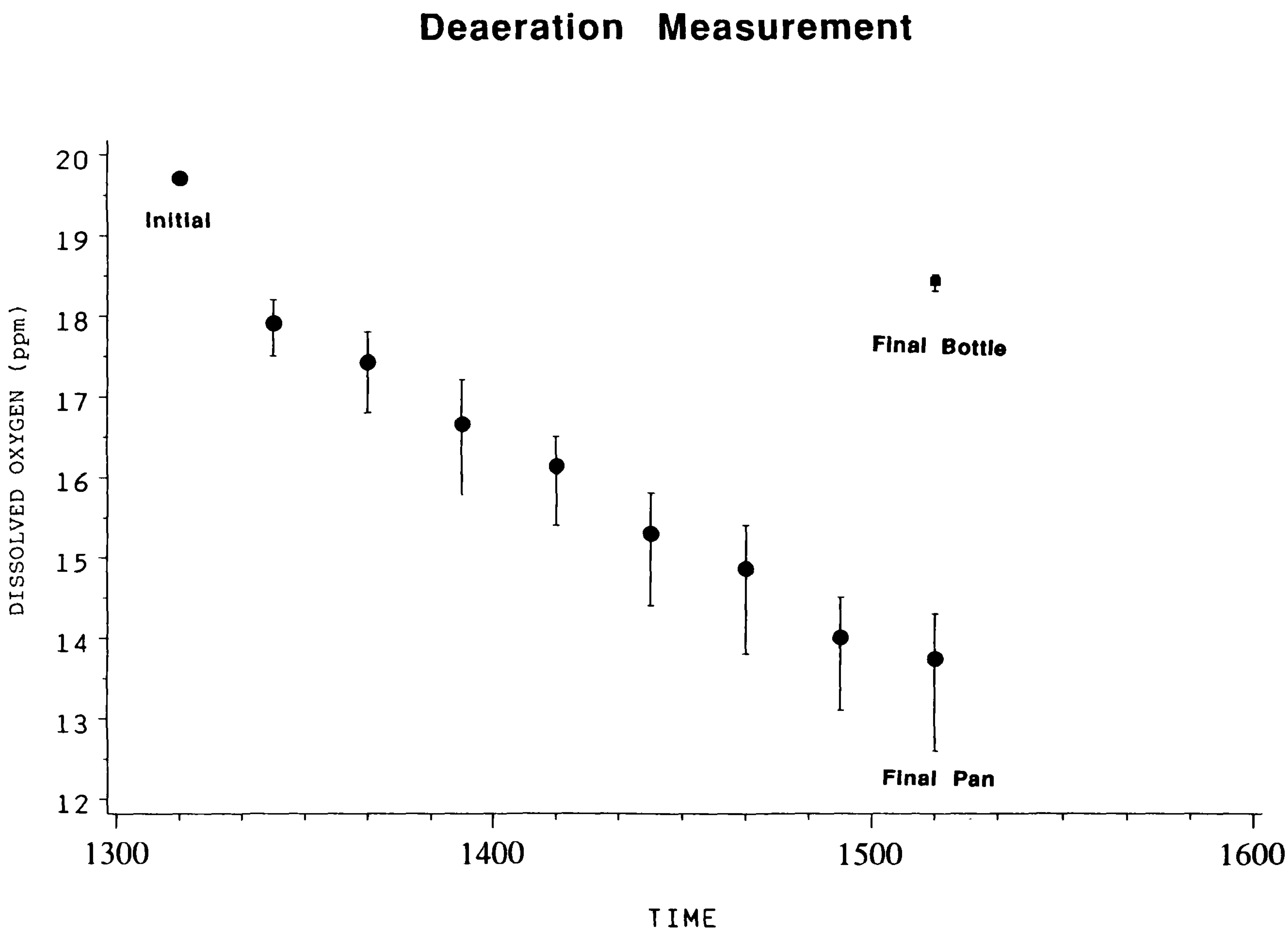


Figure IV-10. Decline of DO (ppm) over time in supersaturated Pigeon River, North Carolina water collected below the oxygenation unit at RM 61.3 and held shallow pans for two hours

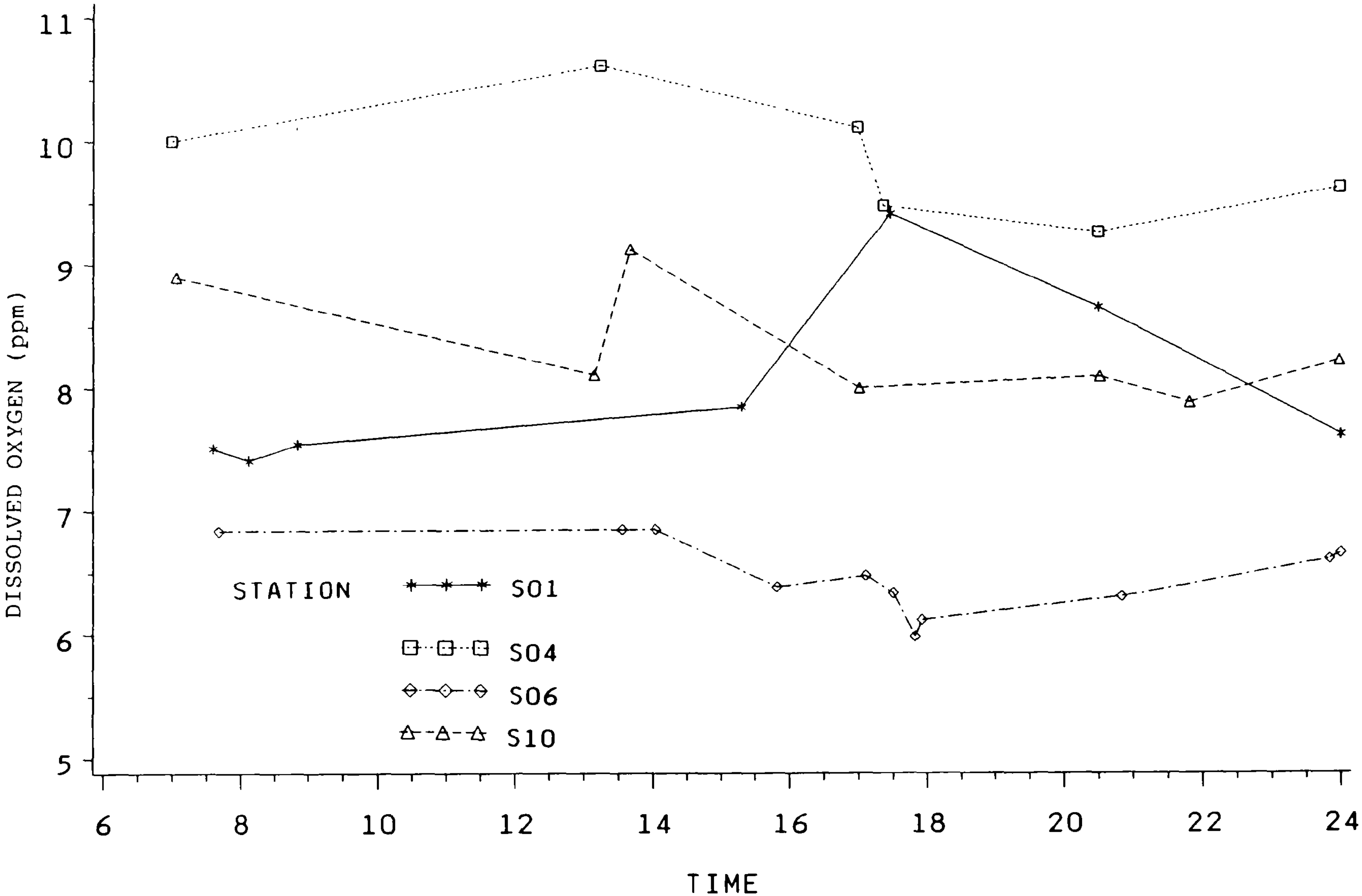


Figure IV-11. Diurnal dissolved oxygen (ppm) levels measured at four intensive sampling stations in the Pigeon River, North Carolina on 27 September 1988

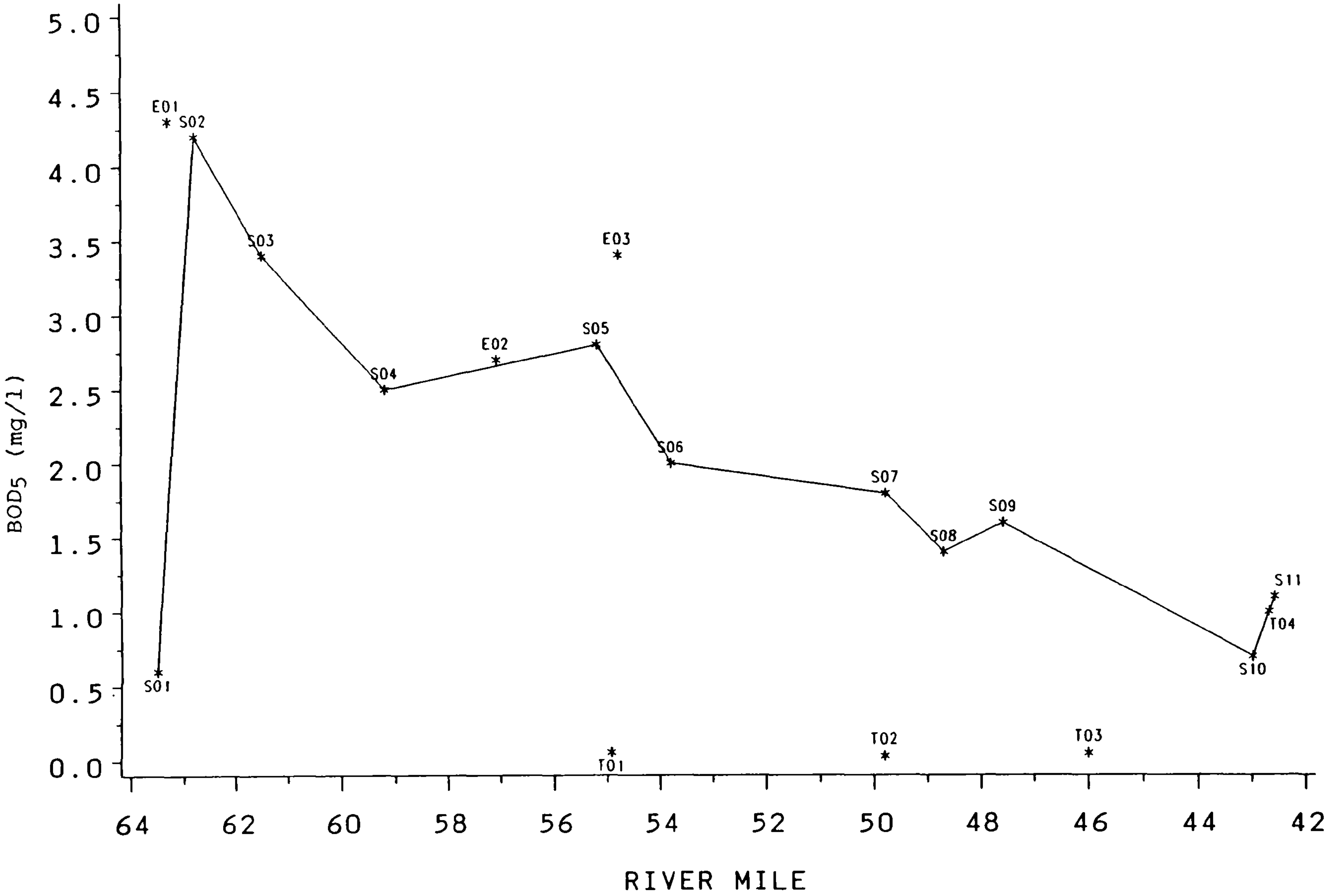


Figure IV-12. Five-day biochemical oxygen demand (BOD_5) at sampling stations in the Pigeon River, North Carolina between 0700 and 1100 on 27 September 1988

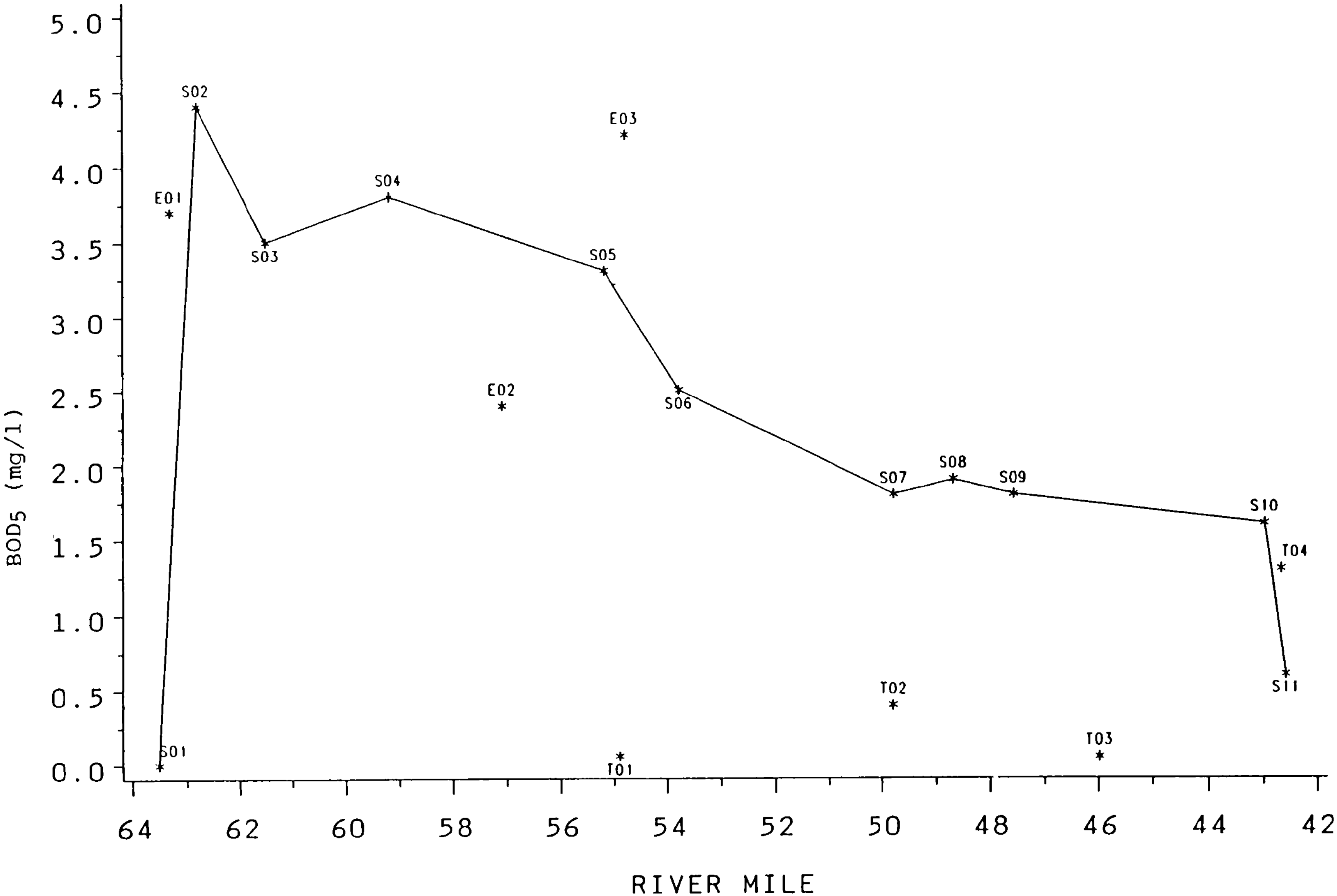


Figure IV-13. Five-day biochemical oxygen demand (BOD_5) at sampling stations in the North Carolina between 1300 and 1700 on 27 September 1988

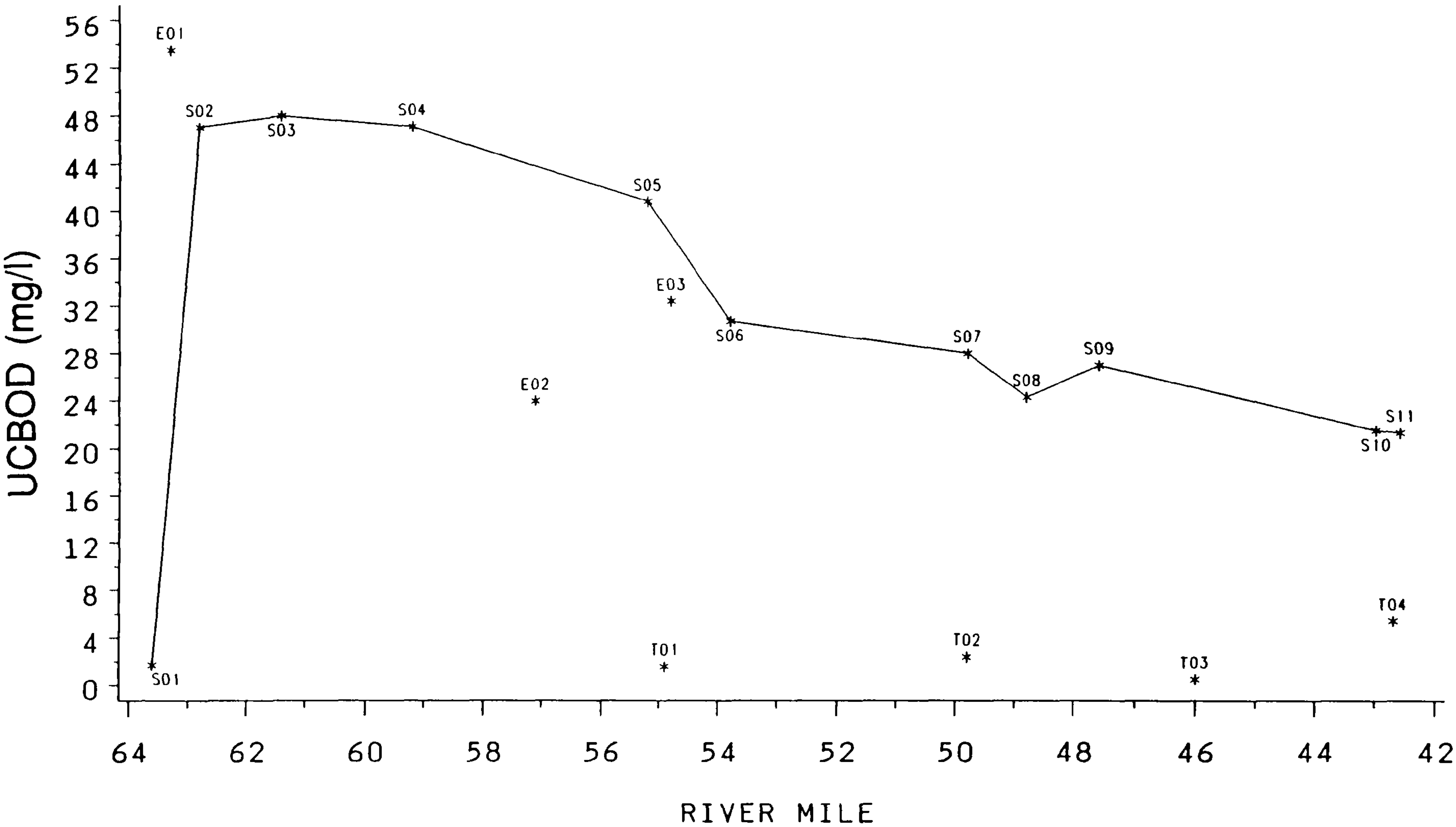


Figure IV-14. Ultimate carbonaceous biochemical oxygen demand (UCBOD) at sampling stations in the Pigeon River, North Carolina between 0700 and 1100 on 27 September 1988

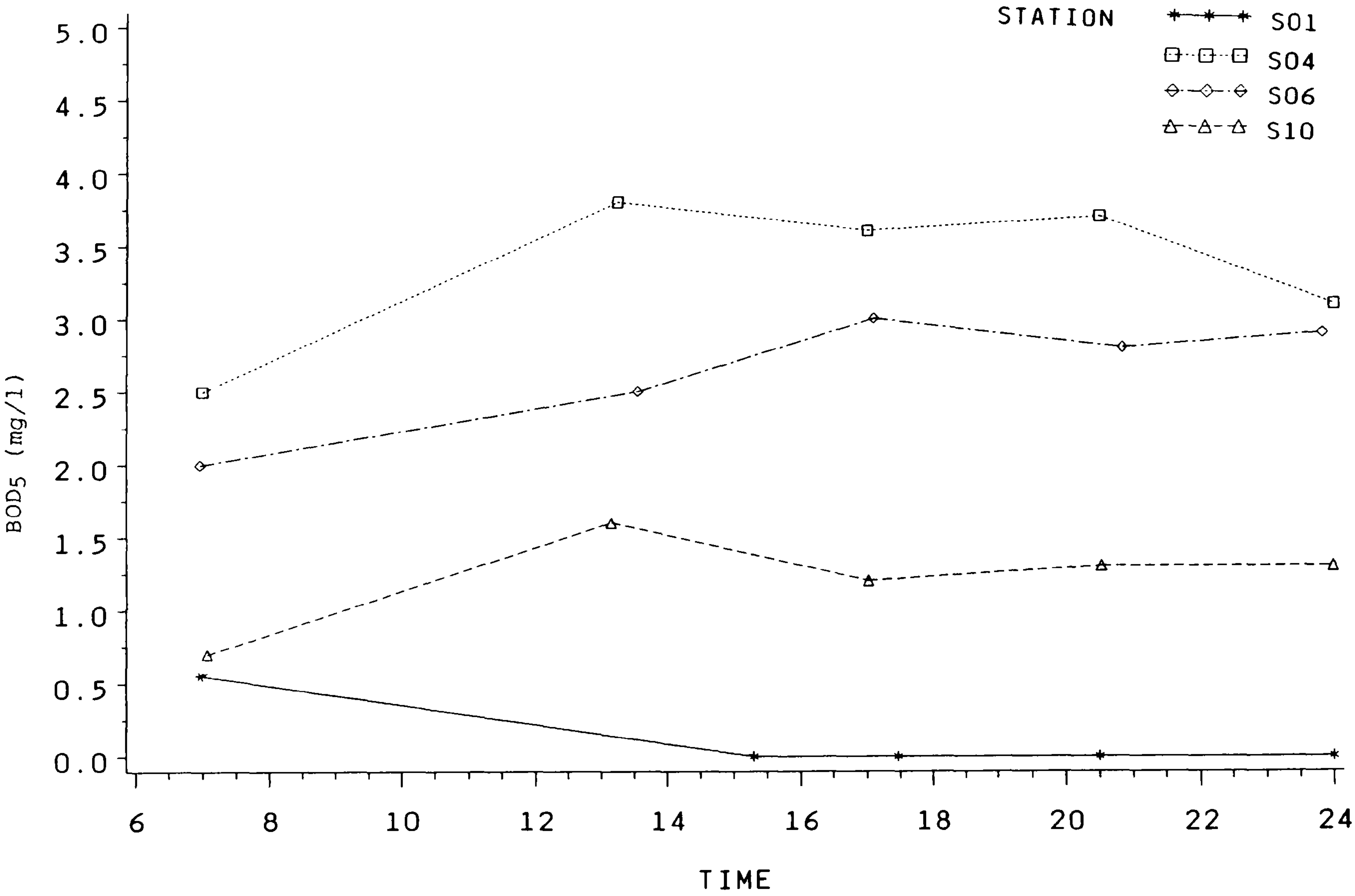


Figure IV-15. Diurnal variation in BOD_5 (mg/l) at four stations in the Pigeon River, North Carolina study area on 27 September 1988

Sediment Oxygen Demand (SOD)

Sediment oxygen demand (SOD) in the study area ranged from zero to 1726 mg O_2/m^2-day (Table IV-1). No longitudinal patterns were evident, and there was considerable variation within samples at a given station. In addition, no consistent differ-nces between light and dark chamber SOD experiments were apparent. The overall mean for the study area below the Champion outfall was 339 mg O_2/m^2/day.

Photosynthesis

As measured by light/dark bottle experiments at each of the four intensive stations, water column photosynthesis rates in the Pigeon River were low during the study; only at station S10 was a net increase in DO observed (66 mg O_2/m^3-h). At S2, S4, S6, and the USGS gauge location at Canton, no change or a slight decrease in DO was observed.

Water column chlorophyll *a* concentrations in the Pigeon River study were consistent with *in situ* light/dark bottle results; no chlorophyll *a* value above 1 mg/l was observed upstream of S6, while mainstem values below Crabtree Creek (S8) were between 3-6 mg/l (Fig. IV-16).

Light attenuation characteristics of the Pigeon River within the study were also consistent with chlorophyll *a* and primary productivity measurements (Fig. IV-17). From the Champion Mill outfall (E1) until Richland Creek (S6), essentially no light penetrated water below 0.2 m. Between Richland Creek (S6) and Jonathans Creek (S9), light penetration increased to more than 0.34 m. Below Jonathans Creek, light penetration increased again to more than 0.6 m.

Nutrients

Nitrogen species concentrations in the study area were generally less than 2 mg/l, except in the discharges from the Clyde and Waynesville WWTPs (E2 and E3), where elevated TKN and nitrate concentrations were observed (Fig. IV-18). Ammonia and TKN values increased sharply below the Champion Mill outfall (S2) and slowly declined with distance downstream. In contrast, nitrate and nitrite values were low at S2 and peaked near Richland Creek (S6). Diurnal fluctuations in nitrogen were small at all four intensive stations (Figs. IV-19 to IV-22).

Table IV-1. Sediment oxygen demand at selected sites in the Pigeon River, North Carolina during 27-28 September 1988

Station	River Mile	Type	SOD mg O_2/m^2/day
S0	64.8	Light	(net increase) 372.2
		Dark	0
S2	62.8	Light	358.2
		Dark	558.9
		Dark	0
S4	59.2	Light	0
		Dark	34.5
		Dark	0
S6	53.8	Light	0
		Dark	1393.5
		Dark	0
S10	43.0	Light	1726.3
		Dark	0
		Dark	0
Mean all SOD samples (excluding S0)			339.3

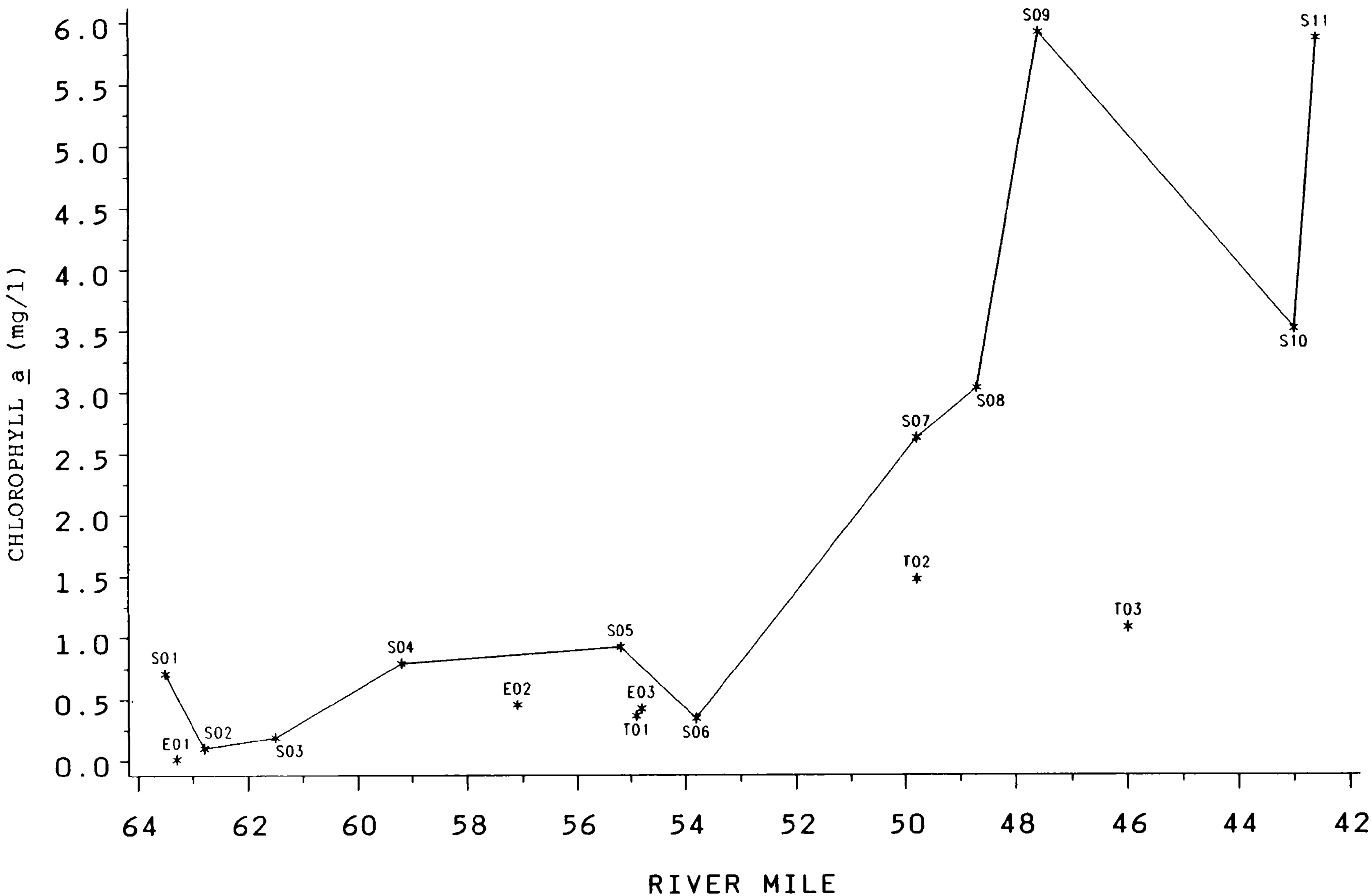


Figure IV-16. Chlorophyll a concentration (mg/l) in the Pigeon River, North Carolina study area on 27 September 1988

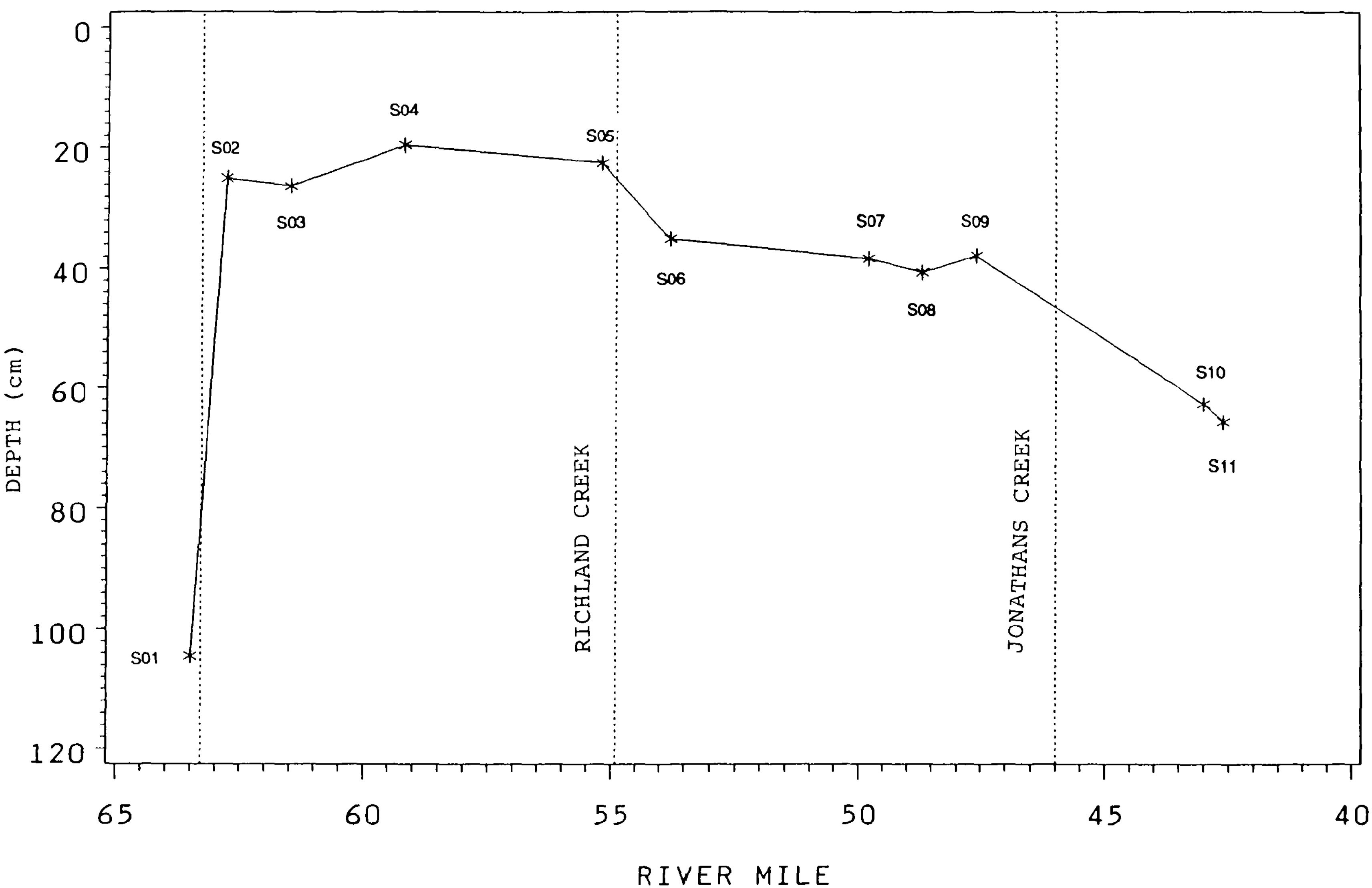


Figure IV-17. Water depth (cm at which 99% of available surface light was attenuated at 11 stations in the Pigeon River, North Carolina on 28 September 1988 (NOTE: 99% depth at S1 may be erroneously shallow due to an inability to sample depths greater than 1m)

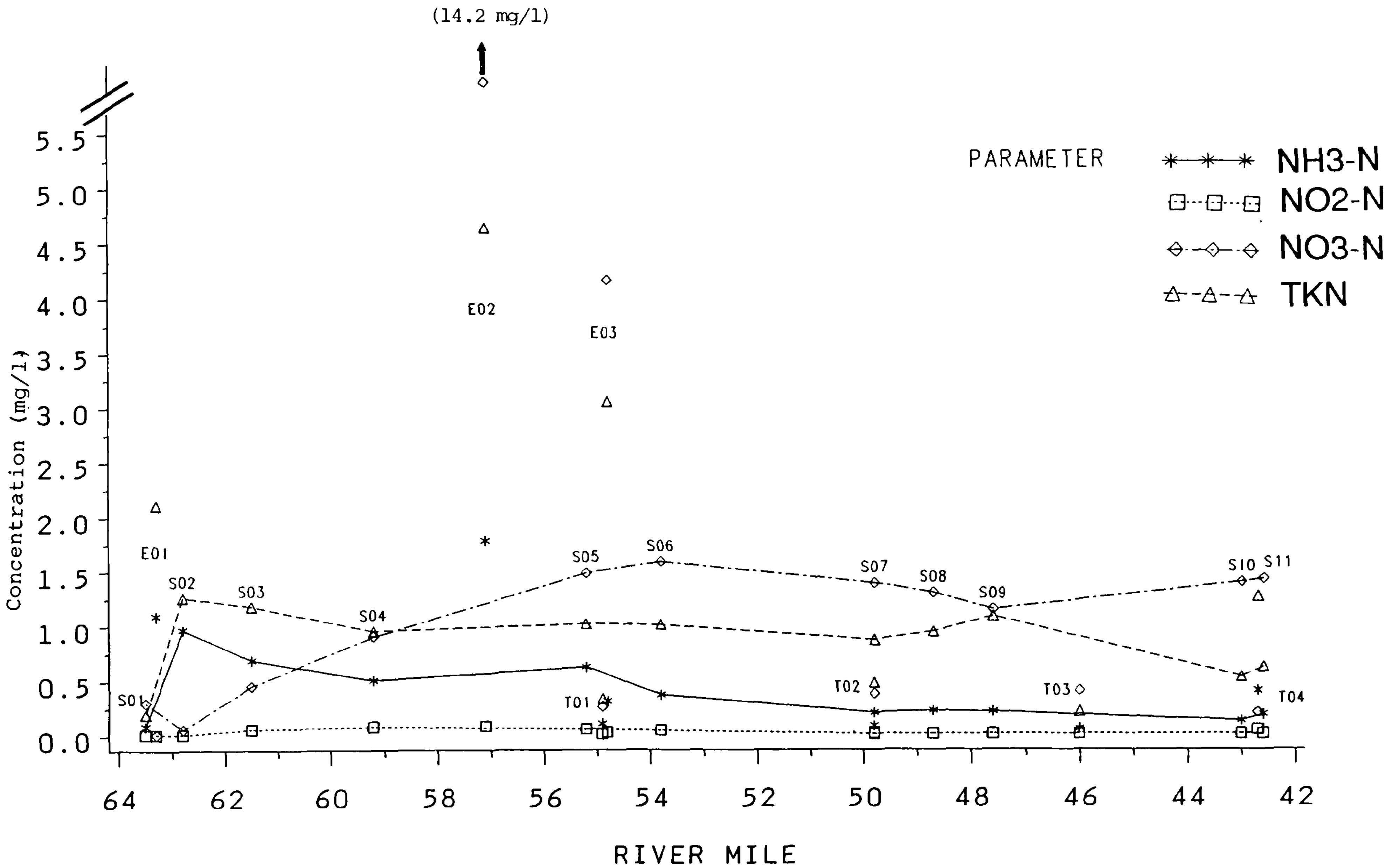


Figure IV-18. Longitudinal concentrations (mg/l) of NH_3-N, total Kjeldhal nitrogen, NO_2-N, and NO_3-N in the Pigeon River, North Carolina study are on 27 September 1988

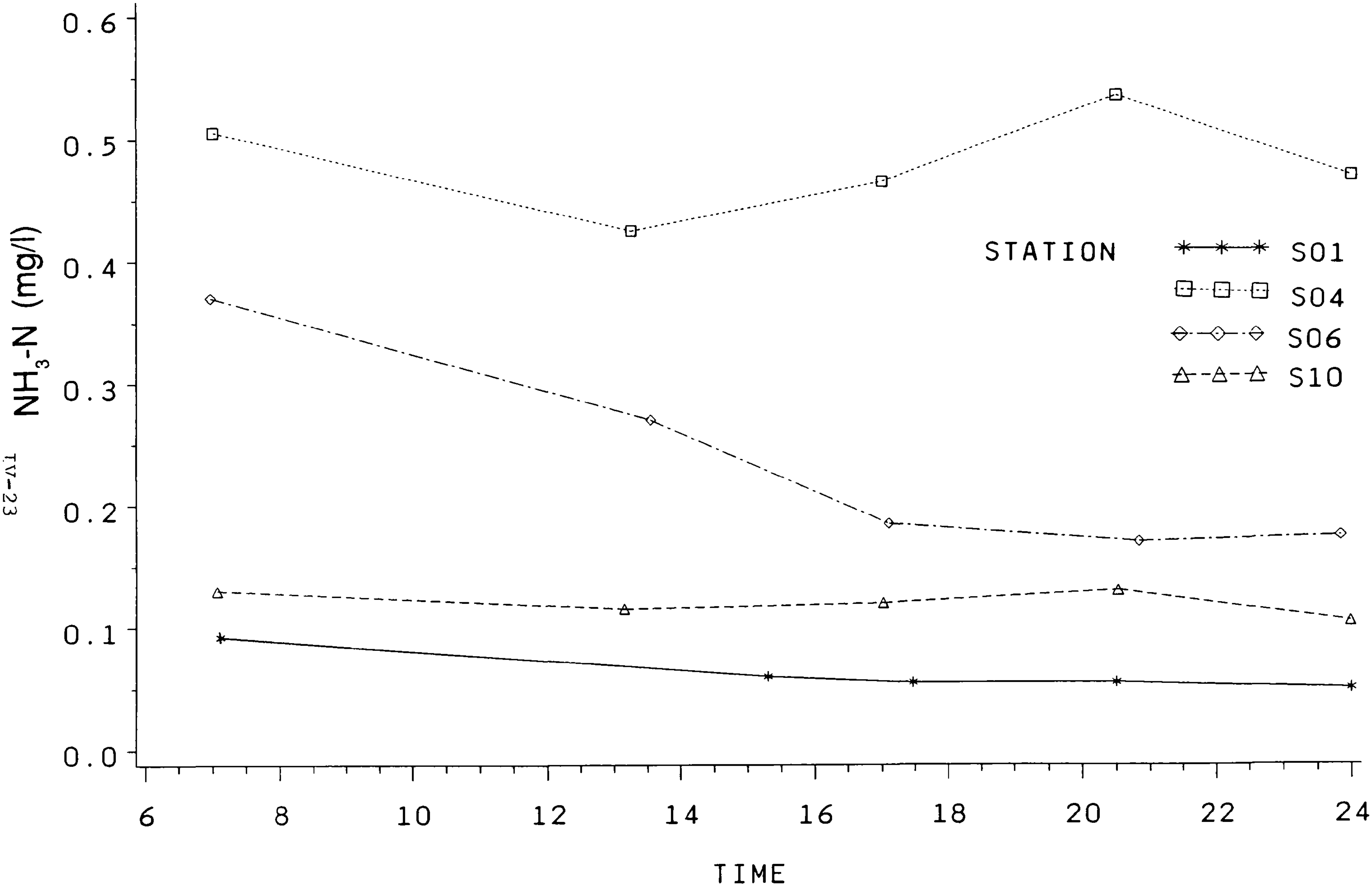


Figure IV-19. Diurnal variation in ammonia as nitrogen (mg/l) at four stations in the Pigeon River, North Carolina study area on 27 September 1988

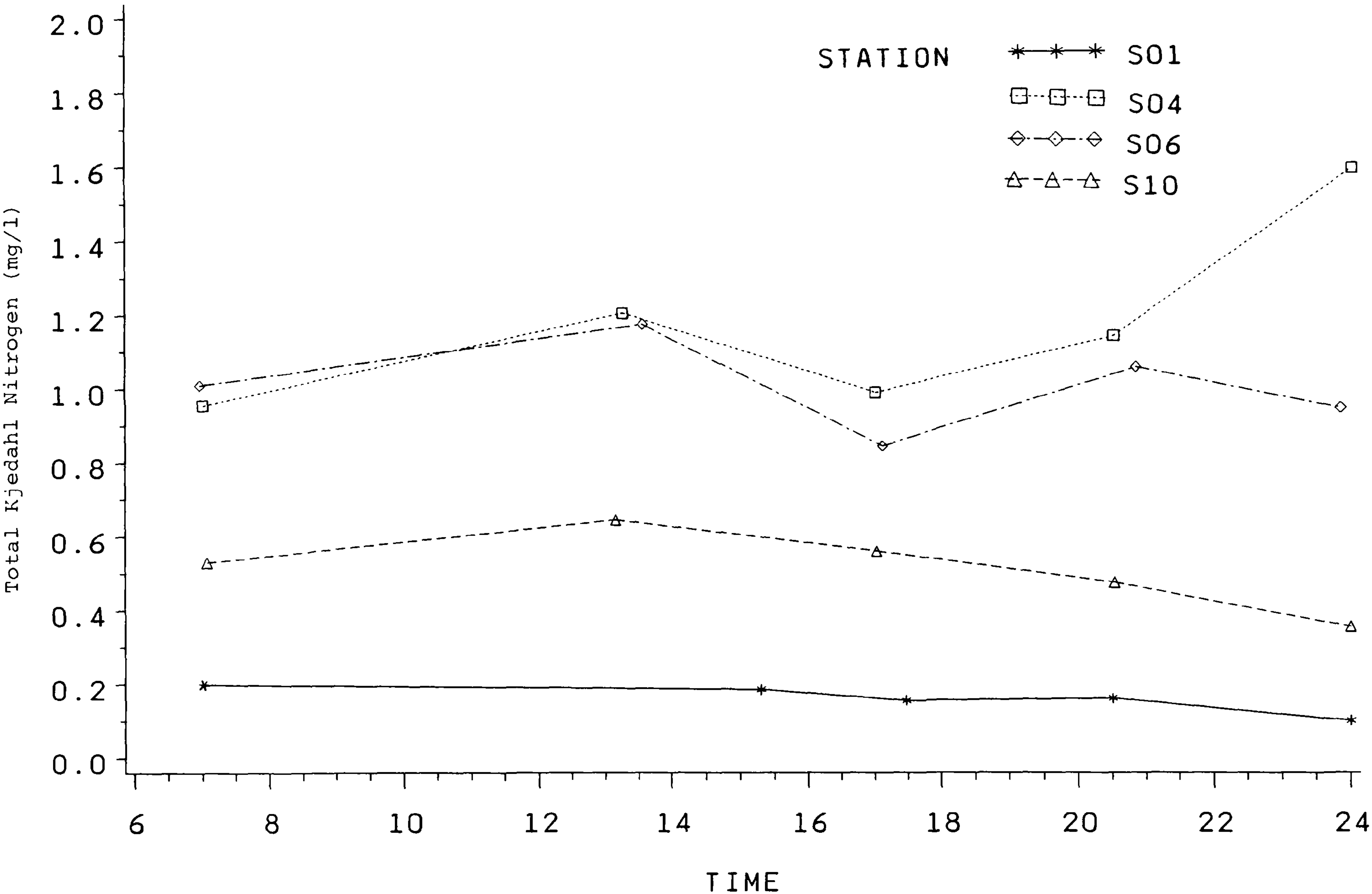


Figure IV-20. Diurnal variation in total Kjeldahl nitrogen (mg/l) at four stations in the Pigeon River, North Carolina on 27 September 1988

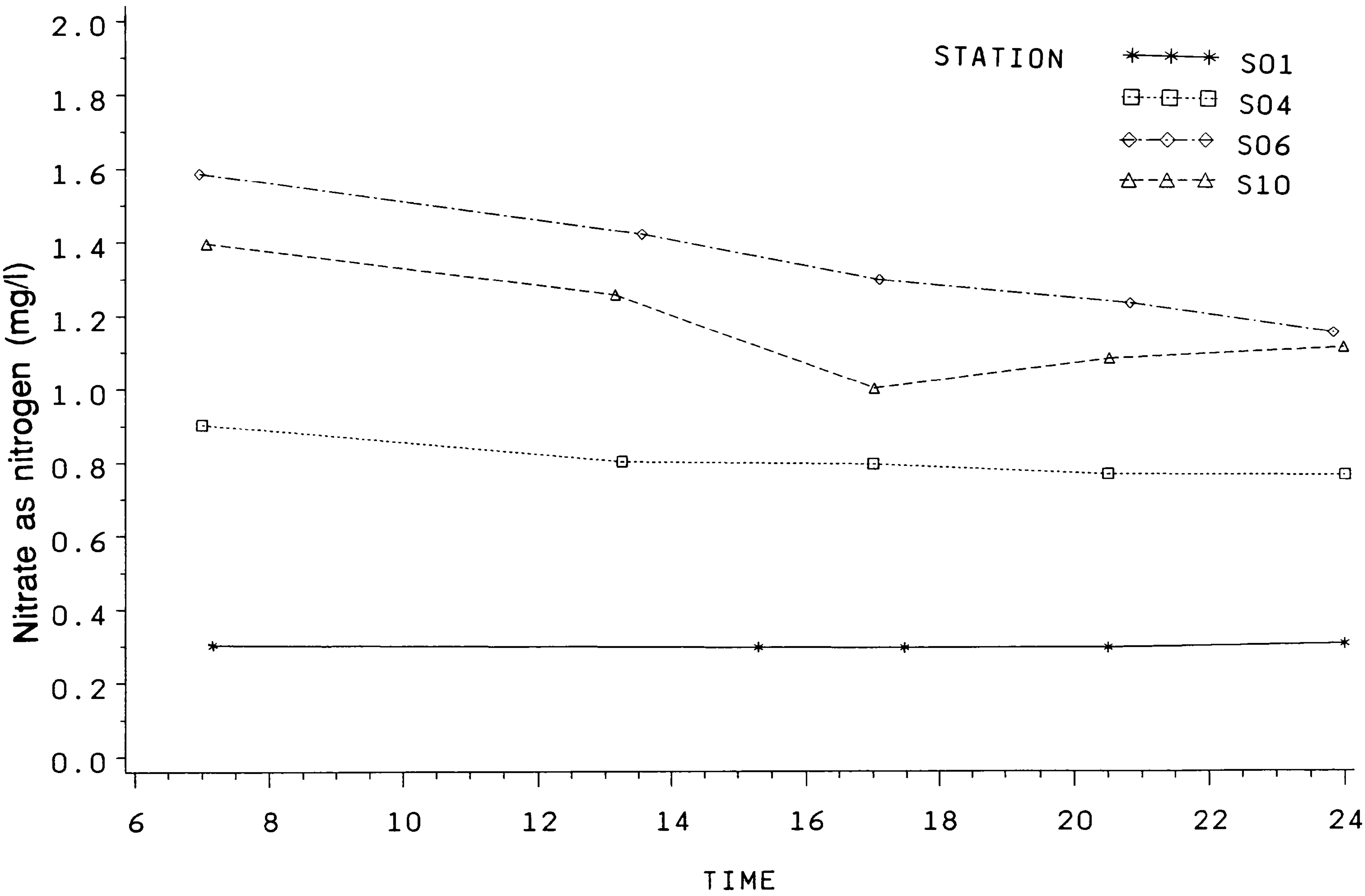


Figure IV-21. Diurnal variation in nitrate as nitrogen (mg/l) at four stations in the Pigeon River, North Carolina on 27 September 1988

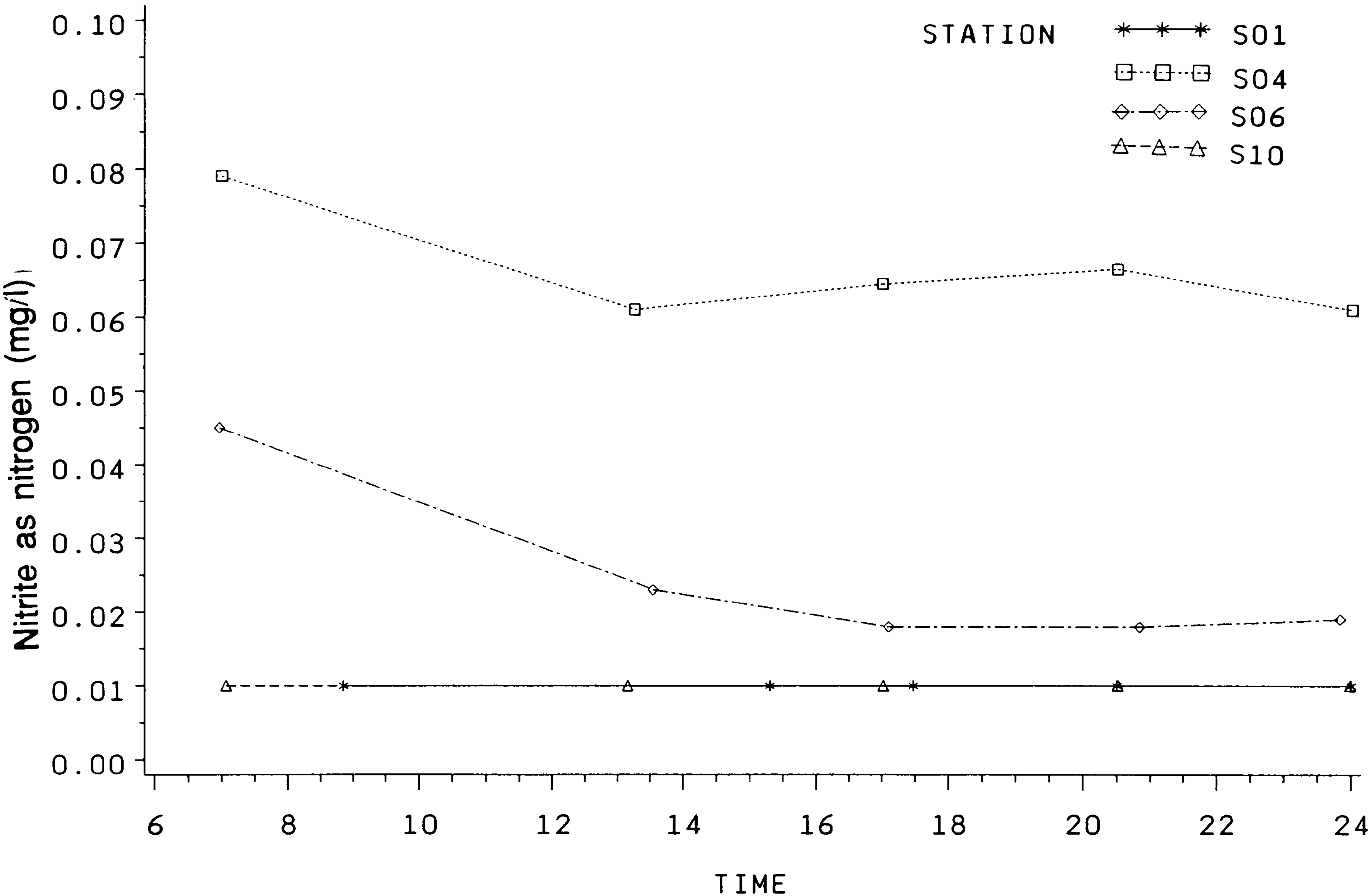


Figure IV-22. Diurnal variation in nitrite as nitrogen (mg/l) at four stations in the Pigeon River, North Carolina on 27 September 1988

Phosphorus concentrations in the Pigeon River mainstem were always less than 1 mg/l, but total phosphorus values of 3.8 mg/l and 1.5 mg/l were recorded from Clyde WWTP (E2) and Waynesville WWTP (E3), respectively (Figure IV-23). Mainstem values increased sharply below the Champion Mill outfall (E1), declined slowly until station S6, and remained nearly constant thereafter. No tributary values for phosphorus exceeded 0.2 mg/l. As with nitrogen species, there were no apparent diurnal fluctuations in total phosphorus and ortho-phosphate (Figs. IV-24 and IV-25).

Chloride

Only a single significant source of chlorides was identified during the study -- the Champion Mill effluent (Fig. IV-26). Correspondingly, mainstem values increased sharply below the outfall and declined in response to the aperiodic addition of flows to the river.

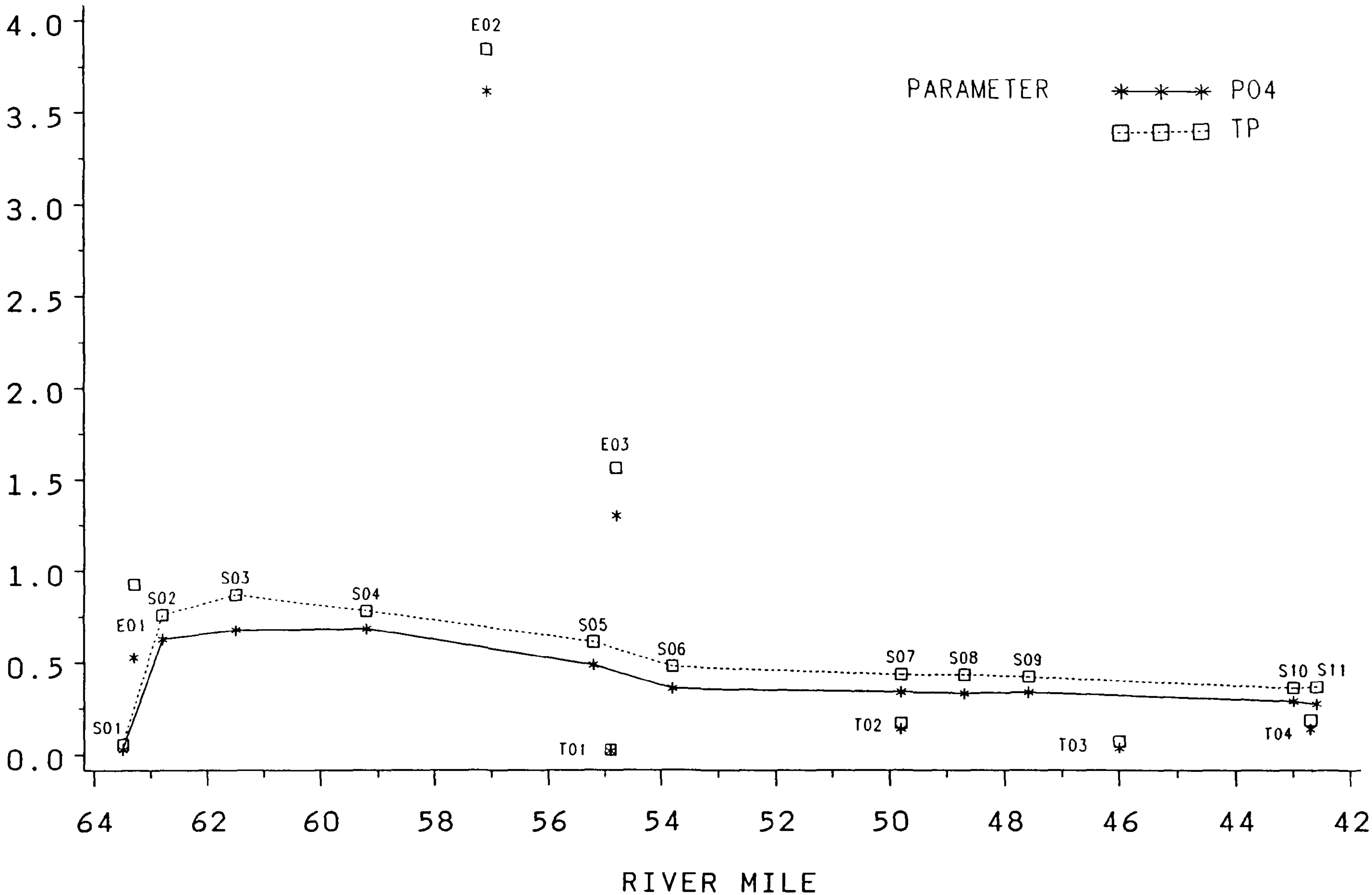


Figure IV-23. Phosphorus concentrations (mg/l) at mainstem and input stations in the Pigeon River, North Carolina study area on 27 September 1988

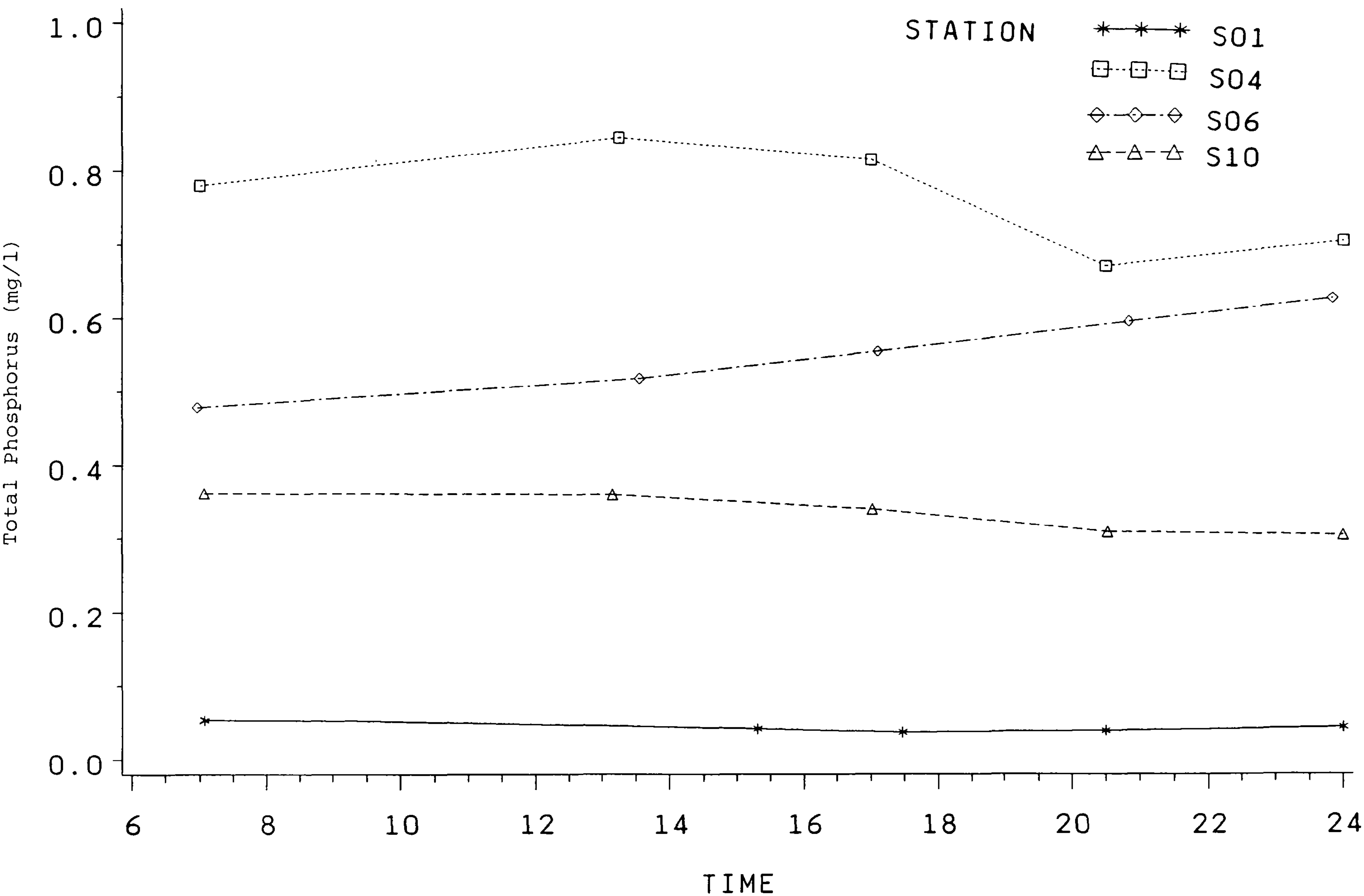


Figure IV-24. Diurnal variation in total phosphorus concentrations (mg/l) at four stations in the Pigeon River, North Carolina study area on 27 September 1988

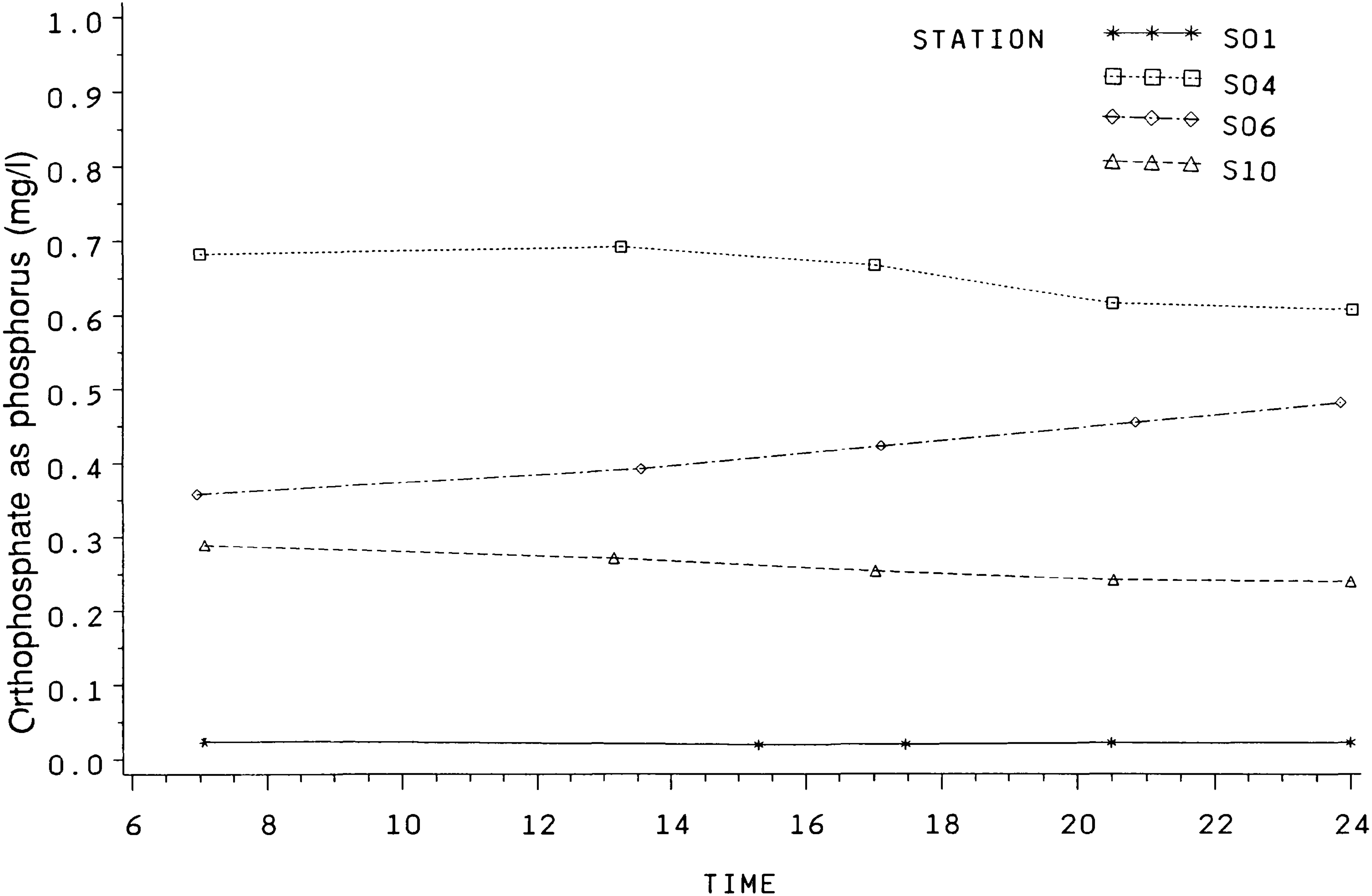


Figure IV-25. Diurnal variation in ortho-phosphate as phosphorus concentrations (mg/l at four stations in the Pigeon River, North Carolina study area on 27 September

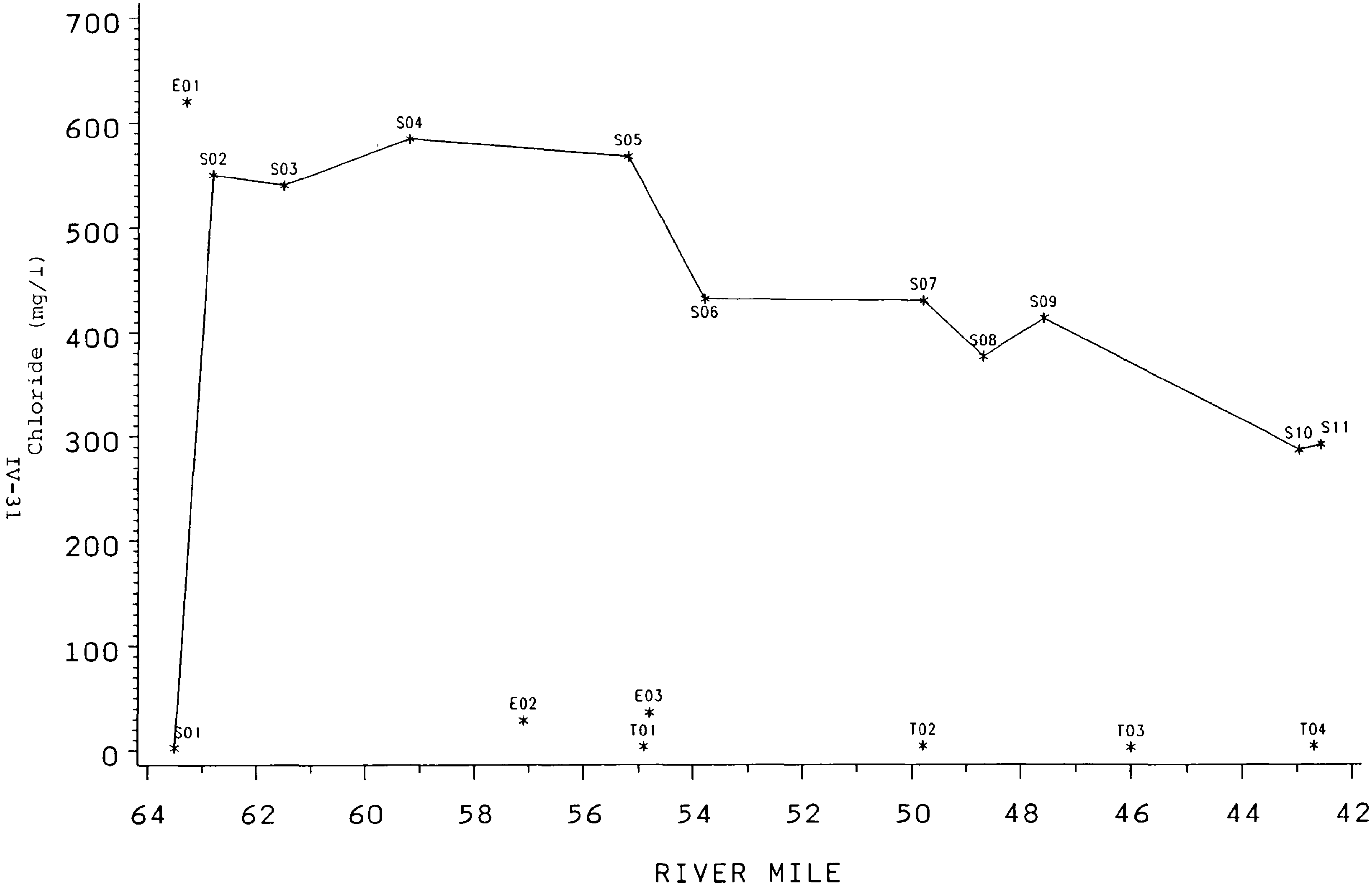


Figure IV-26. Chloride concentration (mg/l) at mainstem and input stations in the Pigeon River, North Carolina study area on 27 September 1988

V. MODELING METHODS

The Pigeon River model was constructed using the QUAL2E-UNCAS model (Brown and Barnwell 1987) and data from the September 27, 1988 field survey described in Chapter IV. The Pigeon River system was modeled from River Mile 63.6 (i.e., just upstream from the Champion discharge) to River Mile 42.8 (i.e., just upstream from Walters Lake). Flow conditions during this period were low (i.e., < 100 cfs at Champion) and were representative of low flow periods during late summer.

A. MODEL STRUCTURE

A conceptual overview of the Pigeon River Model (PRM) is represented schematically in Figure V-1. The wide range of processes affecting dissolved oxygen dynamics within the 20 mile modeled segment is evident from the figure. The processes, in conjunction with point discharges, control the dissolved oxygen concentrations in the river. Also shown in this figure are the four major subsystems within the modeled Pigeon River segment:

- The upstream input subsystem is forced based on measured concentrations of state variables and represents a subsystem high in dissolved oxygen concentration, and low in nutrients and BOD. This subsystem is the initial condition of the Pigeon River prior to the modeled point source additions.

- The riverine point sources are forced based on measured concentrations of the state variables. These point sources include the Champion Paper Mill effluent, three oxygenators, the Clyde and Waynesville WWTPS, and four tributaries to the Pigeon carrying their own point and non-point source loads. These riverine point sources include BOD, various nitrogenous compounds, phosphates, chlorides, oxygen, heat, and water.

- The Pigeon River subsystem is characterized as 105 0.2-mile segments which are dominated by advection. All dynamic processes (e.g., degradation, dilution, and transformation) occur within these modeled segments.

- The downstream subsystem whose inputs are controlled by the combination of advection, transformtion, and degradation within the modeled Pigeon River segment. The downstream subsystem is defined as Walters Lake and

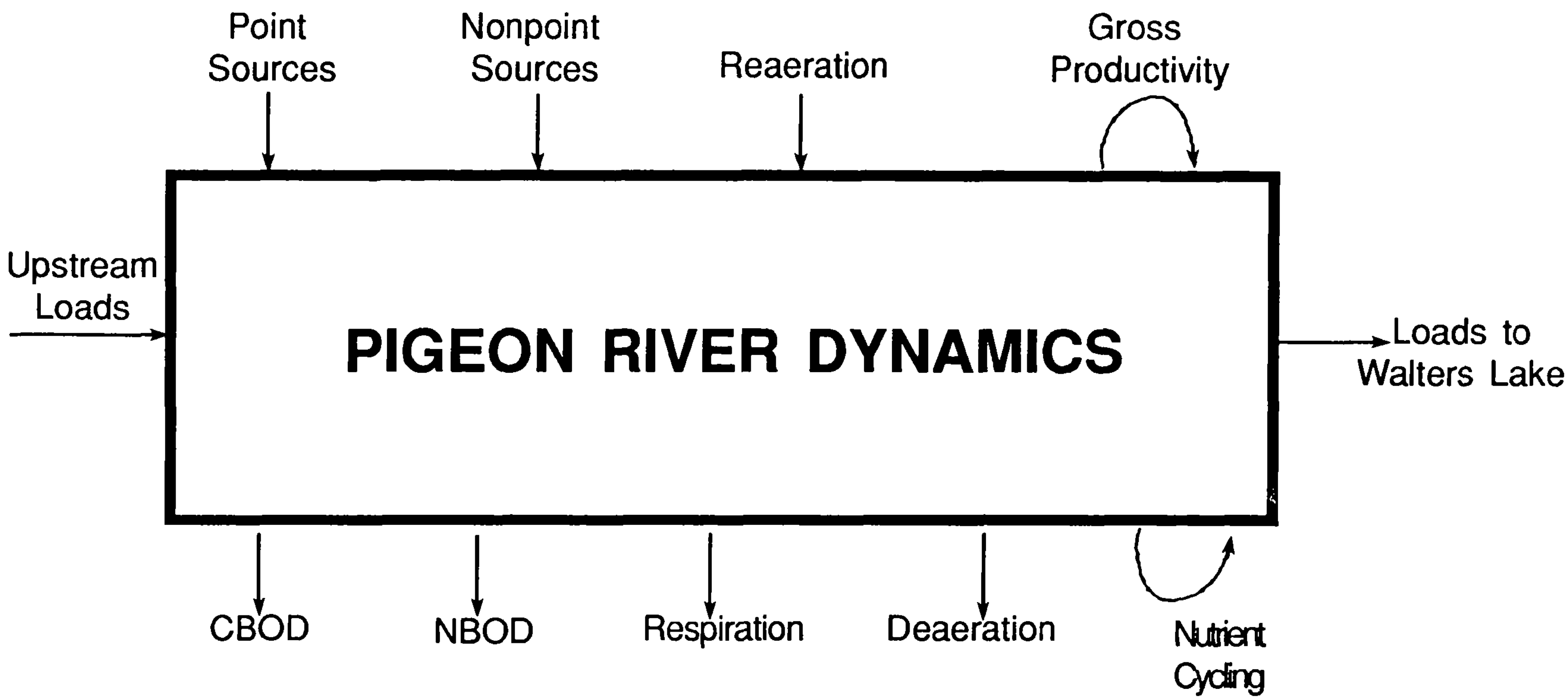


Figure V-1. Schematic representation of Pigeon River Model is not modeled in this effort. The inputs to Walters Lake are defined by the advective materials flows from the final modeled Pigeon River segment at River Mile 42.6.

The physical exchange among the 105 segments used to characterize the Pigeon River is primarily the result of advective flow and instantaneous mixing, and is controlled by upstream and tributary discharges. Exchange of oxygen at the air-water interface in specifically modeled based on in-stream dissolved oxygen measurements and experimentation (see Chapter III). Within-stream settling of organic particles was considered to be minimal based on the rapid travel times within the modeled segments (i.e.,8-20 minutes) and observations during the field sampling.

Based on the conceptual structure, the Pigeon River QUAL2E-UNCAS model was defined with 13 biological/chemical state variables and 6 physical state variables representing the carbon, oxygen, nutrient, and water storages in the subsystem components (Table V-1). A total of nine point sources were used in the model, each with state variable concentrations of their effluents (Table V-2). Figure V-2 is a detailed materials flow diagram illustrating the interactions among these model components and their relationships to the major driving forces within the Pigeon River (i.e., upstream flow, tributary flow, effluents, and temperature). The diagram is essentially a very detailed view of the conceptual model described in Figure V-1.

To depict the 20.8-mile riverine system, 10 reaches of varying lengths were incorporated into the PRM (Table V-3, Fig. V-3). Ten reaches were considered sufficient to characterize individual sections of the river where point sources and tributaries could affect local concentrations of state variables, particularly dissolved oxygen and ultimate biochemical oxygen demand.

The QUAL2E-UNCAS model used to describe the state variable concentrations in the Pigeon River was applied as a steady-state formulation representing late-summer low flow conditions (i.e., <100 cfs). The dominant biological and chemical mechanisms represented in the model structure include microbial/chemical degradation and transformation, respiration, primary productivity, and chemical oxygen demand. The primary physical mechanisms included are advection, reaeration, deaeration, and mixing.

Table V-1. State variables used in the Pigeon River QUAL2E model

<u>Biological/Chemical State Variables</u>
Dissolved oxygen
Carbonaceous BOD
Chlorophyll *a*
Total nitrogen
Organic nitrogen
Ammonia
Nitrite
Nitrate
Organic phosphorus
Dissolved phosphorus
Total phosphorus
Chlorides
Temperature
<u>Physical State Variables</u>
Flow
Travel time
Velocity
Depth
Width
Volume

Table V-2. Point sources used in the Pigeon River QUAL2E model for September 27, 1988

	Flow	Temp	DO	BOD	Cl	Chl*a*	NH_3
Point Sources							
Champion Paper Mill	6V-4	95.9	9.7	53.5	619.0	0.5	1.1
Oxygenator #2	25.0	*	30.0	*	*	*	*
Oxygenator #3	25.0	*	30.0	*	*	*	*
Clyde WWTP	0.2	70.9	7.5	24.0	28.9	0.5	1.8
Waynesville WWTP	4.1	65.4	7.9	32.4	36.4	0.4	0.3
Tributaries							
Richland Creek	24.7	65.0	8.8	1.6	3.6	0.4	0.1
Crabtree Creek	2.7	60.7	8.1	2.4	4.5	15.0	0.1
Jonathan's Creek	30.2	60.2	9.2	0.5	2.8	9.0	0.1
Fines Creek	2.9	59.9	8.7	5.4	4.4	2.4	0.4

*Defined by influent source

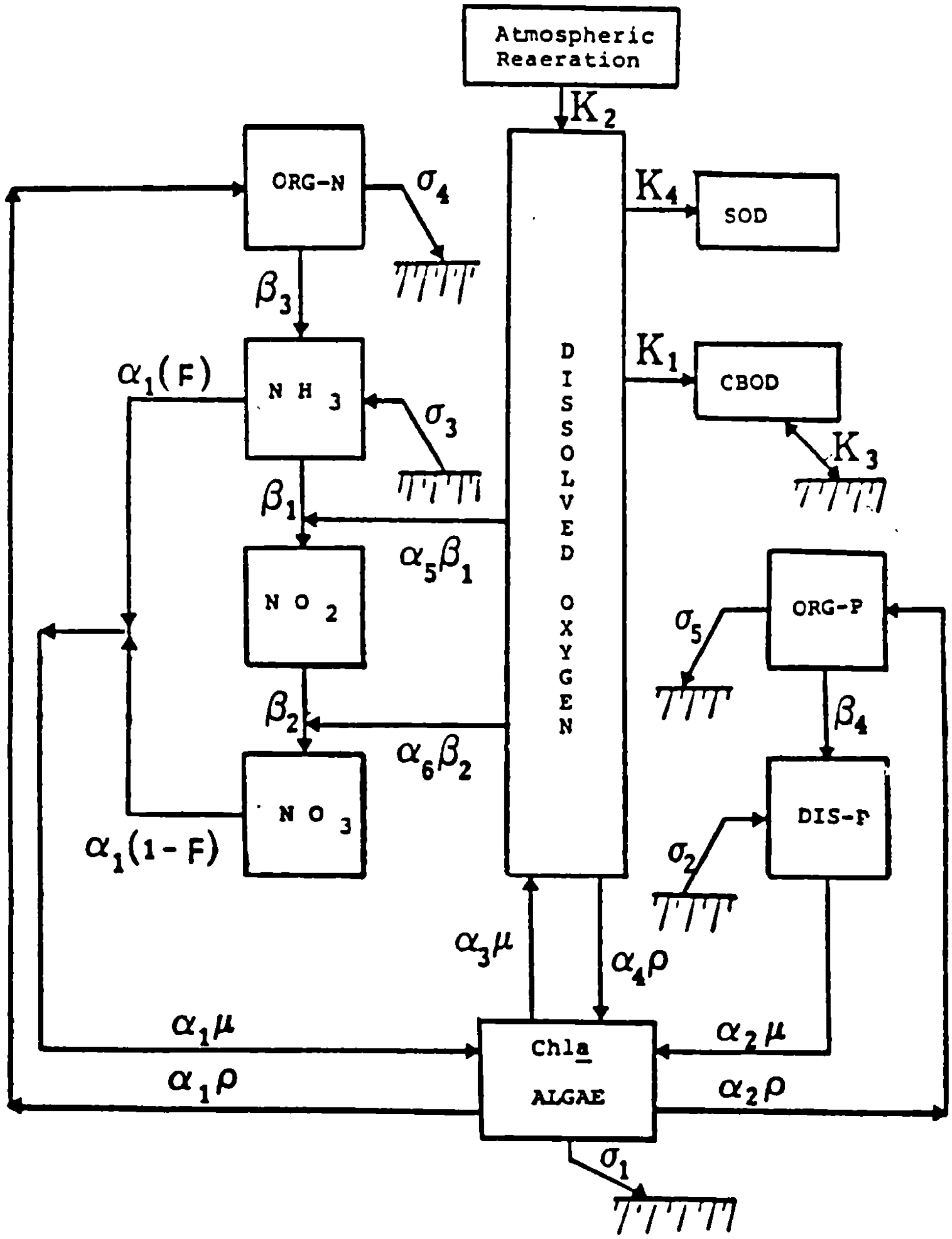


Figure V-2. Detailed flow diagram of Pigeon River QUAL2E model (from Brown and Barnwell 1987)

Table V-3. Lengths and location of modeled river reaches in Pigeon River QUAL2E model

Reach #	Begin River Mile	End River Mile	Length (Mi.)	Number of Elements
1	63.6	62.8	0.8	4
2	62.8	61.4	1.4	7
3	61.4	59.2	2.2	11
4	59.2	55.2	4.0	20
5	55.2	53.8	1.4	7
6	53.8	49.8	4.0	20
7	49.8	48.8	1.0	5
8	48.8	47.6	1.2	6
9	47.6	43.6	4.0	20
10	43.6	42.6	1.0	5

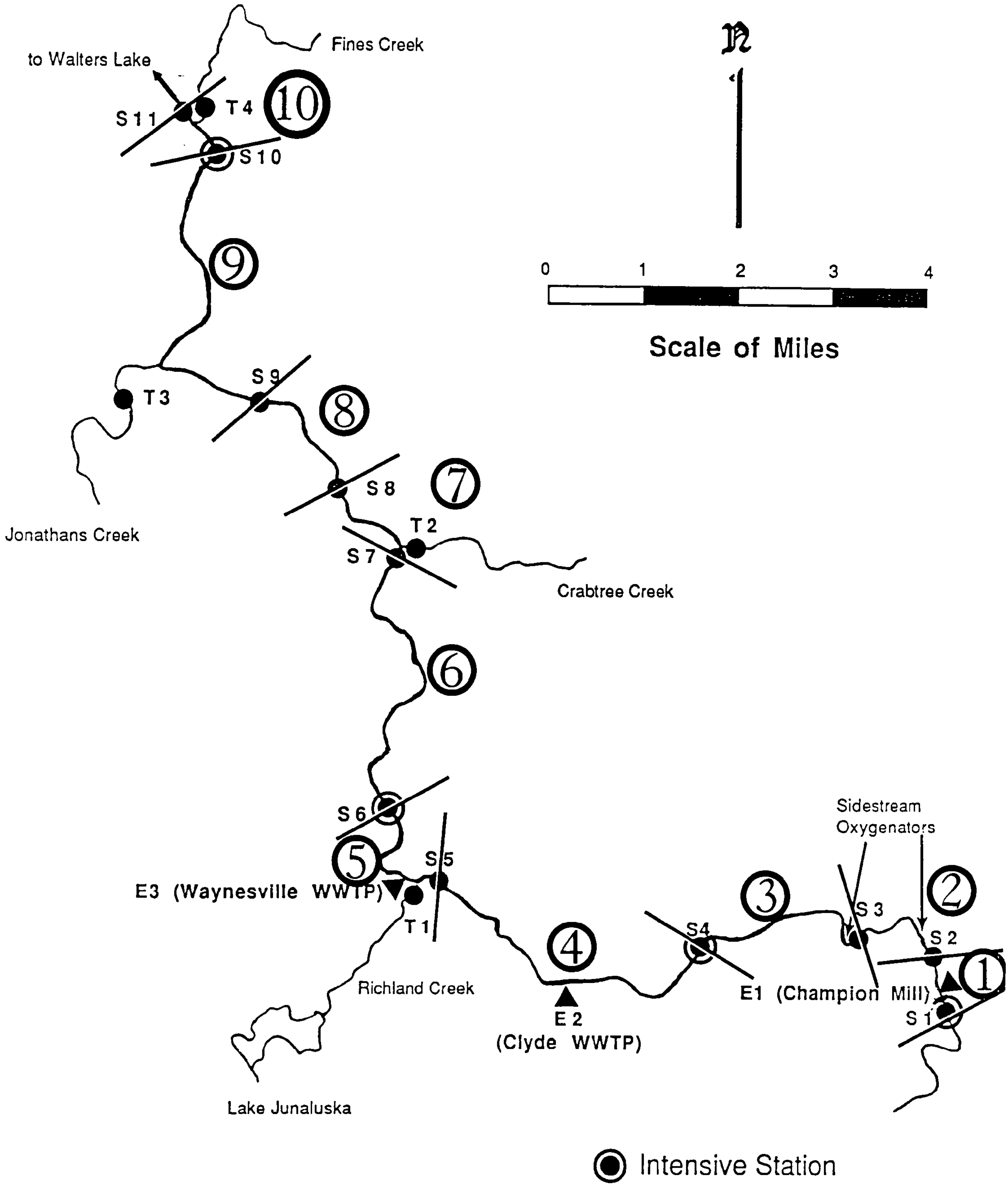


Figure V-3. Location of modeled reaches in Pigeon River QUAL2E Model (reach numbers are circled)

PRM Model Equations and Component Evaluation

The specific mathematical relationships used to represent algal dynamics; BOD decay; nutrient transformations, uptake, and excretion; hydrodynamics; and, transport in QUAL2E-UNCAS are described in detail elsewhere (Brown and Barnwell 1987). The major processes used in PRM are described below by type of process.

Hydraulic Discharge

The QUAL2E model assumes that the stream hydraulic regime is steady state such that the discharge at any location is the sum of the external inflows and/or withdrawals to that element. Given this relationship, discharge coefficients are determined from available data concerning velocity, cross-sectional area, and depth. The discharge coefficients used in PRM are shown in Table V-4 and were determined from empirical data collected at the site.

Carbonaceous BOD

The QUAL2E model assumes a first order linear reaction to characterize the degradation of ultimate carbonaceous BOD. The change in UCBOD concentration is determined as the sum of the degradation and settling, so that:

$$dL/dt = -K_1 L - K_3 L$$

where

L = Concentration of ultimate carbonaceous BOD (mg/l)

K_1 = Deoxygenation rate coefficient, temperature dependent, (day^{-1})

K_3 = Rate of loss of carbonaceous BOD due to settling, temperature dependent, (day^{-1})

Based on laboratory analyses of water column oxygen demand, the deoxygenation coefficient was calculated to be 0.11/day. The settling rate was determined by mass balance for each stream reach and averaged 0.001/day. The factor to convert 5-day CBOD to ultimate CBOD was derived analytically to be 13.2 based on the mean of UCBOD/CBOD5 ratios for stations S2 through S11 and the Champion effluent.

Table V-4. Discharge coefficients used in Pigeon River QUAL2E model

Reach #	Manning Coefficient	Coefficient of Dispersion	Linear Coefficient of Velocity	Power Coefficient of Velocity	Linear Coefficient of Depth	Power Coefficient of Depth
1	0.4	60.0	0.015	0.802	1.98	0.0
2	0.4	60.0	0.016	0.802	1.92	0.0
3	0.4	60.0	0.017	0.802	1.35	0.0
4	0.4	60.0	0.024	0.802	1.58	0.0
5	0.4	60.0	0.016	0.802	1.64	0.0
6	0.4	60.0	0.013	0.802	1.50	0.0
7	0.4	60.0	0.010	0.802	1.63	0.0
8	0.4	60.0	0.011	0.802	1.61	0.0
9	0.4	60.0	0.013	0.802	1.27	0.0
10	0.2	60.0	0.020	0.802	1.24	0.0

Dissolved Oxygen

The balance of dissolved oxygen in a stream reach is determined by the sum of its sources, sinks, and reaeration/ deaeration. The major sources of oxygen within the modeled portion of the Pigeon River are reaeration in the segments after River Mile 50, artificial infusion of oxygen into the streamflow by three oxygenators operated by the Champion Paper Mill, and tributary inflows. The Champion oxygenators infuse highly oxygenated water (i.e., 30-50 ppm) at the Champion discharge, River Mile 62.4, and River Mile 61.0. The major sinks for oxygen include the degradation of CBOD and NBOD and biotic respiration.

Reaeration

The reaeration method of Tsivoglou and Wallace (1972) was used to estimate reaeration rates for the Pigeon River. This method assumes that the reaeration coefficient for a reach is proportional to the change in elevation of the reach and is inversely proportional to the travel time within the reach. The reaeration coefficients used in PRM fall within the bounds suggested by Brown and Barnwell (1987) for streams with less than 3000 cfs. In addition, the reaeration rates become "deaeration" rates following the infusion of oxygen at the Champion aerators. These deaeration rates were estimated using the results of the simple experiment described in Chapter IV. These results would underestimate the diffusion of oxygen to the atmosphere because the oxygenated water was held motionless in the experiment and highly oxygenated flowing water would tend to deoxygenate faster than water in the experimental situation.

Nitrogen Cycle

The nitrogen cycle is modeled in QUAL2E as a stepwise transformation from organic nitrogen to ammonia, to nitrite, and finally to nitrate. The PRM models all four of these nitrogen constituents using estimates of hydrolysis from organic nitrogen to ammonia, settling rates, algal excretion and uptake rates, benthic regeneration rates, and oxidation rates for nitrogenous compounds.

Phosphorus Cycle

The phosphorus cycle is modeled in QUAL2E as a transformation cycle from organic phosphorus to dissolved phosphorus. The concentration of phosphorus is modeled based on algal uptake and excretion rates, decay rates, settling rates, and benthic regeneration rates.

Mass Transport

The basic equation used by QUAL2E for the transport of materials between model elements is the one-dimensional advection-dispersion mass transport equation. This equation is numerically integrated over space and time for each water quality constituent by including the effects of advection, dispersion, dilution, constituent reactions and interactions, and sources and sinks. For any constituent, C, this equation can be written as:

$$dM/dt = [(d(A_x D_L^{(dC/dx)})/dx]dx - [d(A_x uC)/dx] + (A_x dx)(dC/dt) + s$$

where

M = mass (M)

x = distance (L)

t = time (T)

C = concentration (ML^{-3})

A_x = cross-sectional area (L^2)

D_L = dispersion coefficient (L^2T^{-1})

u = mean velocity (LT^{-1})

s = external sources or sinks (MT^{-1}).

Using this approach, a set of differential equations was developed to describe the oxygen/BOD/nutrient dynamics of the Pigeon River by combining all mathematical terms representing inflows and outflows for the biological and chemical processes described above.

The initial conditions for the PRM were determined from the results of the field survey conducted in September 1988 (Chapter IV). Additional coefficients and rate constants were derived from the published literature and an unpublished time of travel study conducted by the North Carolina Department of Environmental

Monitoring (NCDEM). The values of initial conditions used in the Pigeon River Model are listed in Appendix A.

Model Calibration

The field survey data and the results of laboratory analyses were used to calibrate the initial QUAL2E model structure. The primary state variables of interest were dissolved oxygen, UCBOD and chlorides (i.e., as a conservative check for mass conservation). In addition, the model included a series of nitrogenous compounds (i.e., total Kjeldahl nitrogen, nitrites, nitrtes, and ammonia), total and dissolved phosphorus, and chlorphyll a. The model was calibrated using visual correspondence between model and field observations to approximate the best "fit" (Summers et al. 1980). Further calibration was completed objectively by systematically modifying each parameter over a small, defined range to create the matrix of parameter values which represented the smallest total sum squared error between the field and modeled data. The result of this calibration process is listed in Appendix A.

B. MODEL VALIDATION

Validation I - 28 September 1988

Initial validation of the Pigeon River QUAL2E model was completed using the Champion self-monitoring data taken on September 28, 1988, the day following the intensive field survey. This date was selected such that the primary driving forces of the model (e.g., flow, temperature, effluents) would be approximately the same as those used in the nominal model condition. The major differences between the nominal data set and this validation data set are the locations of collection and the personnel conducting the monitoring. Only UCBOD and DO were validated using this data set. The validity of the model runs for both state variables were compared by visual correspondence. In addition, validity was examined statistically by performing a linear regression of modeled versus observed data. Ideal correspondence would result in a regression with a slope of 1.0 and an intercept of 0.0. Our criteria for an acceptable validation was that the 95% confidence limits of the regression slope and intercept not be significantly different from 1.0 and 0.0, respectively.

Validation II - 7 July 1987

In addition to validating the model using late summer 1988 monitoring data, the validity of the model to describe higher flow (200-400 cfs) conditions was examined. Using data from an intensive field monitoring program completed for Champion in July 1987 (EA 1988), the model structure was tested to determine if the simulation could replay the observations made at high flow conditions. Criteria for acceptance were the same as the initial validation. The major difference between the two validations was that UCBOD was not used in this simulation. Rather than UCBOD, BOD_5 was simulated because the ratio between UCBOD and BOD_5 would not necessarily be the same as measured in September of 1987. Without knowing that the Champion effluent contained the same types of carbonaceous materials in July 1987 as September 1988, the ratio developed in 1988 would be invalid. This validation procedure included chlorides, dissolved oxygen, BOD_5, nitrogenous compounds, and phosphorus compounds.

C. MODEL UNCERTAINTY

QUAL2E is equipped with an uncertainty assessment processor (UNCAS) to permit evaluation of parameter sensitivity, first-order error propagation, and overall uncertainty using Monte Carlo analyses. A set of Monte Carlo simulations was completed to assess the potential level of error in the Pigeon River QUAL2E predictions. The uncertainty package (UNCAS) is based on the assumption that the inputs to the model or its parameters are normally distributed with known coefficients of variation. All inputs and parameters are assumed to be independent. Values for parameters are randomly selected for use in the Monte Carlo simulations from these normal distributions based on the coefficient of variation. Five hundred Monte Carlo simulations were performed to address each uncertainty estimate. The standard deviation of the 500 runs represents a statistical estimate of the uncertainty associated with the model prediction for that state variable.

Monte Carlo analyses were conducted for seven different uncertainty scenarios to pinpoint the primary causes of prediction uncertainty. The degree of variability in the Monte Carlo runs was determined by the coefficient of variation of the 27 September field survey data (i.e., diurnal variability), when possible. When no measure of diurnal variation was available, best scientific judgement was used to estimate the coefficient of variation. The uncertainity simulations included:

- o Varying all point source loads by 10-15% without modifying point source discharge rates

- Varying all headwater water quality concentrations by 10-15% without modifying headwater flow rates

- Varying all headwater water quality concentrations by 10-15% and headwater flow rates by 6%

- Varying all reaction coefficients affecting dissolved oxygen concentrations by 3-20%

- Varying the reaction coefficient for the decay of carbonaceous materials by 15%

- Varying all reaction coefficients affecting nitrogen or phosphorus concentrations by 3-20% and reaction coefficients affecting nitrogenous oxidation by 10%

- Varying all reaction coefficients, model parameters, and point source discharges by 3-20% without modifying streamflow.

The QUAL2E-UNCAS model package limits the comparison of prediction uncertainties with the nominal model predictions to five locations within the modeled portion of the Pigeon River. The following five comparison sites were selected:

- River Mile 63.2 - Immediately after the Champion discharge

- River Mile 61.0 - Immediately after the third and final Champion oxygenator

- River Mile 57.0 - Clyde STP discharge

- River Mile 54.8 - Waynesville STP discharge directly into the Pigeon River

- River Mile 42.6 - Confluence of the Pigeon River with the upstream end of Walters Lake.

These locations allow the maximum utility to be made of the comparative data to evaluate the uncertainty associated with the model predictions, to examine potential modeling scenarios concerning the effluents of Champion and the two WWTPS, and to ascertain additional information that might be needed to further characterize the modeled segment of the Pigeon River.

CHAPTER VI. MODEL RESULTS

A. CALIBRATION

The calibration of the QUAL2E Pigeon River Model "fit" the observed field survey data remarkably well (Figures VI-1 through VI-9). The correspondence of the simulated curves for dissolved oxygen, ultimate biochemical oxygen demand, and chlorides are very good and generally fall within the 95% confidence intervals of the observed data. The dissolved oxygen simulation accurately characterizes the rapid increases in oxygen level near the oxygenators and the systematic deaeration following the oxygenation. The simulated nutrient data (N and P) are also good, with the exception of nitrite. The nitrite simulation suggests that nitrite should be measurable at the 0.03 to 0.05 ppm level while field observations show the value to be less than 0.01 ppm.

Chlorides

The modeling of chlorides for the Pigeon River was done to verify that the flow regimes used in the model for the Pigeon River and its tributaries, the inflow rates of the point sources, and the dilution processes within the river were reasonable. In theory, chlorides added to the river should not be degraded in any manner and any observed changes in concentration would be simply due to dilution. Modeled chloride concentrations increase from approximately 2 ppm upstream of the mill to 618 ppm at the Champion discharge and remain constant until subsequently diluted by the inflows from Richland Creek, Crabtree Creek, Jonathans Creek, and Fines Creek (Fig. VI-1). Upstream and tributary concentrations of modeled chlorides were minimal (i.e., 2.3-4.5 ppm) and the only appreciable sources of chloride were the Champion discharge (i.e., 619 ppm) and the Clyde and Waynesville WWTPs (i.e., 28.9 and 36.4 ppm, respectively). The addition of chlorides from the Clyde and Waynesville WWTPS actually diluted the instream concentrations of chlorides to a small degree.

The simulated chlorides confirms that the hydraulic system used by the model conserves chlorides in the proper concentrations to reasonably match the observed field data. The early over-estimates of the model from River Mile 62 to 56 suggest an error in the field estimates of the chloride concentrations. The field data show that the chloride input from the Champion discharge was 619 ppm and represented 100% of the river flow, yet regions immediatedly downstream of the discharge were measured to

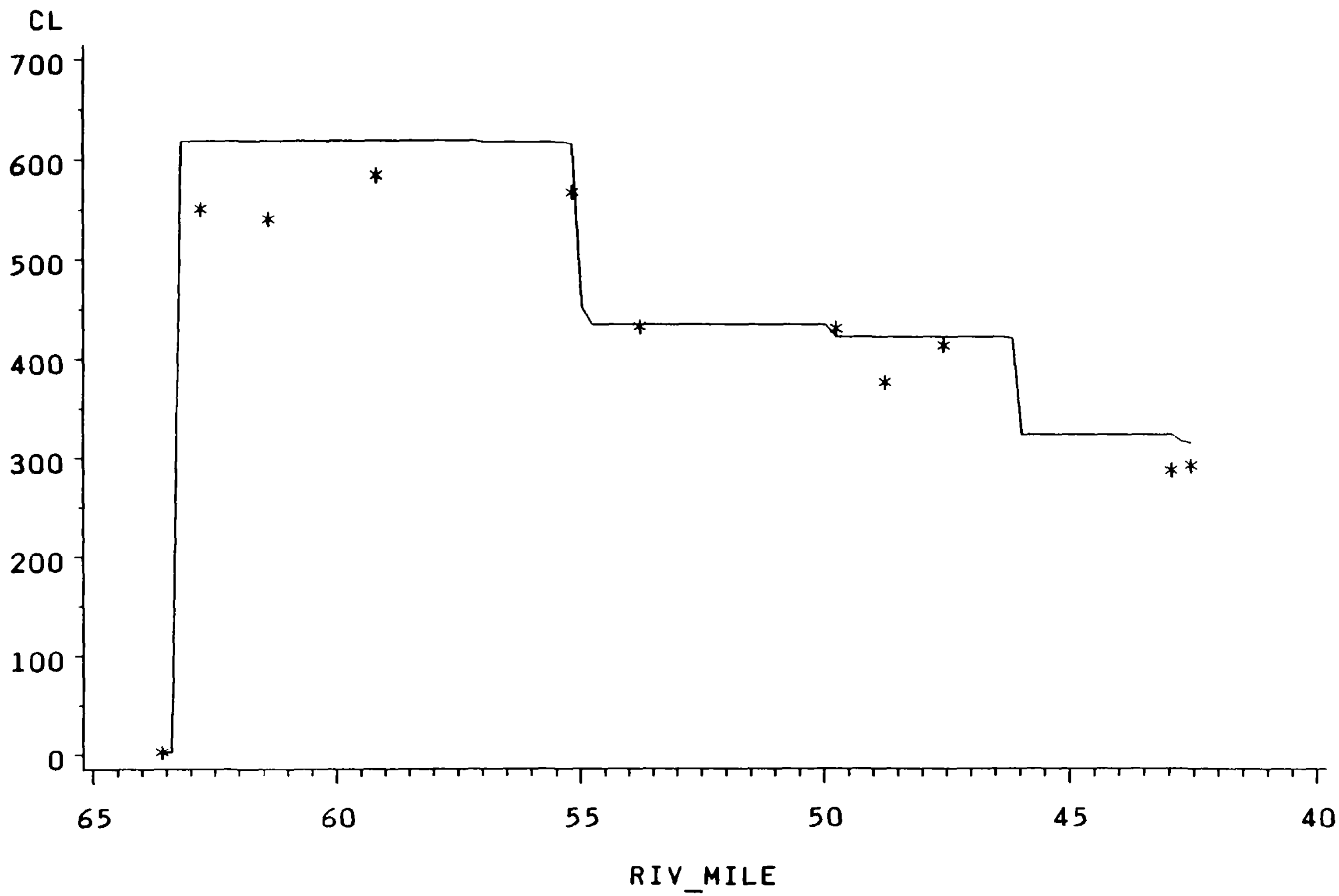


Figure VI-1. Observed (*) and simulated (__) values of chloride (ppm).

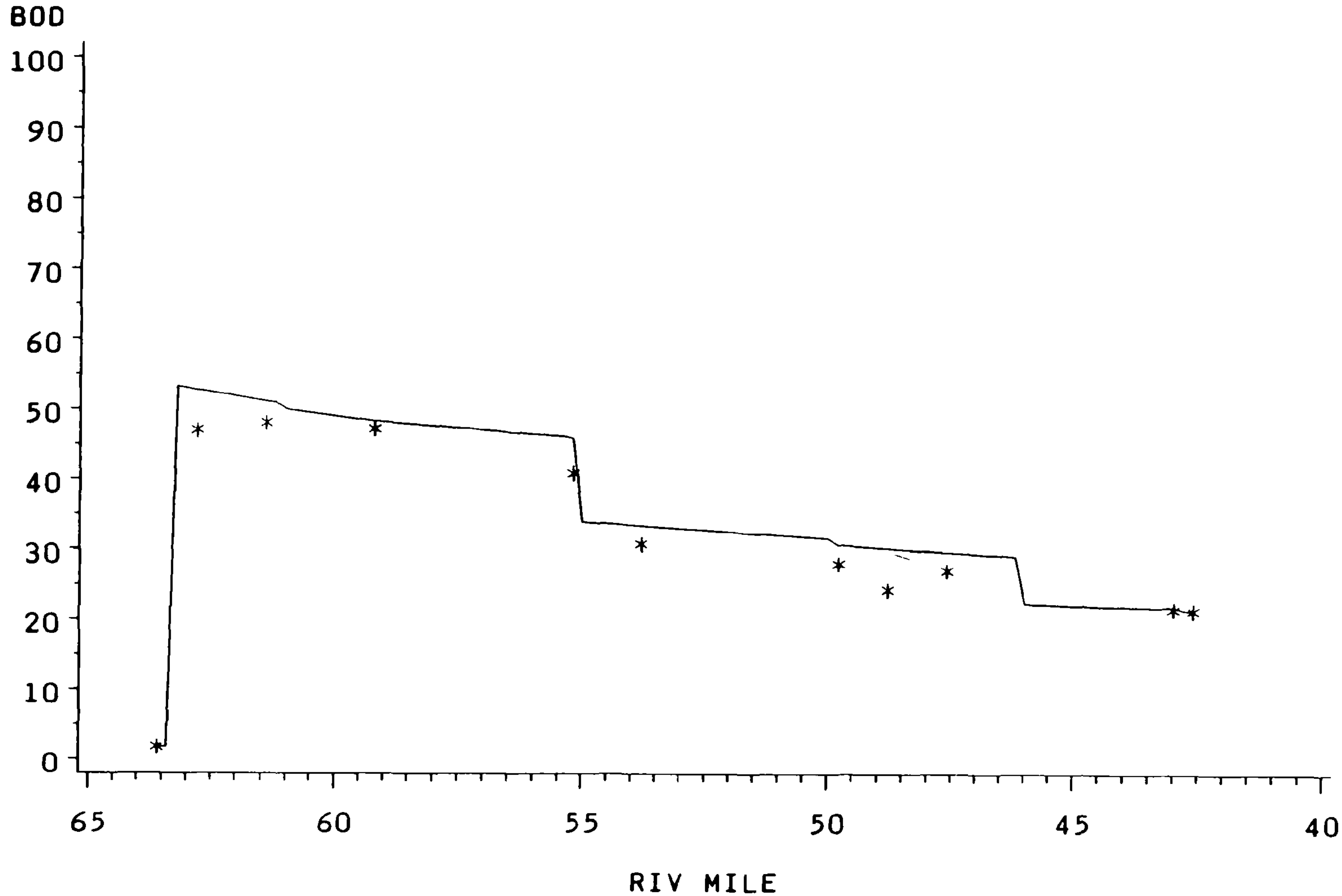


Figure VI-2. Observed (*) and simulated (__) values of ultimate carbonaceous biochemical oxygen demand (ppm).

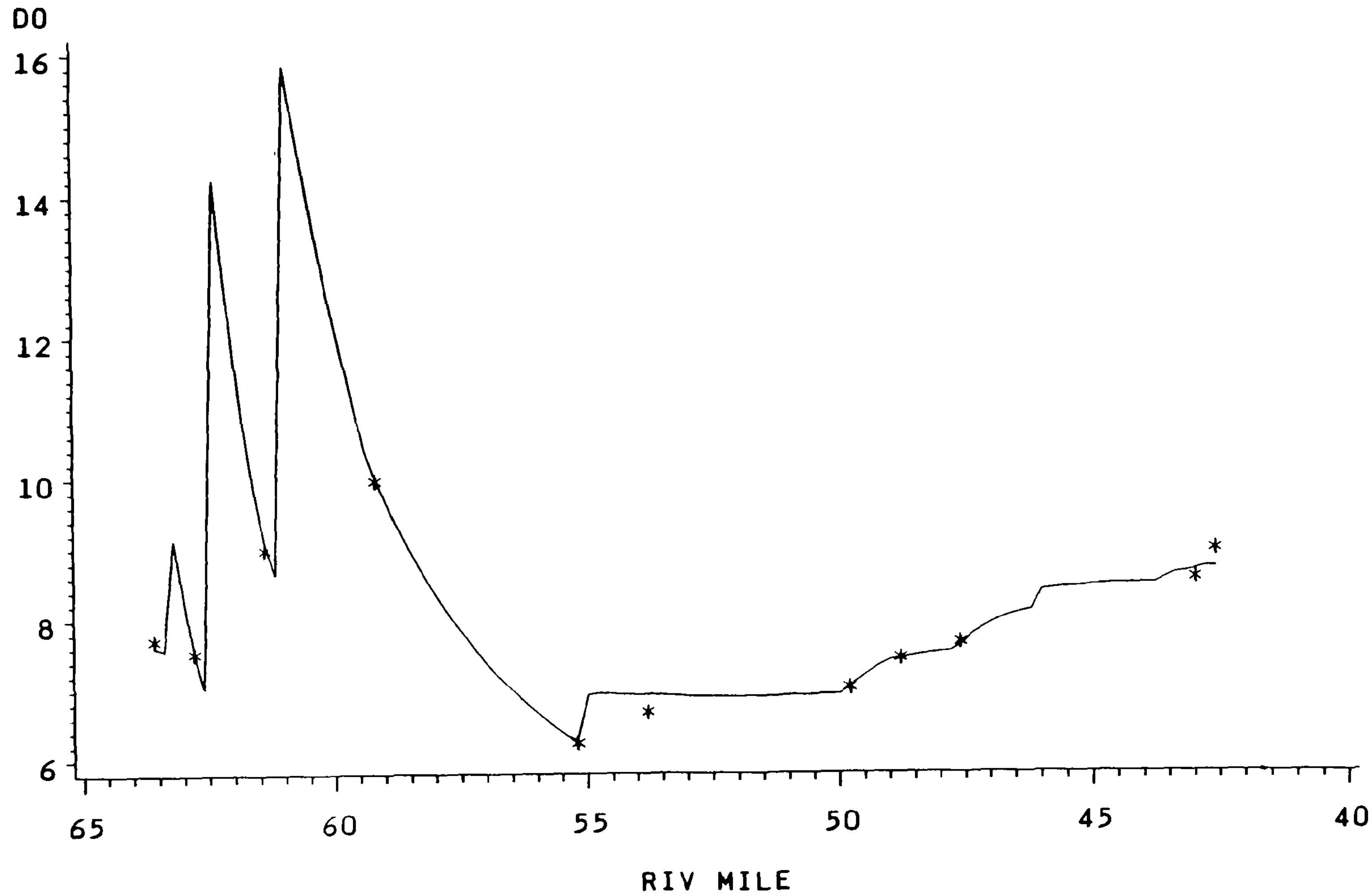


Figure VI-3. Observed (*) and simulated (__) values of dissolved oxygen (ppm).

Table VI-1. Coefficients used in Tsivoglou and Wallace (1972) estimation of reaeration/deaeration

Reach #	Slope of Energy Gradient (S_e) (ft/ft)	Escape Coefficient (c) (ft^{-1})	Mean Tsivoglow and Wallace K_2 (day^{-})
1	0.0019	0.050	3.640
2	0.0019	0.050	3.825
3	0.0019	0.020	1.605
4	0.0019	0.025	2.910
5	0.0019	0.045	4.632
6	0.0019	0.045	3.657
7	0.0034	0.045	5.446
8	0.0034	0.045	5.856
9	0.0049	0.045	12.440
10	0.0049	0.045	18.232

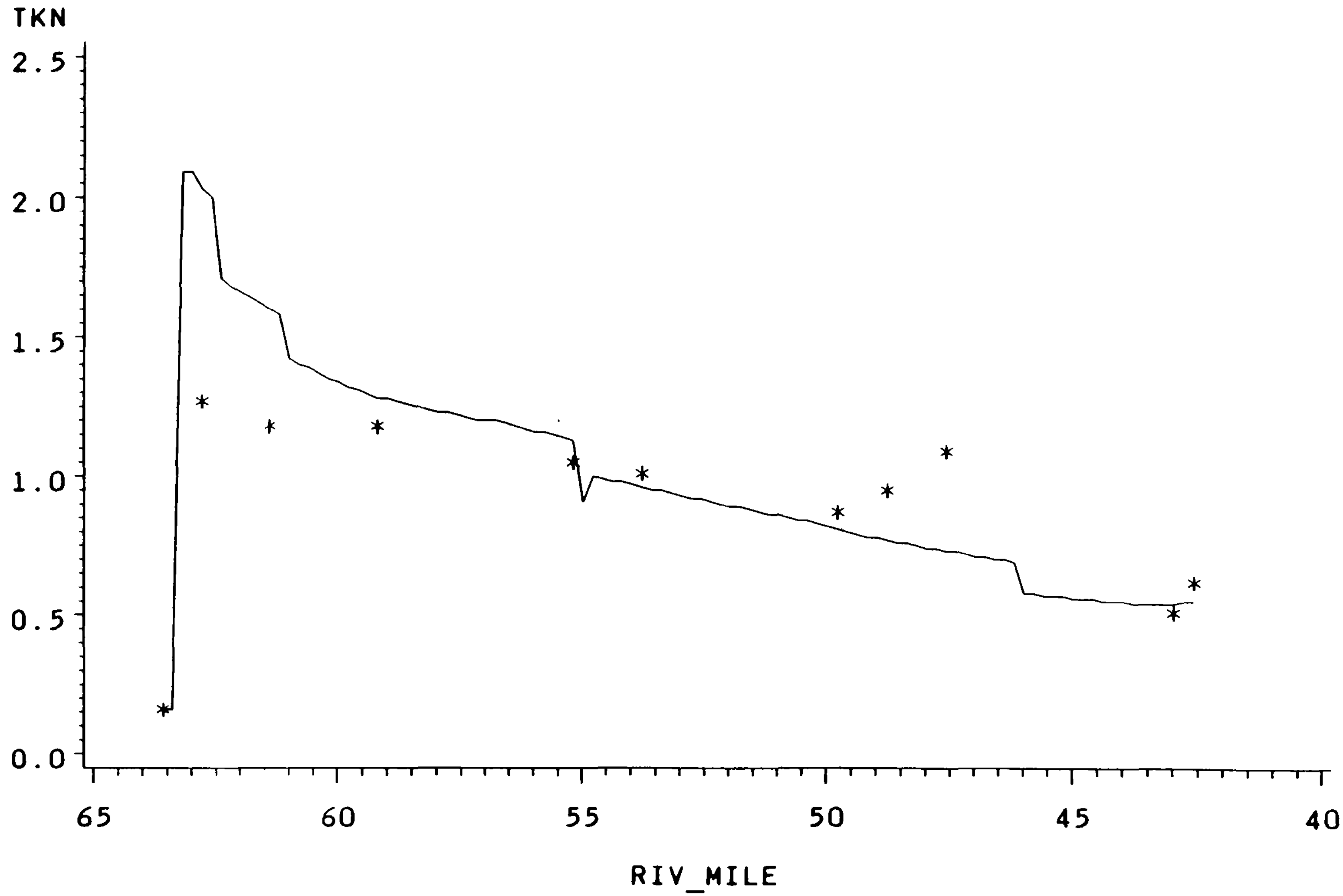


Figure VI-4. Observed (*) and simulated (__) values of total Kjeldahl nitrogen (ppm).

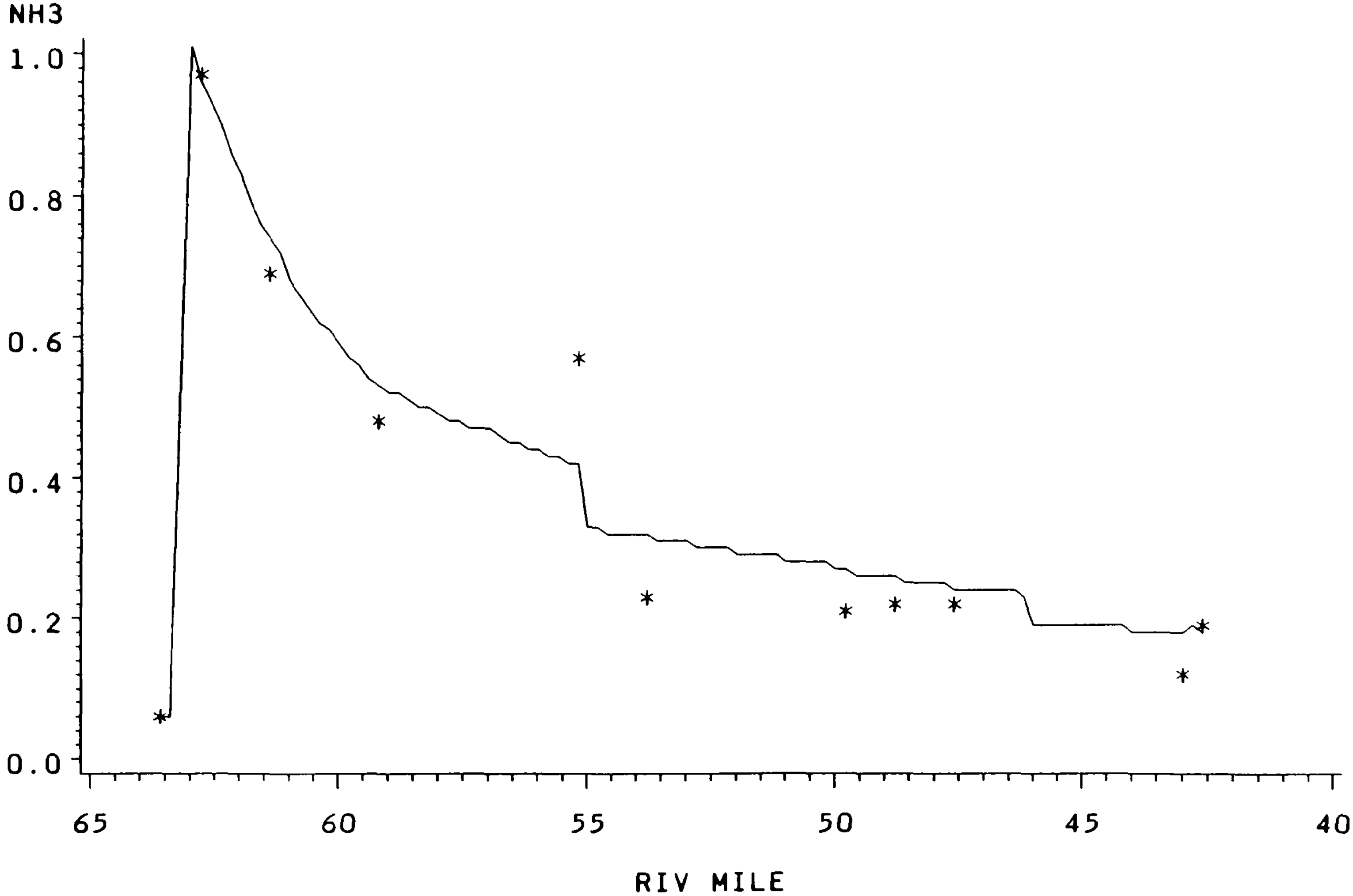


Figure VI-5. Observed (*) and simulated (__) values of ammonia as nitrogen (ppm).

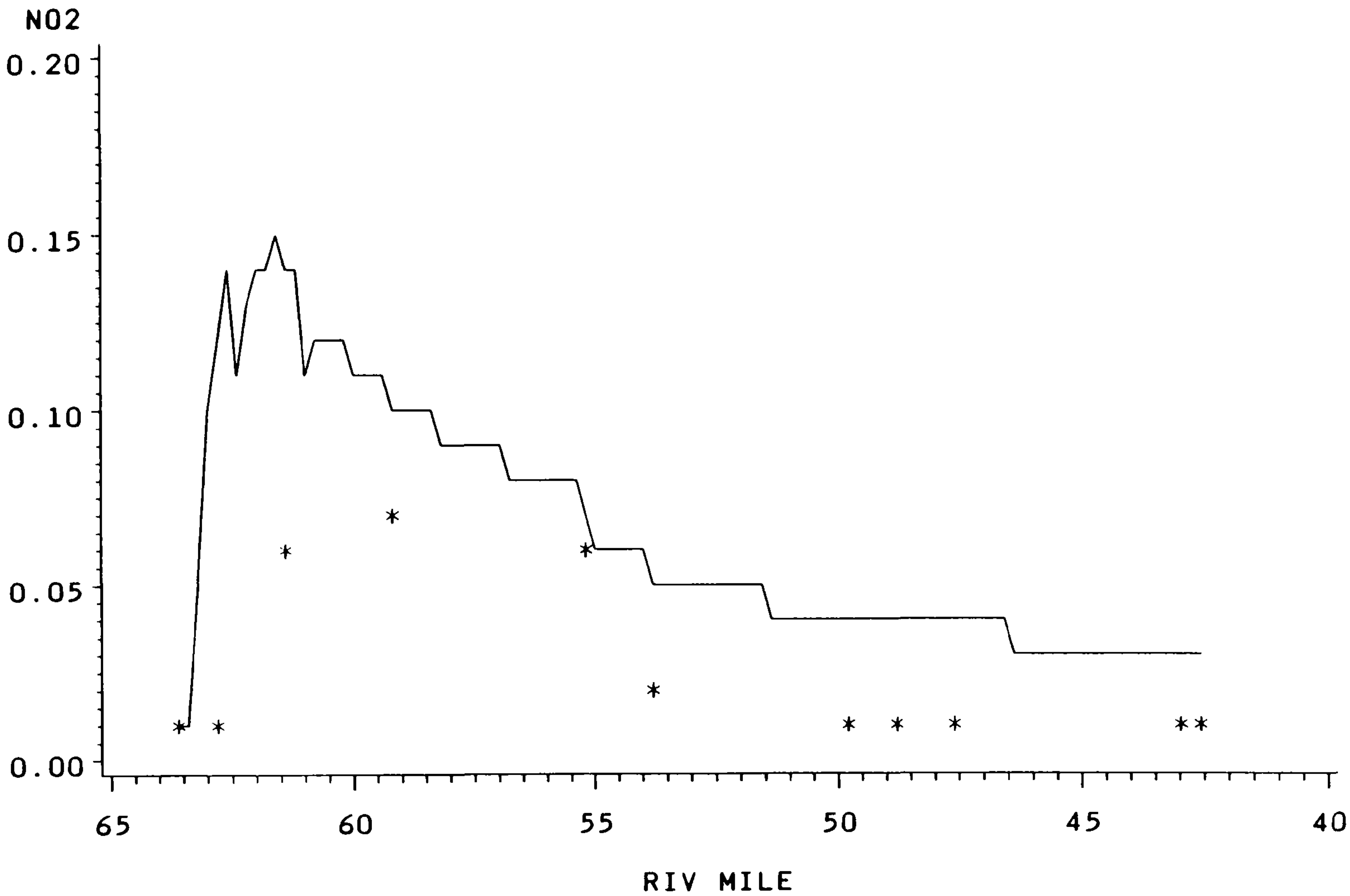


Figure VI-6. Observed (*) and simulated (--) values of nitrite as nitrogen (ppm).

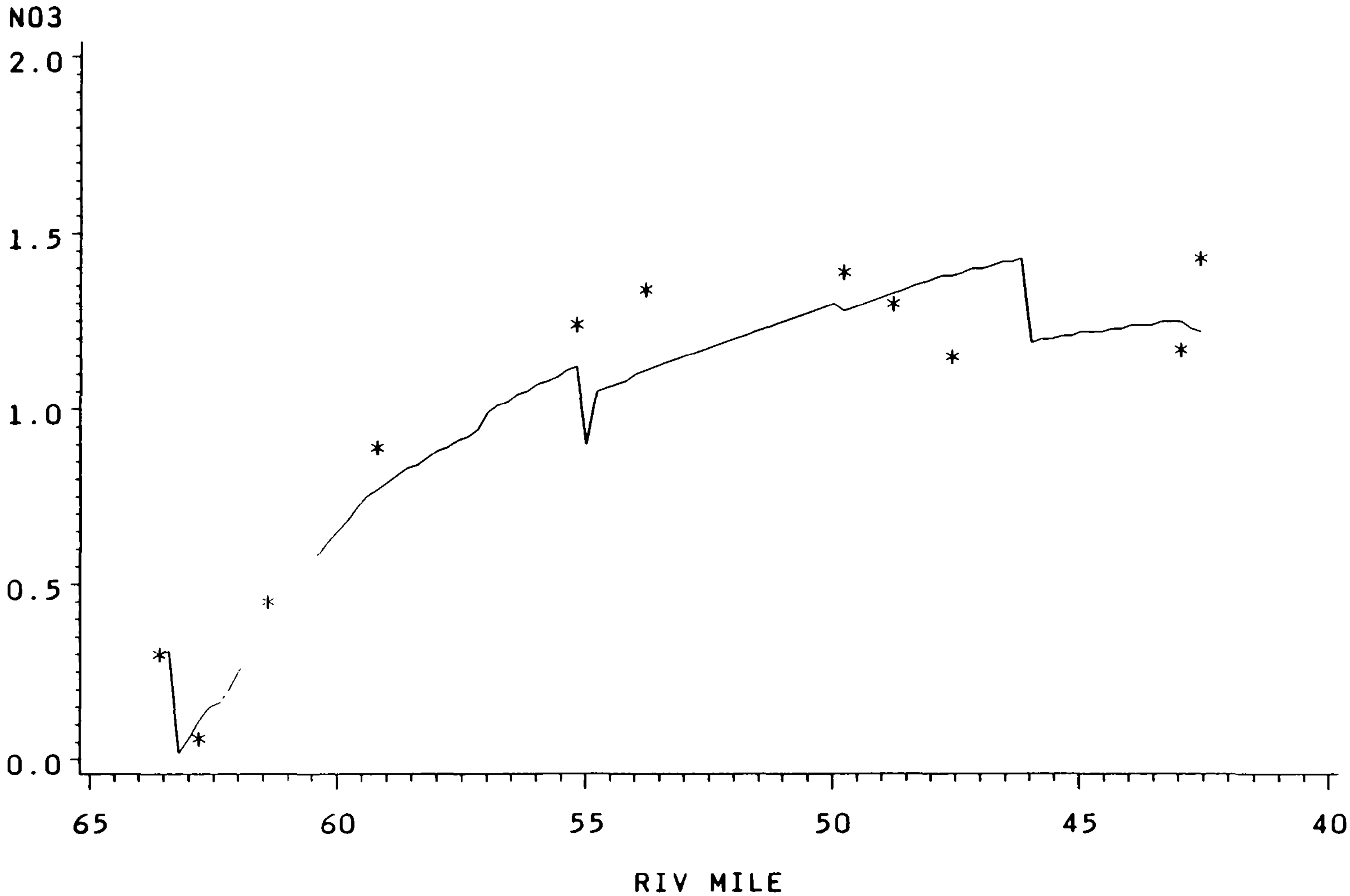


Figure VI-7. Observed (*) and simulated (__) values of nitrate as nitrogen (ppm).

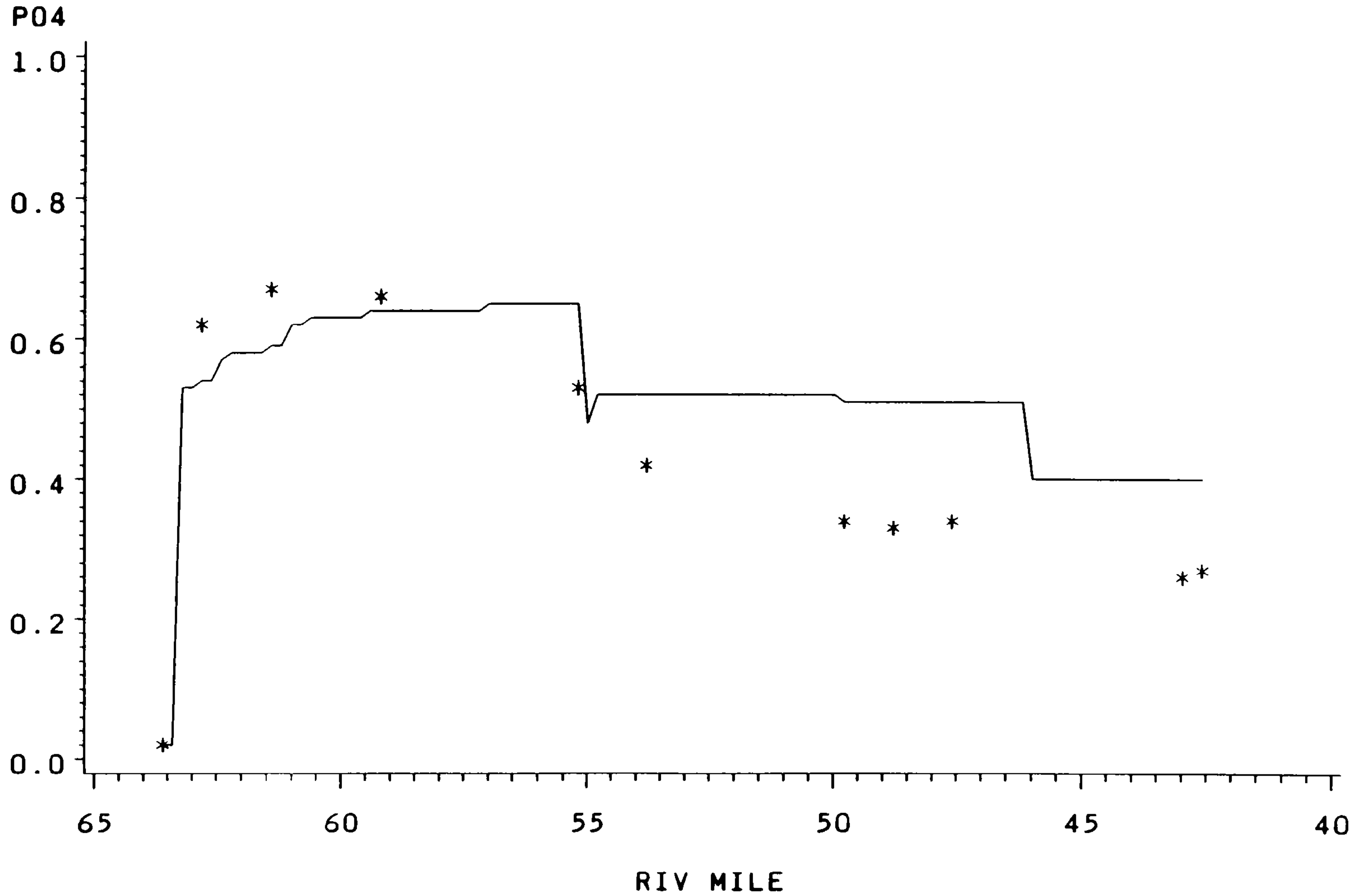


Figure VI-8. Observed (*) and simulated (__) values of dissolved phosphorus (ppm).

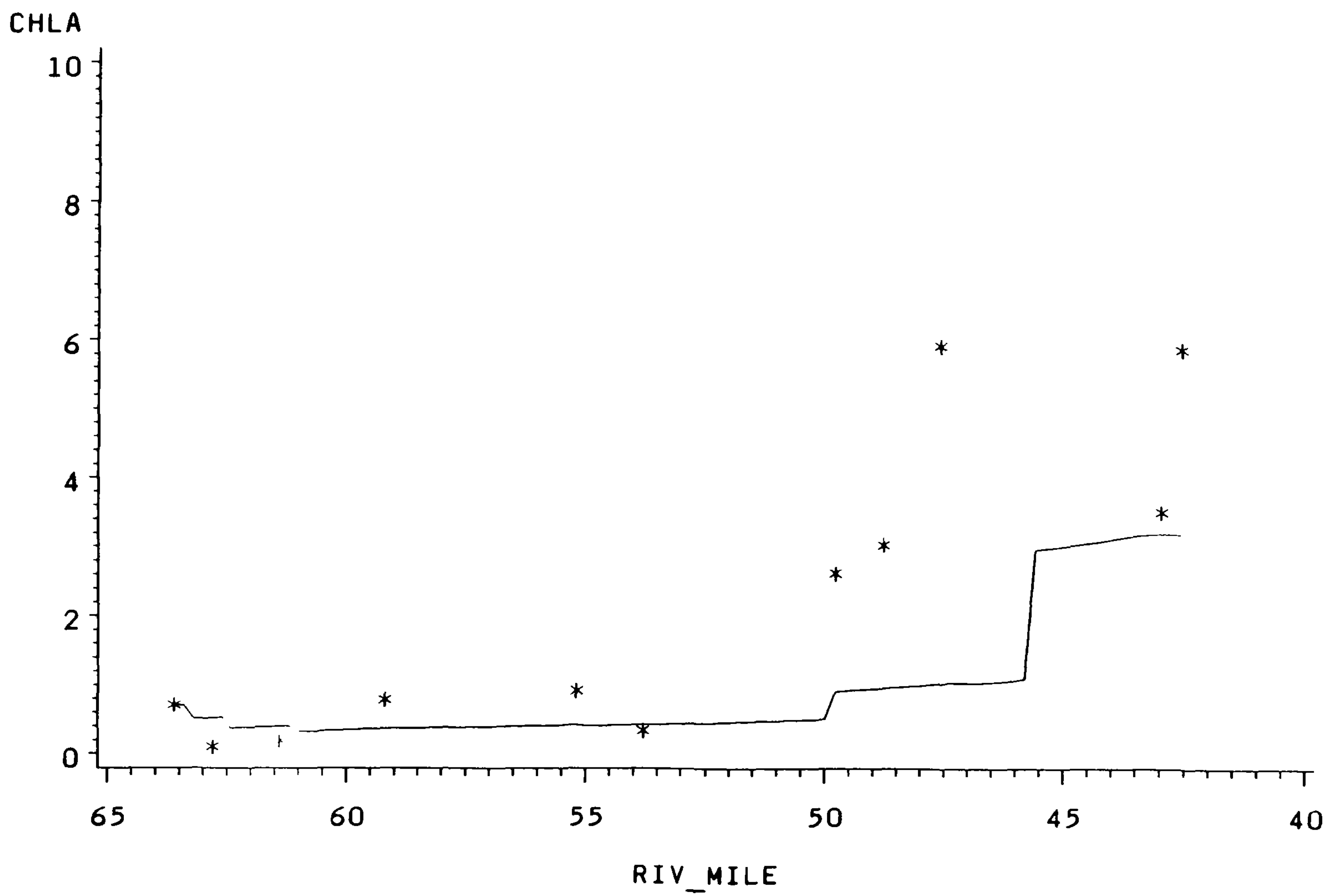


Figure VI-9. Observed (*) and simulated (__) values of chlorophyll a (ppm).

have between 550 and 600 ppm chlorides without any dilution flow. Clearly, the two sets of measurements do not correspond but the effect on the simulated results is minimal.

Ultimate Carbonaceous Biochemical Oxygen Demand

The major sources of simulated UCBOD in the river are the Champion effluent (53.5 mg/l) and the Clyde and Waynesville WWTPs (24.0 and 32.4 mg/l, respectively) (Fig. VI-2). Although the concentrations of these discharges appear somewhat similar, the slow rate of degradation of the Champion BOD materials (i.e., a linear degradation rate of 11% per day) results in the WWTPs' flows diluting the instream concentrations of UCBOD. The primary mechanism affecting UCBOD concentration in the Pigeon River is dilution. Streamflow increases by approximately a factor of 2 from the Champion discharge to Walters Lake, resulting in the reduction of any conservative material by 50%. UCBOD decreases from 53 ppm at the Champion discharge to 21 ppm at Walters Lake (decrease of 60%). Given the further additions of UCBOD materials from the WWTPs and the tributaries, oxidation of carbonaceous UCBOD materials can account for only about 10-20% of the modeled reduction in UBOD. With a travel time of approximately two days, this reduction corresponds to a degradation rate on the order of 10% per day.

Dissolved Oxygen

Simulated upstream DO concentrations were relatively high (7.6 ppm) and augmented at the Champion discharge by the domed cascade which returns the riverflow at 9.7 ppm (Fig. VI-3). This supersaturated concentration is reduced largely by deaeration to approximately 7 ppm by River Mile 62.4, the location of the first sidestream oxygenator. There, approximately 37% of the river is withdrawn and supersaturated to 30 ppm resulting in an immediate dissolved oxygen concentration of about 14 ppm at the oxygenator discharge. Below the first sidestream oxygenator, simulated DO concentrations are again reduced by deaeration to about 9 ppm when a second sidestream oxygenation unit withdraws about 37% of the flow and supersaturates it to about 30 ppm, resulting in a local concentration of 16 ppm. Simulated dissolved oxygen steadily decreases from deaeration to about 6 ppm when Richland Creek enters the Pigeon River, significantly increasing streamflow and dissolved DO concentrations. The remainder of river is characterized by increased slope, and natural reaeration and high-DO tributary flows combine to increase to simulated DO about 9 ppm at the river's confluence with Walters Lake.

Simulated dissolved oxygen (DO) concentrations were determined in the model using all sources and sinks for oxygen.

All of these sources and sinks were measured (i.e., photosynthesis, sediment oxygen demand, UCBOD, NBOD) except reaeration/deaeration. The Tsivoglou and Wallace (1972) estimate of reaeration is proportional to the change in elevation for a stream reach; and represented by:

$$K_2 = ac\, S_e\, \bar{\mu}$$

where

a = constant to convert to units of feet/day

c = escape coefficient (ft^{-1})

$\bar{\mu}$ = mean velocity in reach (ft/sec)

S_e = slope of the energy gradient (ft/ft).

The slope of the energy gradient (S_e) was estimated from available data concerning the slopes of individual stream reaches and are shown in Table VI-1. The value of the escape coefficient for each stream reach was determined by calibration (i.e., by difference) to the observed September 27, 1989 data set as all other parameter values were available. The escape coefficients for each reach are shown in Table VI-1. The only constraint placed upon the calibration was that the escape coefficients be similar to the values determined by Tsivoglou and Neal (1976). The escape coefficient values in the region of the Pigeon River not affected by the sidestream oxygenators are either 0.050 or 0.045 ft^{-1} which are relatively close to Tsivoglou and Neal's (1976) recommendation of 0.054 ft^{-1} for streams at 20° C and flows of 15-3000 cfs. Calibration of the escape coefficients in the region near the sidestream oxygenators decreased to 0.020-0.025 ft^{-1} as the oxygen deficit increased substantially in these areas (e.g., deficit is > 8 ppm above saturation at sidestream oxygenator #3).

The lesser escape coefficients in the area below the oxygenators may result from an underestimate of oxygen infusion rates. Based on information supplied by Champion, the oxygenators were infusing 18 ppm into the withdrawn water. This should have led to oxygen levels downstream of the final oxygenator of less than 15 ppm. Actual measurements, though, revealed DO levels in excess of 20 ppm. The infusion rate necessary to account for 20+ ppm concentrations in the water would be about 45 ppm.

Comparison of our measured deaeration rate from the pan experiment (1.8 ppm/hr) and our modeled rate (1.2 ppm/hr) further suggest that our modeled escape coefficients in the reaches containing the oxygenators were low. Because the river is subject to turbulence not experienced in the pans, the deaeration

Table VI-1. Coefficients used in Tsivoglow and Wallace (1972) estimation of reaeration/deaeration

Reach #	Slope of Energy Gradient (S_e) (ft/ft)	Escape Coefficient (c) (ft^{-1})	Mean Tsivoglow and Wallace K_2 (day^{-})
1	0.0019	0.050	3.640
2	0.0019	0.050	3.825
3	0.0019	0.020	1.605
4	0.0019	0.025	2.910
5	0.0019	0.045	4.632
6	0.0019	0.045	3.657
7	0.0034	0.045	5.446
8	0.0034	0.045	5.856
9	0.0049	0.045	12.440
10	0.0049	0.045	18.232

rate in the experiment should be less than that in the model. Doubling of the infusion efficiency, as suggested above, would resolve this inconsistency.

Changes to the supplied infusion rate were not made in the model because measured rates were not available. However, this change in oxygen infusion rate would have relatively little effect on the simulated downstream oxygen levels since the oxygen values at stations S3 and S4 are simulated correctly (i.e., the low DO values after the effects of the oxyge nators dissipates). The only effect would be to roughly double the escape coefficients for the two stream reaches (i.e., #3 and #4) making these values similar with the remaining escape coefficients. The effect of this parameter change would be to simply force the additional oxygen into the atmosphere.

Nitrogen

Below the Champion discharge, simulated TKN valves increased from near zero to about 2 ppm (Fig. VI-4). This TKN concentration is reduced by about 50% (to 1 ppm) in the region between the Champion discharge and Richland Creek and declines steadily thereafter. Figure VI-6 shows an influx of NH_3-N from the Champion discharge (1.1 ppm) which is reduced by 70% (converted to nitrite and then nitrate) within the region between the Champion discharge and Richland Creek. Ample oxygen supply is available in this region due to the oxygenators to reduce the available ammonia. Simulated nitrite-nitrogen, a relatively short-lived component, builds up to about 0.15 ppm and is reduced to less than 0.05 ppm before any sewage treatment discharges are added to the river (Fig. VI-6). Finally, Figure VI-7 shows the steady increase in nitrate between the Champion discharge and Richland Creek due to the oxidation of ammonia, the dilution by Richland Creek, the continued oxidation (at a slower rate) between Richland Creek and Jonathans Creek, and its subsequent dilution by Jonathans Creek. The increase of nitrates-nitrogen from 0.3 to 1.1 ppm prior to the addition of any sewage treatment effluents shows a significant oxidation of nitrogenous materials in the region of the river which includes the Champion oxygenators. Oxidation of ammonia requires 4.57 mg O_2 for each milligram of ammonia-N; thus, significant dissolved oxygen reduction can be attributed to the oxidation of ammonia in this region of the river. Due to the degraded condition of the Pigeon River waters (i.e., dark color), this increased nitrate level was found not to be used to produce algal biomass. As a result, the increased simulated nitrate load flows into Walters Lake.

Phosphorus

The primary sources of simulated dissolved phosphorus are the Champion effluent (0.53 ppm) and the Clyde and Waynesville STPs (3.6 and 1.3 ppm, respectively) (Fig. VI-8). Dissolved phosphorus is not consumed in the river due to the lack of algal production, but is diluted from about 0.6 ppm to 0.3 ppm by the influx of low phosphorus tributary waters).

Chlorophyll a

The simulated values of chlorophyll a are extremely low at the upstream boundary of the model, and increase only slightly in downstream areas (Fig. IV-9). The low simulated values are uncharacteristic of many freshwater streams but accurately reflect field data from the river.

Simulation of chorophyll a underestimated the observed chlorophyll values. The field data show a 400-600% increase in chlorophyll in the region of Crabtree Creek and Jonathans Creek. Given the streamflows of these tributaries, chlorophyll a concentrations in excess of 100 mg/l would be required from Crabtree Creek or 20-30 mg/l from Johnathons Creek to produce to observed 5-6 mg/l chlorophyll at River Mile 43. Both of these estimated chlorophyll requirements from the Pigeon River tributaries substantially exceed the measured chlorophyll a concentrations in these tributaries. Documentation of the calibration model run is provided in Appendix A.

B. VALIDATION

Validation I - 28 September 1988

The values of observed UCBOD (estimated using the 5-day BOD measurements adjusted by the UCBOD/BOD_5 ratio measured on 27 September 1988 were higher than those observed on 28 September. The simulation using these higher effluent loads matched the observed data (Figure VI-10). Regression of observed and modeled UCBOD data produced a significant statistical model (R^2=0.98) with a slope and intercept meeting the required criteria. The simulated dissolved oxygen simulation appeared to overestimate observed DO by less than 1.0 ppm (Fig. VI-11). Regression of observed and simulated data met the validation acceptance criteria with a intercept of 0.93 ± 5.0 and a slope of 1.05 ± 0.6. The Pigeon River QUAL2E model was determined to validly represent the conditions occurring in late summer 1988. Appendix B shows the documentation of the QUAL2E Validation I run.

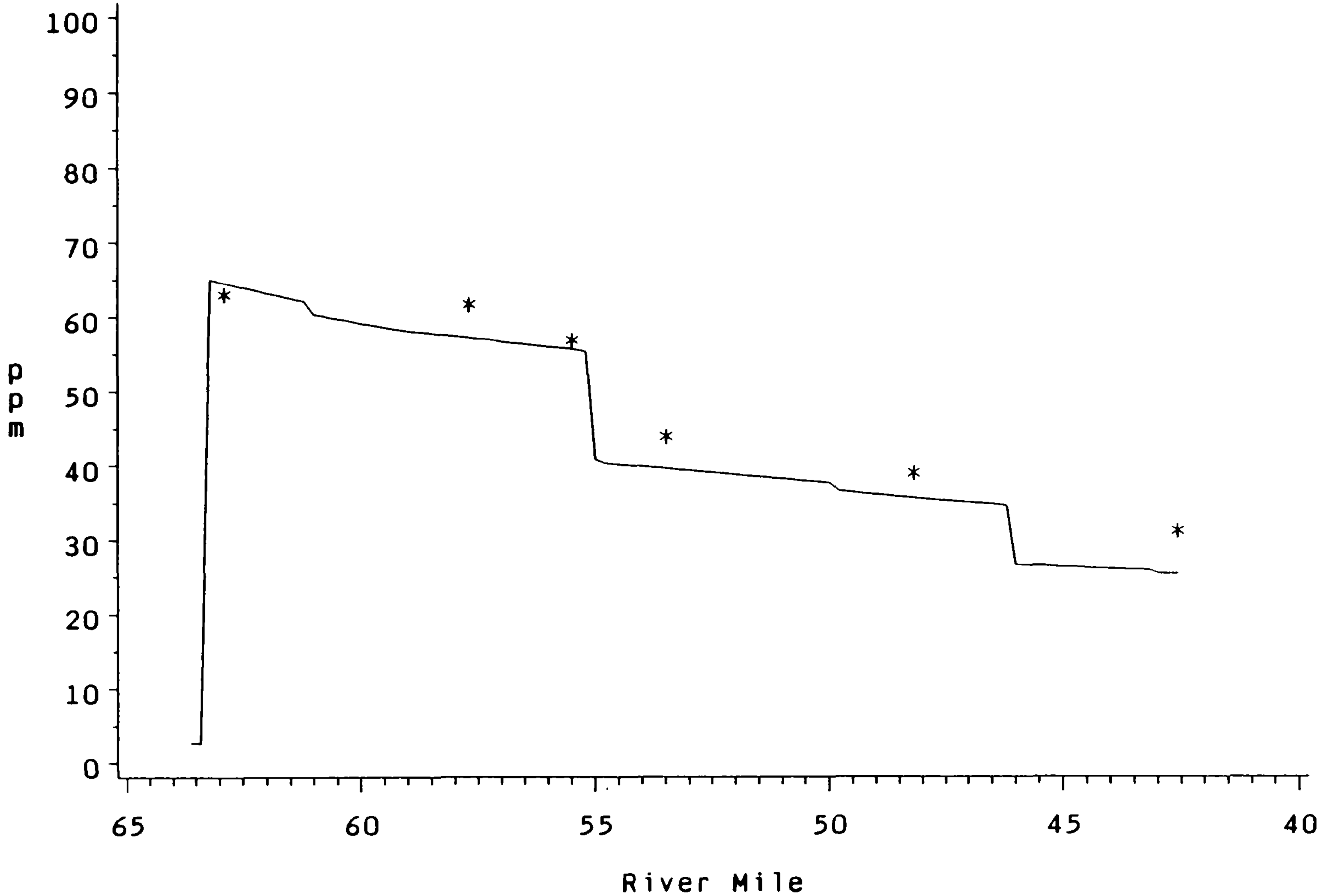


Figure VI-10. Validation of observed (*) and simulated (__) values of ultimate carbonaceous biochemical oxygen demand (ppm) for 28 September 1988.

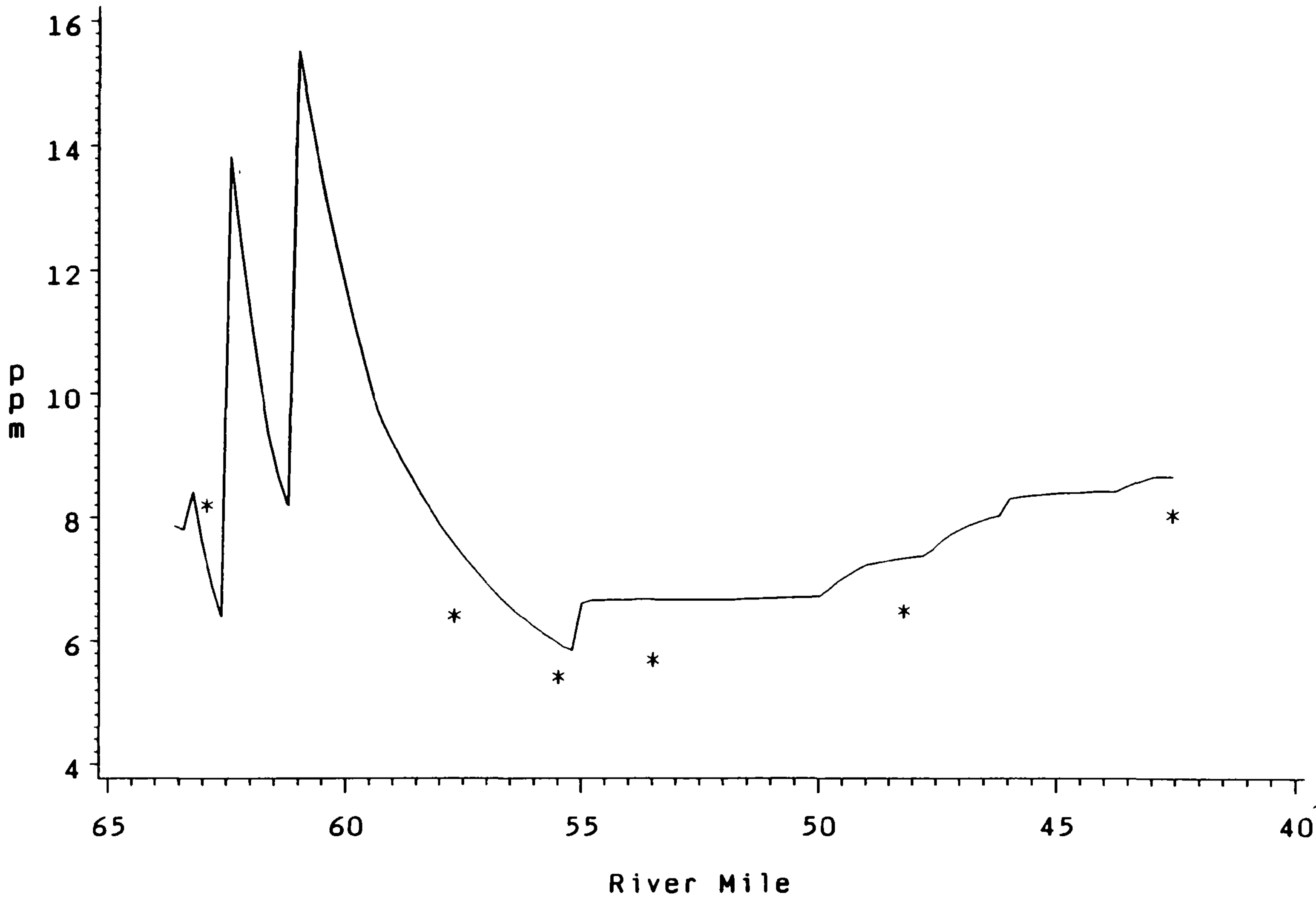


Figure VI-11. Validation of observed (*) and simulated (__) values of dissolved oxygen (ppm) for 28 September 1988.

Validation II - 7 July 1987

When natural streamflow exceeds Champion withdrawal rate (Fig. VI-12), the effects of chloride additions from the Champion facility (507 ppm) on the Pigeon River are reduced (Fig. VI-13). The immediate effect of the discharge on chlorides is to increase concentrations from 2 ppm to 215 ppm. Chlorides are subsequently diluted by tributary flows.

Simulations of carbonaceous BOD_5 during the higher flow regime underestimates observed BOD_5 in the region between the Champion discharge and Richland Creek (Fig. VI-14). However, one of the observed BOD_5 values taken just downstream of the discharge at the Fiberville Bridge shows a BOD_5 value of 15.0. Examination of Champion self-monitoring data suggest that this field measurement was in error. In addition, the BOD_5 measure depicted in the EA report represents all biochemical demand including nitrogenous demand. The simulation only represents carbonaceous demand and early simulation runs (nominal case) suggest that nitrogenous demand is high in the portion of the river between the Champion discharge and Richland Creek.

Under the higher flow regime, Champion's oxygenators have a much reduced effect on local DO concentrations (Fig. VI-15). According to the observed data, water between the third oxygenator and the Clyde WWTP deaerated too rapidly, yet the appropriate DO concentration was reached by River Mile 54. In general, the simulated DO concentrations match the observed DO values.

Total Kjeldahl nitrogen and ammonia were consistently overestimated by the model by about 1 ppm (Figs. VI-16, VI-17), but the simulated concentration of nitrate closely resembled the observed data (Figure VI-18). Since nitrate is generated in the Pigeon River system primarily by the oxidation of ammonia and it is not being consumed by algal photosynthesis, the disparity would suggest that at least one of the field measurements collected in 1987 was in error.

Figures VI-19 and VI-20 describe the simulated behavior of total organic phosphorus and dissolved phosphorus under high flow conditions. Once the phosphorus compounds are added to the Pigeon River at the Champion discharge, changes in phosphorus levels are primarily the result of dilution; the river is moving too rapidly to permit settling, and the residence time is too short and the light penetration too minimal to permit sufficient photosynthesis to reduce the dissolved phosphorus concentration.

With the exception of total organic nitrogen and ammonia, all simulations of the 7 July 1987 data set meet the criteria for validation. Documentation of this validation simulation is provided in Appendix C.

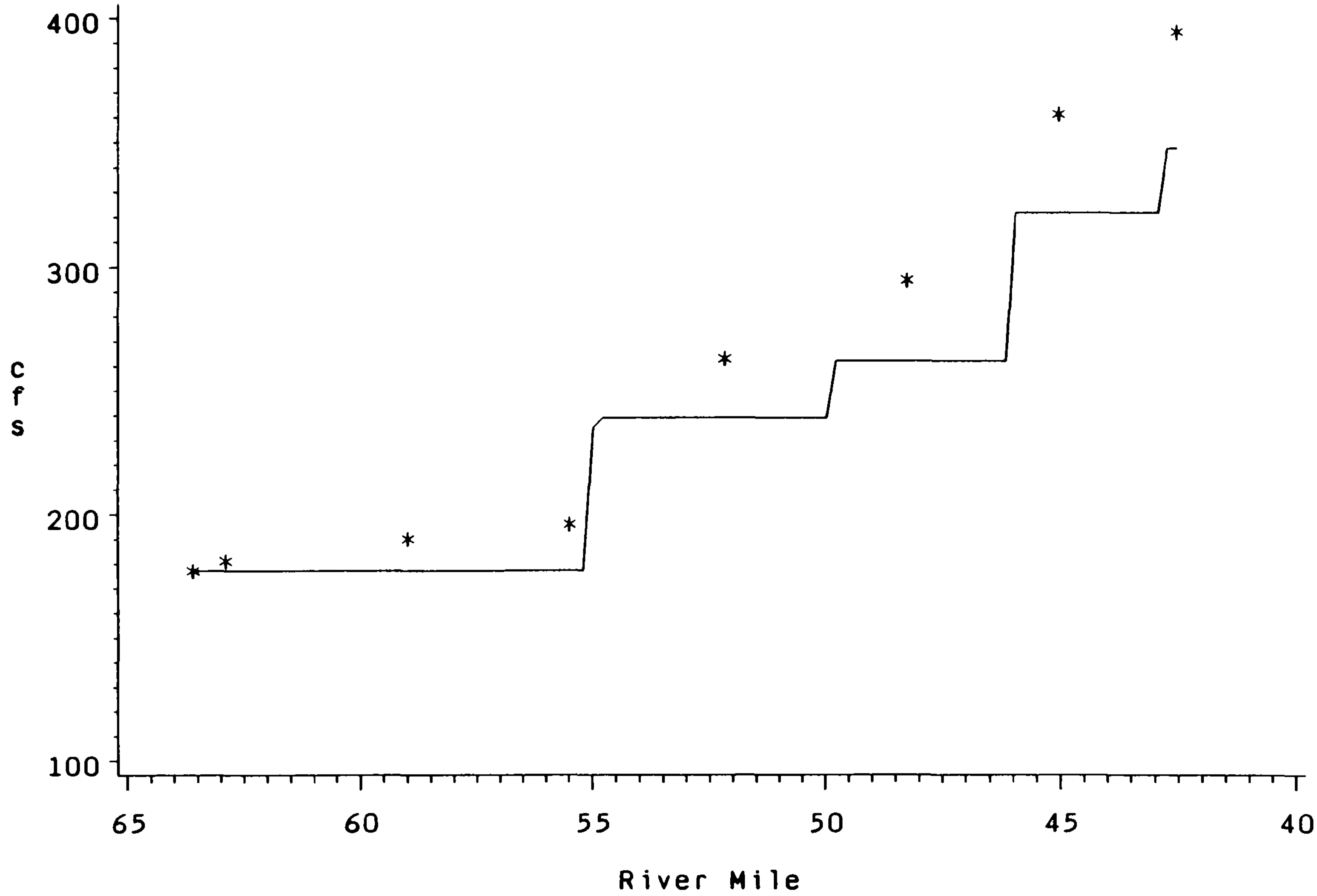


Figure VI-12. Validation of observed (*) and simulated (__) streamflow values (CFS) for 7 July 1987.

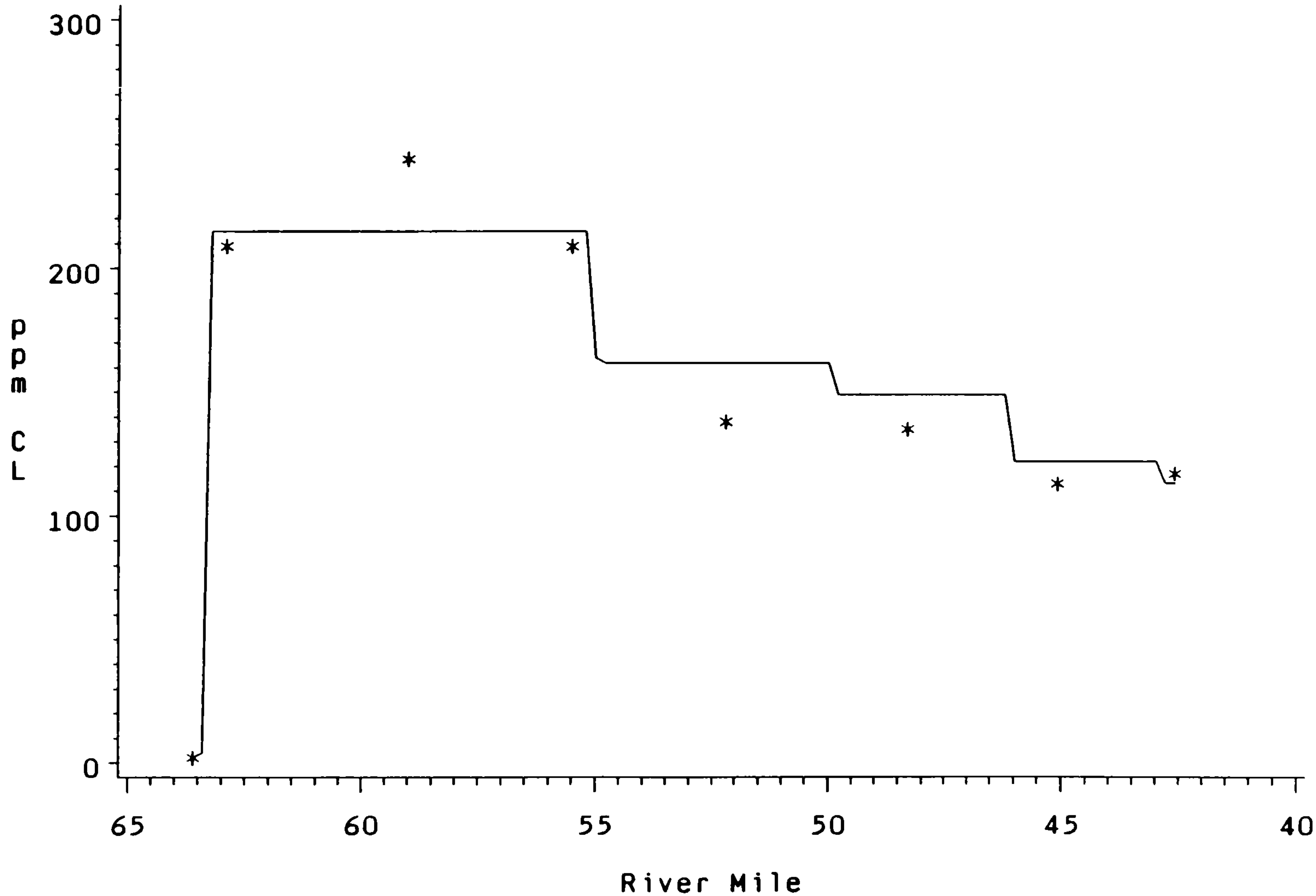


Figure VI-13. Validation of observed (*) and simulated (__) chlorides values (ppm) for 7 July 1987.

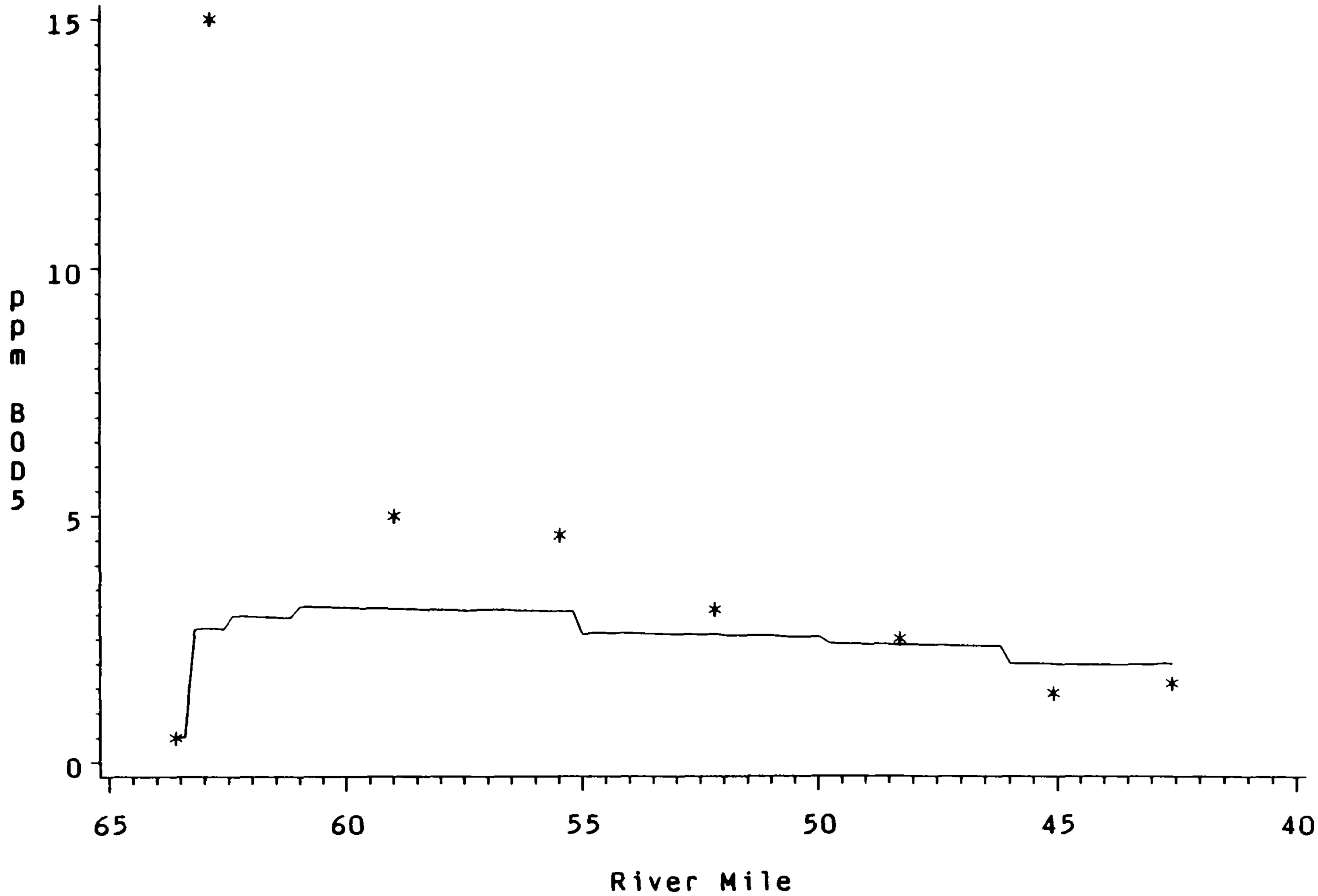


Figure VI-14. Validation of observed (*) total 5-day biochemical oxygen demand and simulated (__) carbonaceous BOD_5 values (ppm) for 7 July 1987.

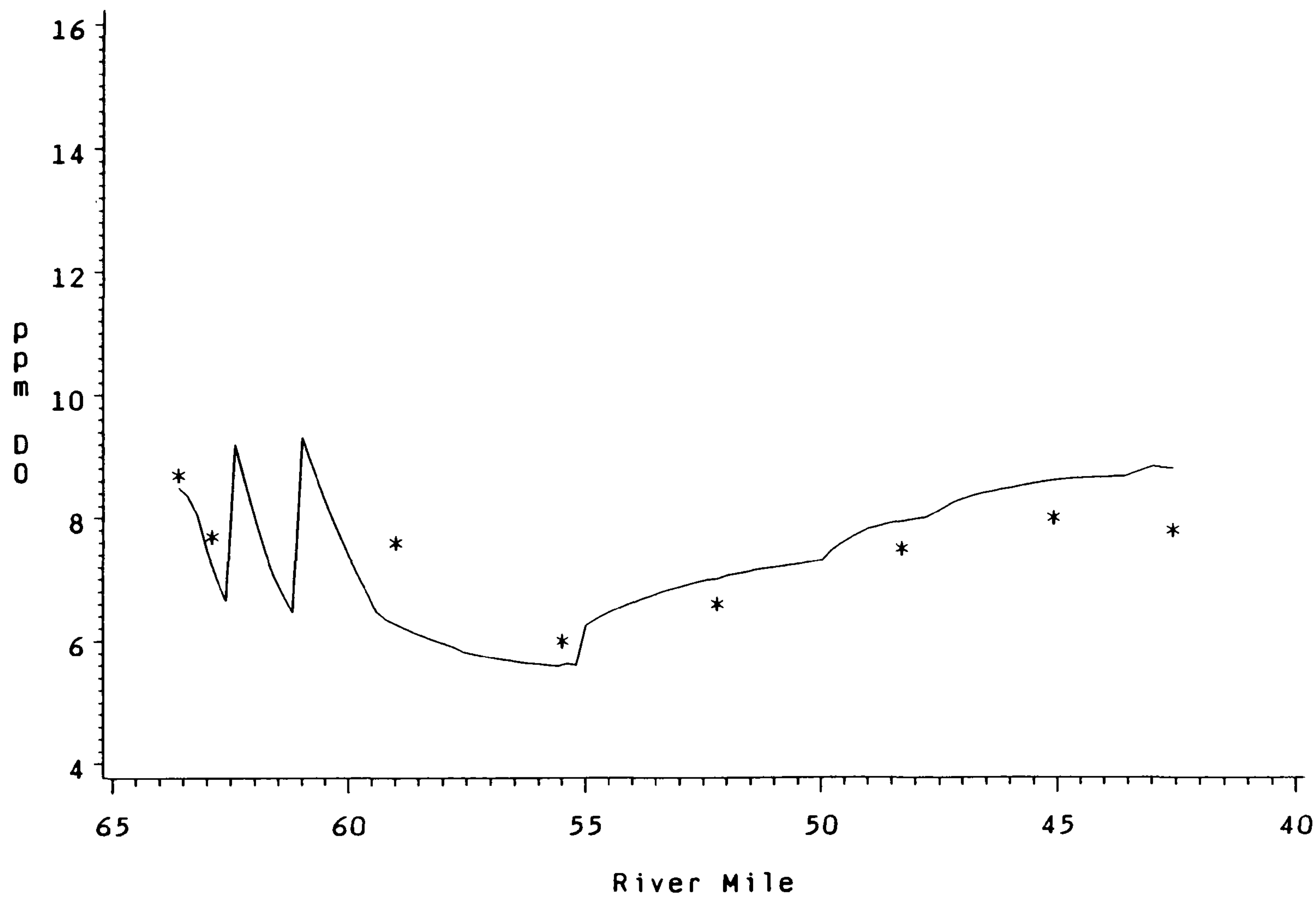


Figure VI-15. Validation of observed (*) and simulated (__) dissolved oxygen values (ppm) for 7 July 1987.

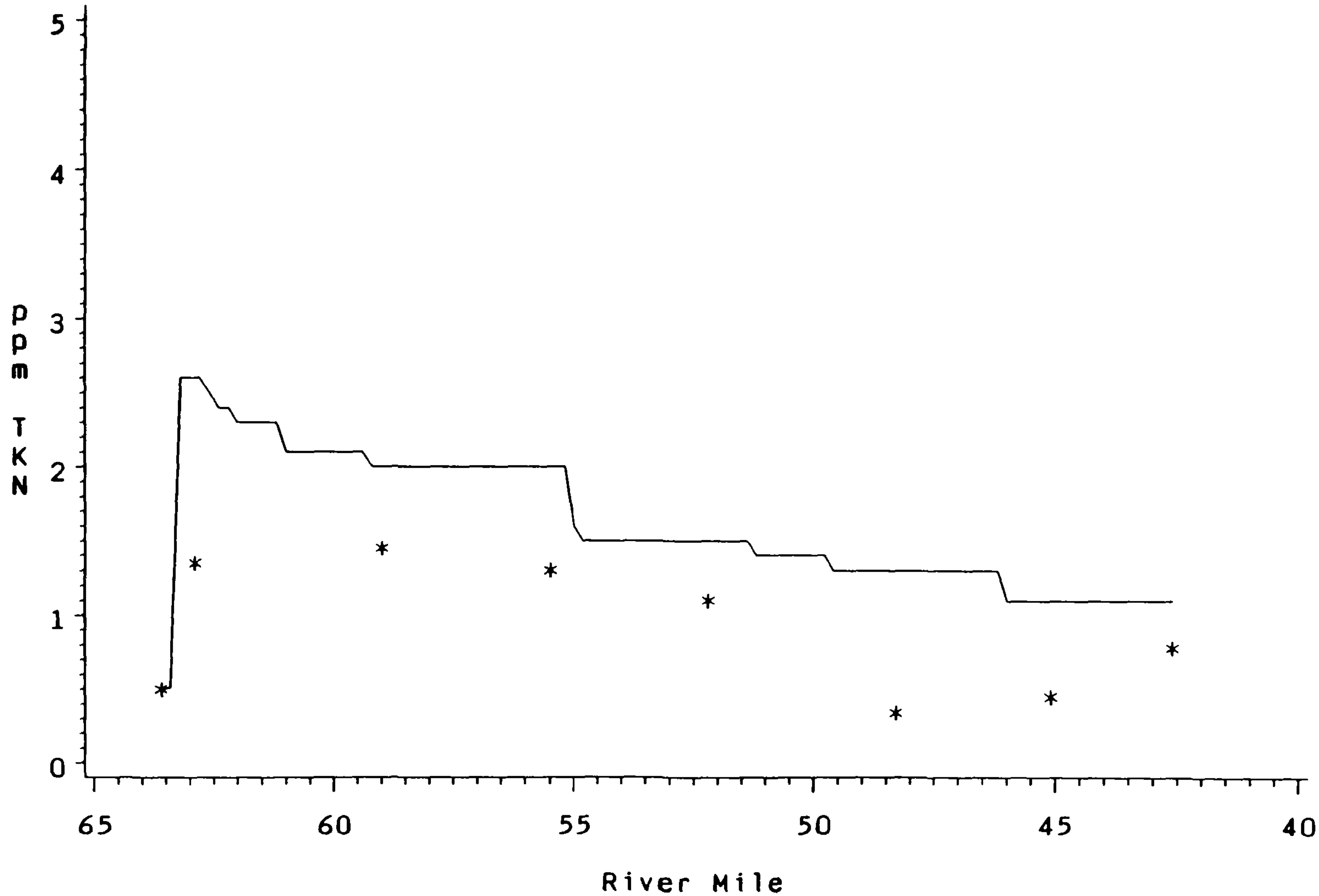


Figure VI-16. Validation of observed (*) and simulated total Kjeldahl nitrogen values (ppm) on 7 July 1987.

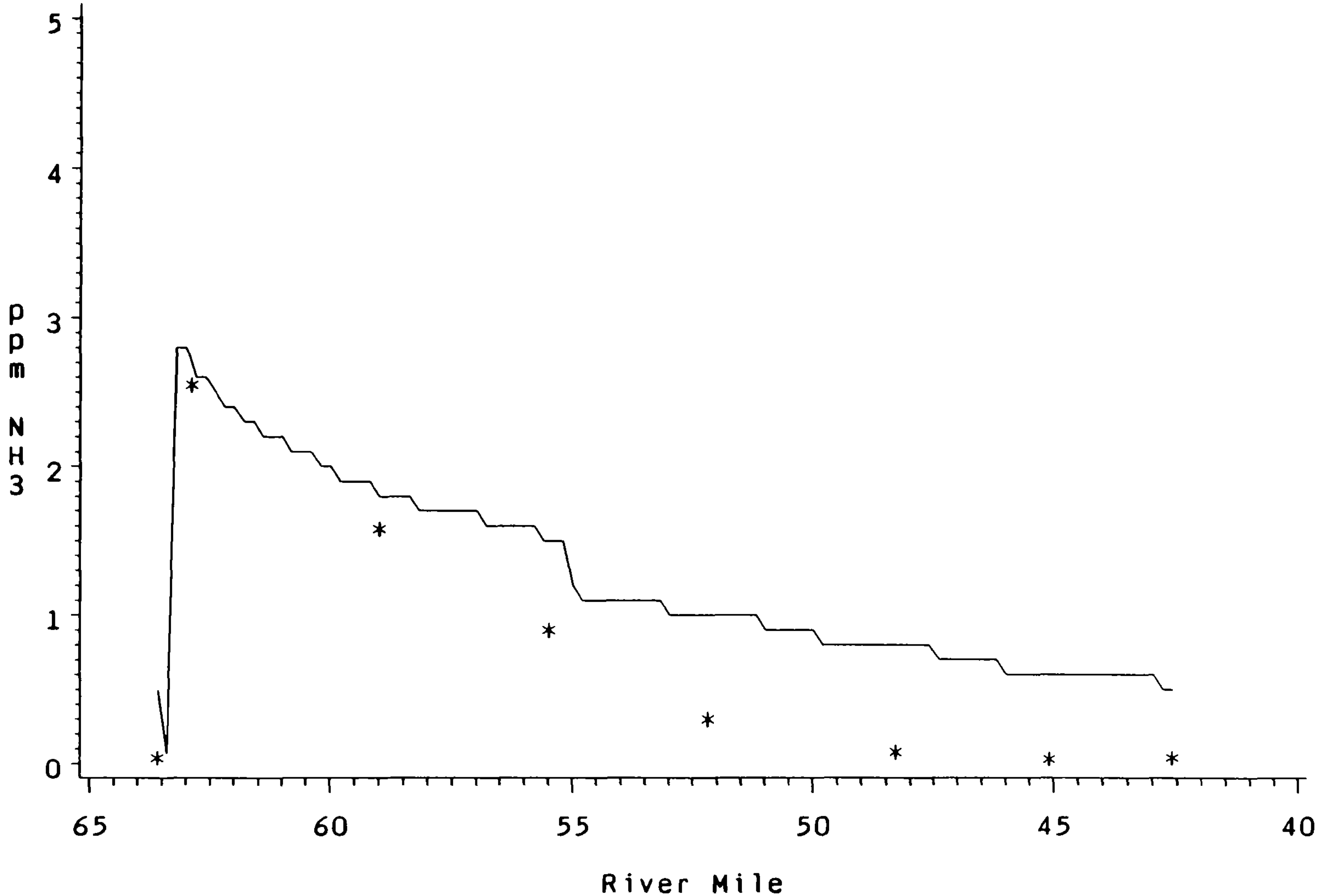


Figure VI-17. Validation of observed (*) and simulated (__) NH_3-N values (ppm) on 7 July 1987.

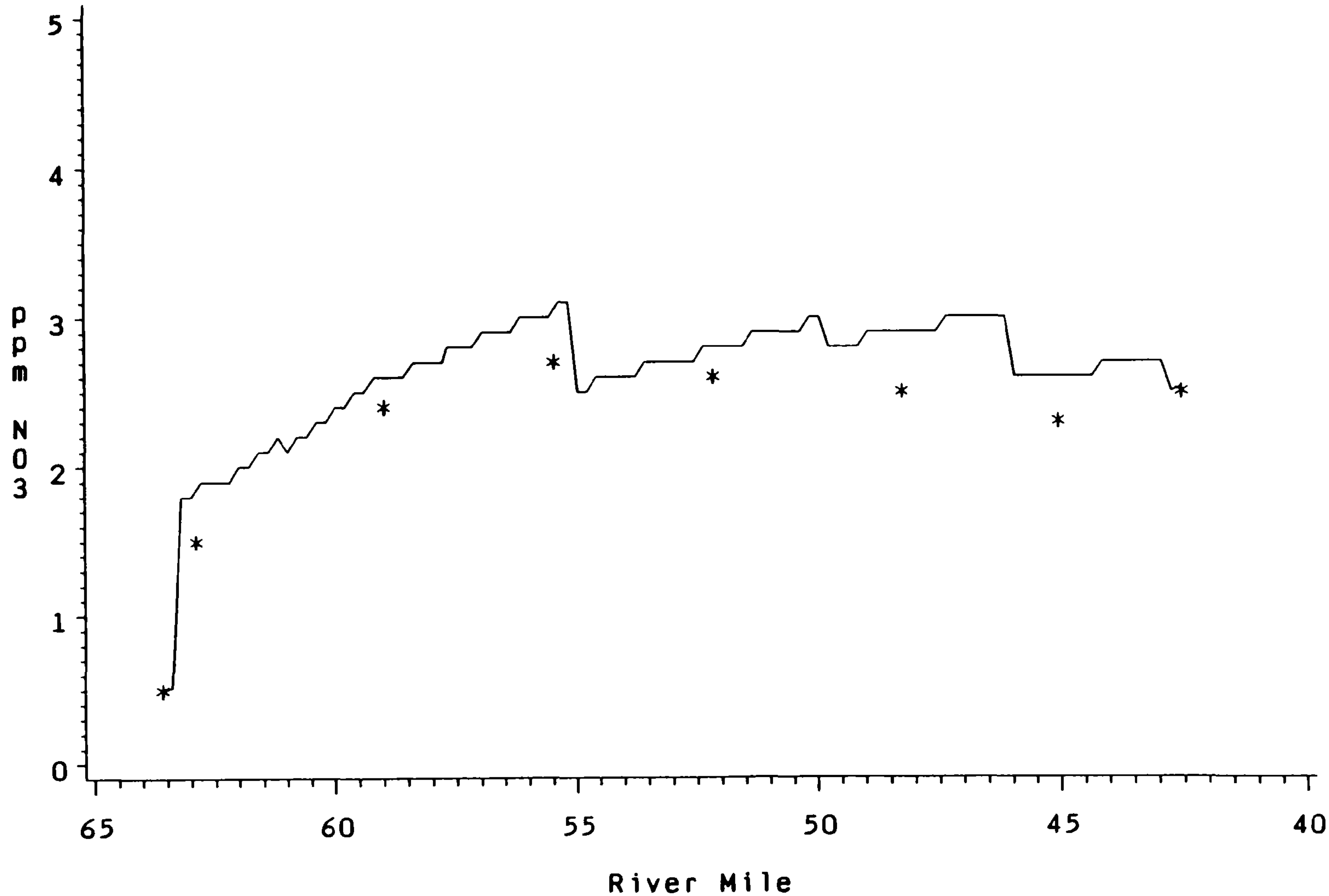


Figure VI-18. Validation of observed (*) and simulated nitrate-nitrogen values (ppm) on 7 July 1987.

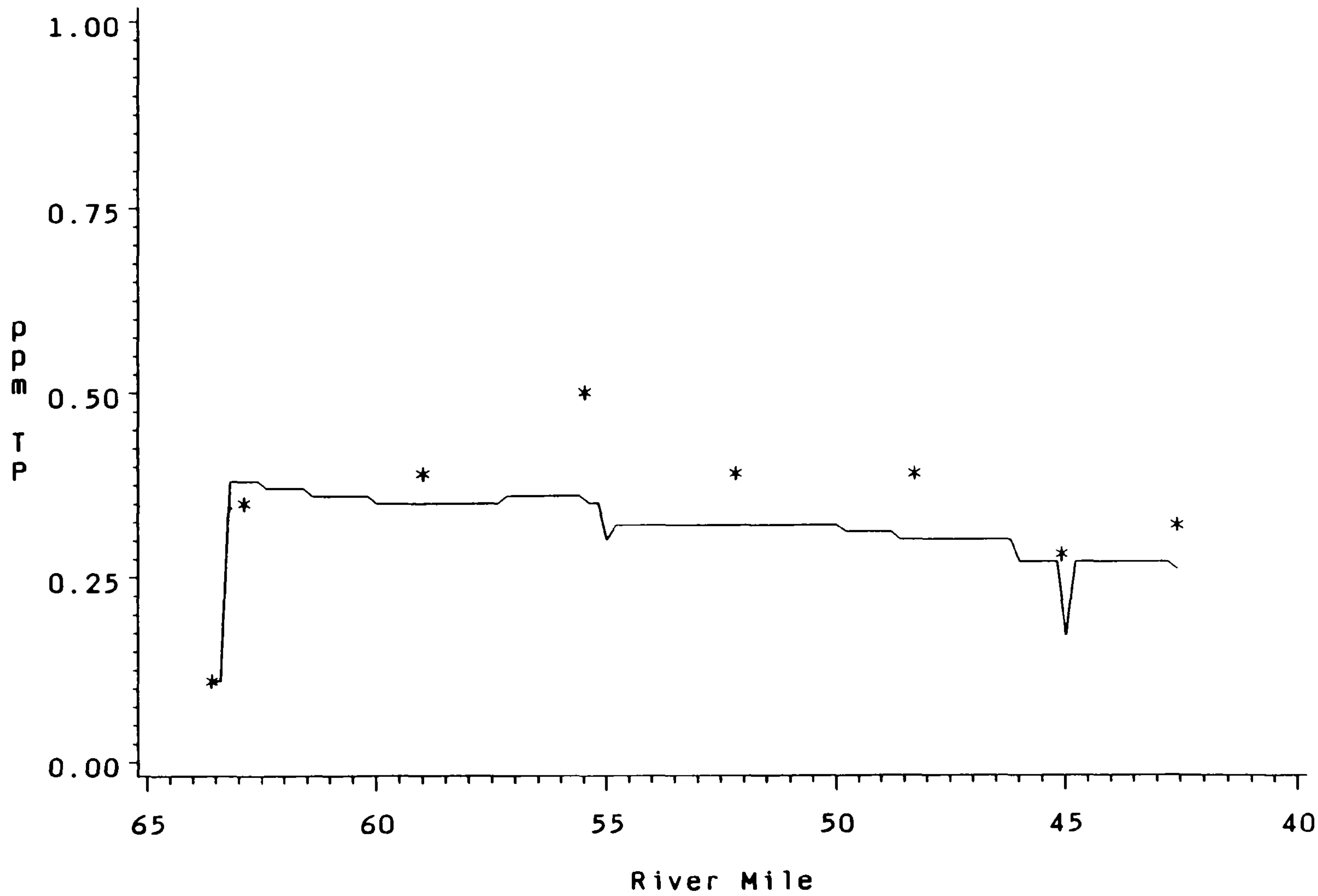


Figure VI-19. Validation of observed (*) and simulated total organic phosphorus values (ppm) on 7 July 1987.

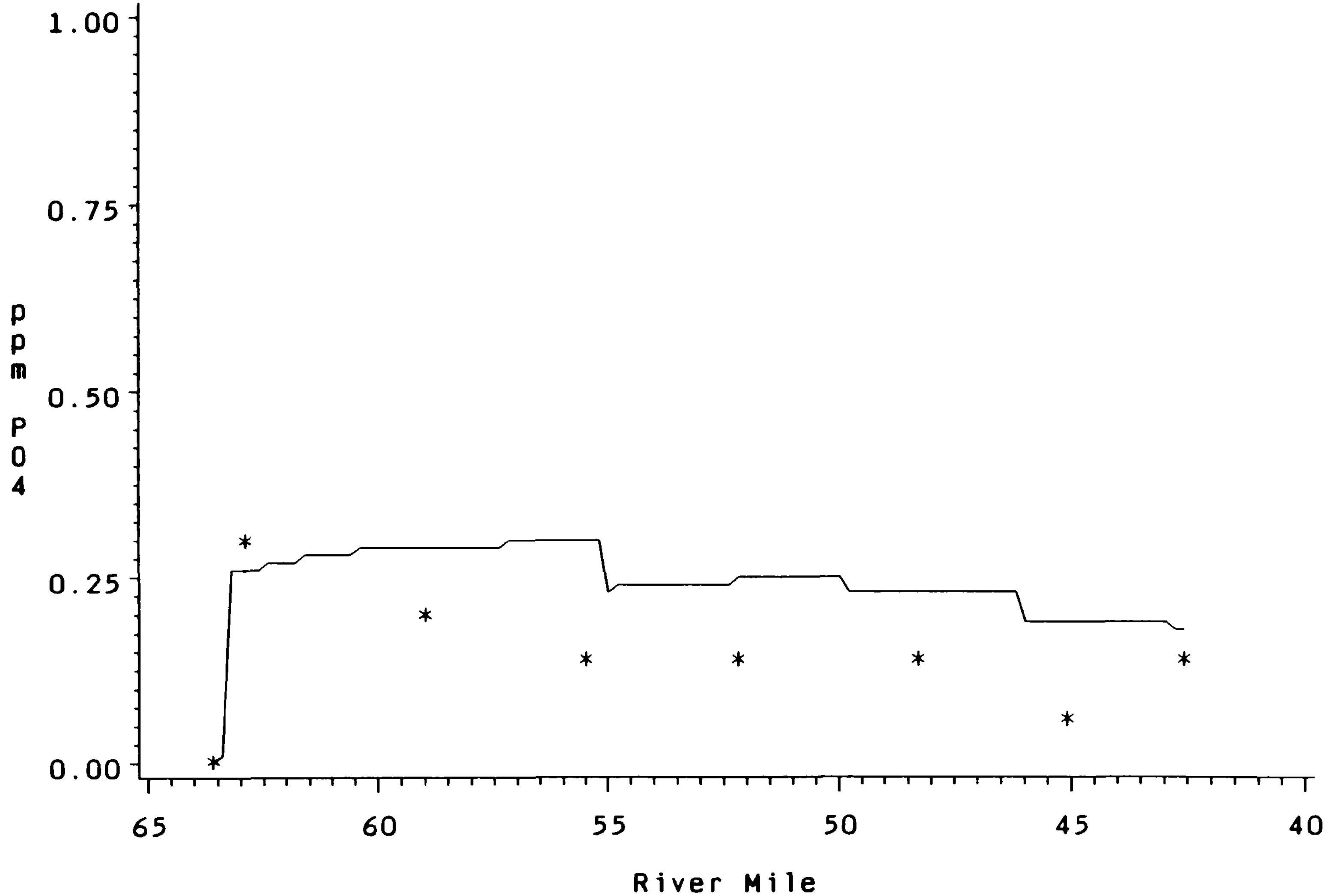


Figure VI-20. Validation of observed (*) and simulated(__) dissolved phosphorus values (ppm) on 7 July 1987.

C. MODEL UNCERTAINITY

The results of the 3500 Monte Carlo simulations comprising the uncertainty analyses indicate that point loads have the most pronounced effect on the prediction uncertainties of the nine modeled constituents (Table VI-2, Appendix D). These modeled variables responded linearly to the modification of point discharge concentrations. The coefficients of variation for the nine modeled state variables ranged from 9% for NO_3 to 15% for BOD, TKN, and PO_4. Chlorides, as would be expected, are sensitive only to modifications in the discharge of chlorides and streamflow (Appendices D and E). Dissolved oxygen concentrations are most affected by point source loads (Appendix D) but are minimally affected by changes in the reaction coefficients (Appendix F). Regardless of the uncertainty modifications, the dissolved oxygen concentrations at the confluence of the Pigeon River with Walters Lake are nearly constant. UBOD concentrations were directly affected by changes in point source loads (Appendix D), but were unaffected by a ± 15% change in the BOD decay rate (Appendix G). Concentrations of nitrogen and phosphorus were more sensitive to changes in reaction coefficients (Appendix H) than DO or UBOD. Modifications to the upstream concentrations of DO, UBOD, nitrogen, phosphorus, or chlorophyll a had no affect on local concentrations of these state variables (Appendix I). Only the modification of headwater streamflow (Appendix E) affected downstream concentrations of these state variables and this affect was generally minor (2-6%).

Table VI-2. Results of Monte Carlo uncertainty analysis. Coefficient of variation represents the error in the model prediction associated with the aggregate error in the inputs and parameters.

Uncertainty Scenario	Coefficent of Variation (%)								
	CL[1]	DO	UCBOD	TKN	NH_3-N	NO_2-N	NO_3-N	PO_4	CHL
UNC-1[2]	10	11	15	15	13	11	9	14	15
UNC-2	<1	<1	<1	<1	<1	<1	<1	<1	<1
UNC-3	6	1	3	2	2	2	6	3	4
UNC-4	0	5	2	1	20	20	10	<1	3
UNC-5	0	1	1	0	0	0	0	0	0
UNC-6	0	2	1	5	20	20	10	1	20
UNC-7	10	7	16	16	22	25	15	14	26

[1] CL=Chlorides; DO=Dissolved Oxygen; UBOD=Ultimate Biochemical Oxygen Demand; TKN=Total Kjeldahl Nitrogen; NH_3=Ammonia; NO_2=Nitrite; NO_3=Nitrate; PO_4=Dissolved Phosphorus; CHL=Chlorophyll *a*

[2] UNC-1: Point source concentrations varied (Appendix D)
UNC-2: Headwater water quality concentrations varied (Appendix I)
UNC-3: Headwater water quality concentrations and flow varied (Appendix E)
UNC-4: Dissolved oxygen reaction coefficients varied (Appendix F)
UNC-5: UBOD reaction coefficients varied (Appendix G)
UNC-6: Nutrients reaction coefficients varied (Appendix H)
UNC-7: All model parameters varied except headwater streamflow (Appendix J)

VII. PIGEON RIVER MODEL SCENARIOS

To evaluate the effects of alternative loading conditions at the Champion, Clyde, and Waynesville discharges on Pigeon River DO, BOD, and ammonia concentrations, EPA Region 4 requested that the following set of 5 scenarios be examined using the Pigeon River QUAL2E model:

- Scenario #1 - Examine the effects of removing the Clyde and Waynesville WWTPs discharges
- Scenario #2 - Examine the effects of assigning maximum secondary treatment standards for BOD (30 ppm) and ammonia (15 ppm) at the Waynesville WWTP
- Scenario #3 - Examine the effects of reducing the Champion discharge flow to 30 MGD (i.e., 46.4 cfs) while maintaining the present concentrations in the Champion effluent (i.e., reduced loadings)
- Scenario #4 - Examine the combined effects of maximum secondary treatment standards at the Waynesville WWTP and reduction of the Champion discharge to 30 MGD
- Scenario #5 - Examine the effects of removing the two sidestream oxygenators.

The validated Pigeon River QUAL2E model was used to evaluate each of these alternative loading scenarios. The results of the model evaluations are described below by specific scenario.

Scenario #1 - Removal of WWTP Discharges

The input values for the point source flows corresponding to the Clyde and Waynesville WWTPs were altered to represent zero discharge from these facilities and the model was rerun. Figures VII-1 through VII-3 show the effects of this management scenario on dissolved oxygen, BOD, and ammonia, respectively, and the model run is documented in Appendix K. The removal of the WWTP flows has no effect on the dissolved oxygen concentrations in the river; the nominal case (i.e., 27 September validated model; solid line in Figure VII-1) is not different from the scenario case (i.e., dashed line on Figure VII-1). The removal of the WWTP discharges has no effect on the the BOD concentrations in the river (Figure VII-2) and results in very minor reduction in

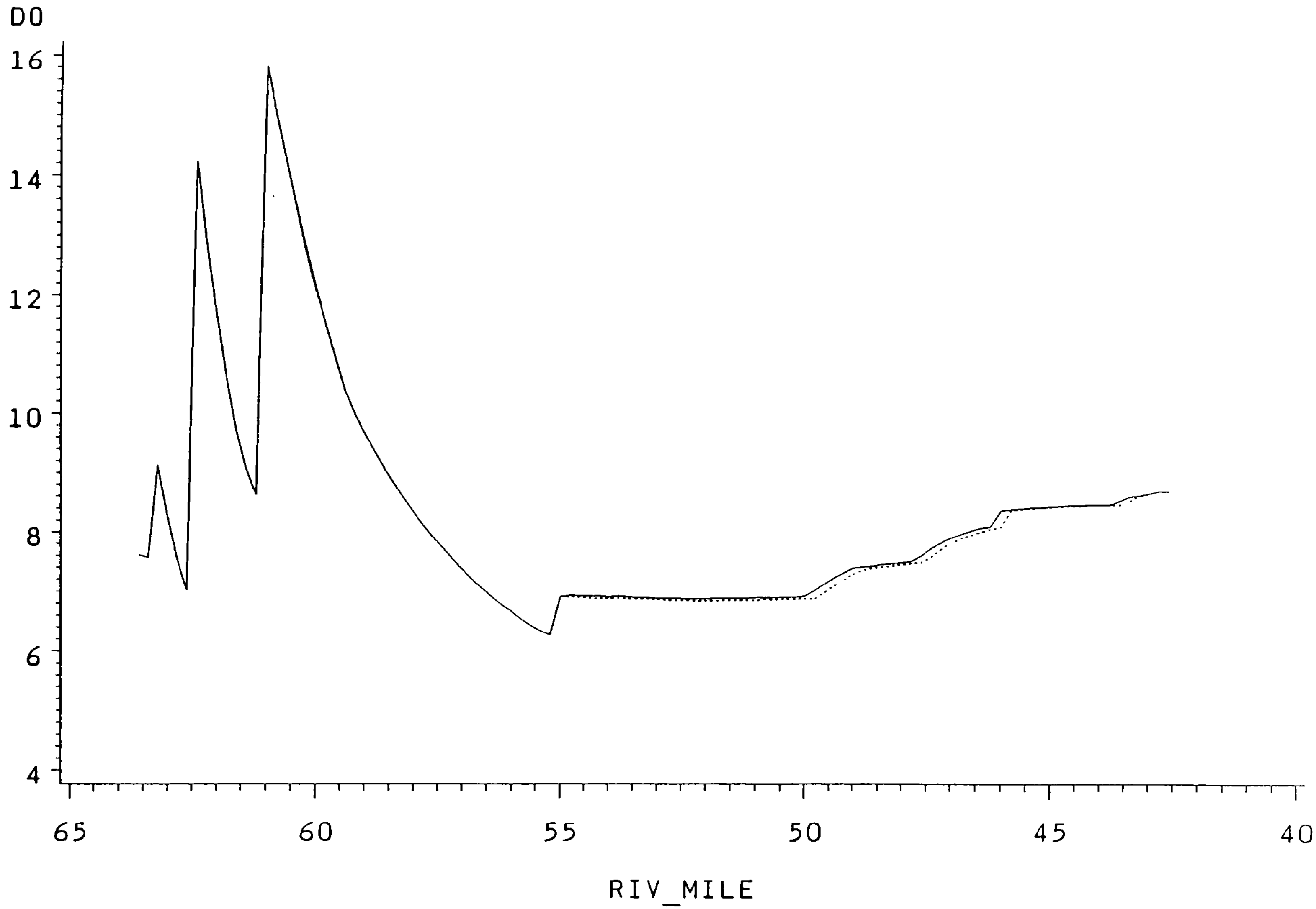


Figure VII-1. The simulated effect of removing the discharges of the Clyde and Waynesville WWTPs on Pigeon River dissolved oxygen concentrations (Nominal run = __; Scenario = --).

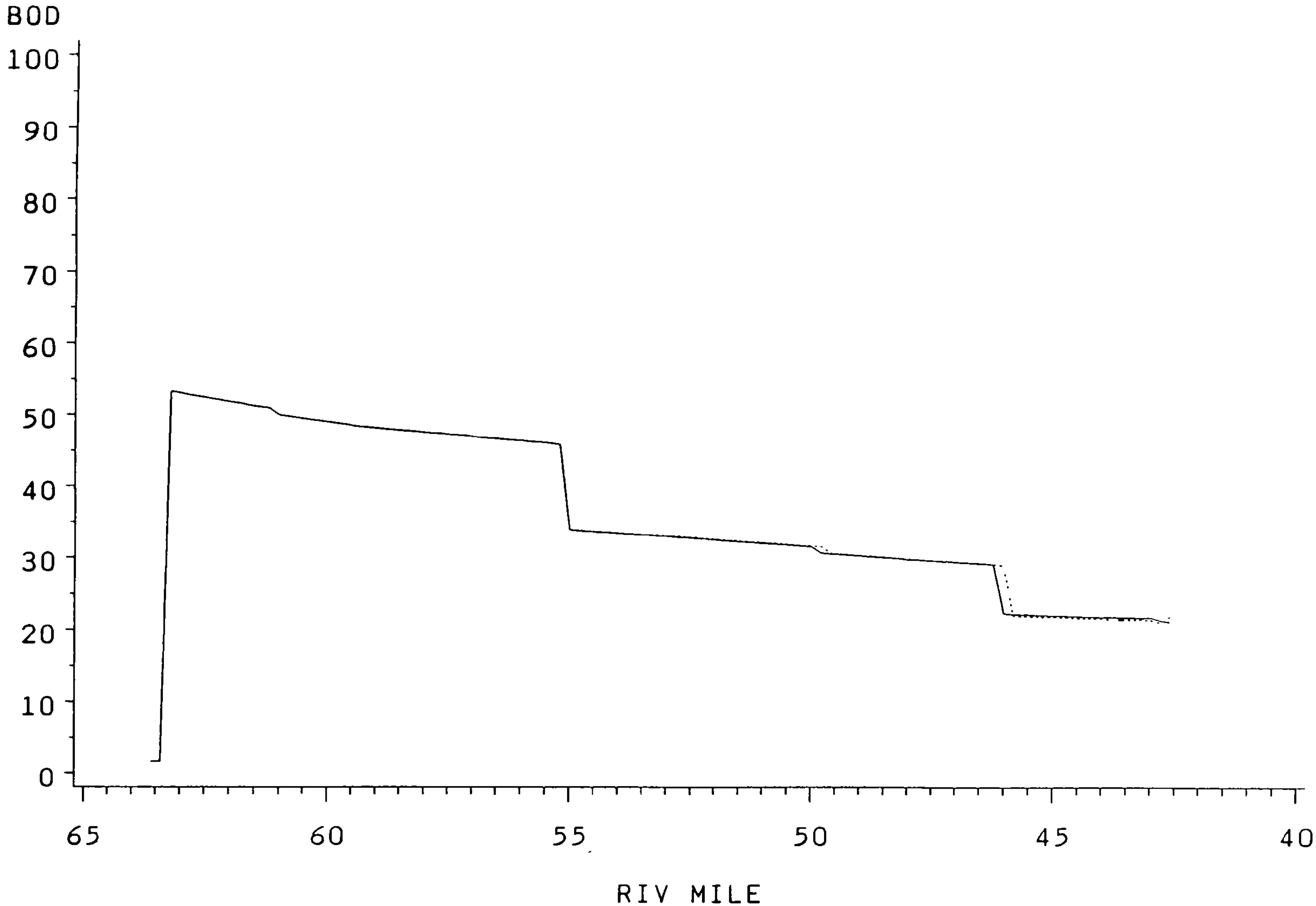


Figure VII-2. The simulated effect of removing the discharges of the Clyde and Waynesville WWTPs on Pigeon River UCBOD concentrations (Nominal run = __; Scenario = --).

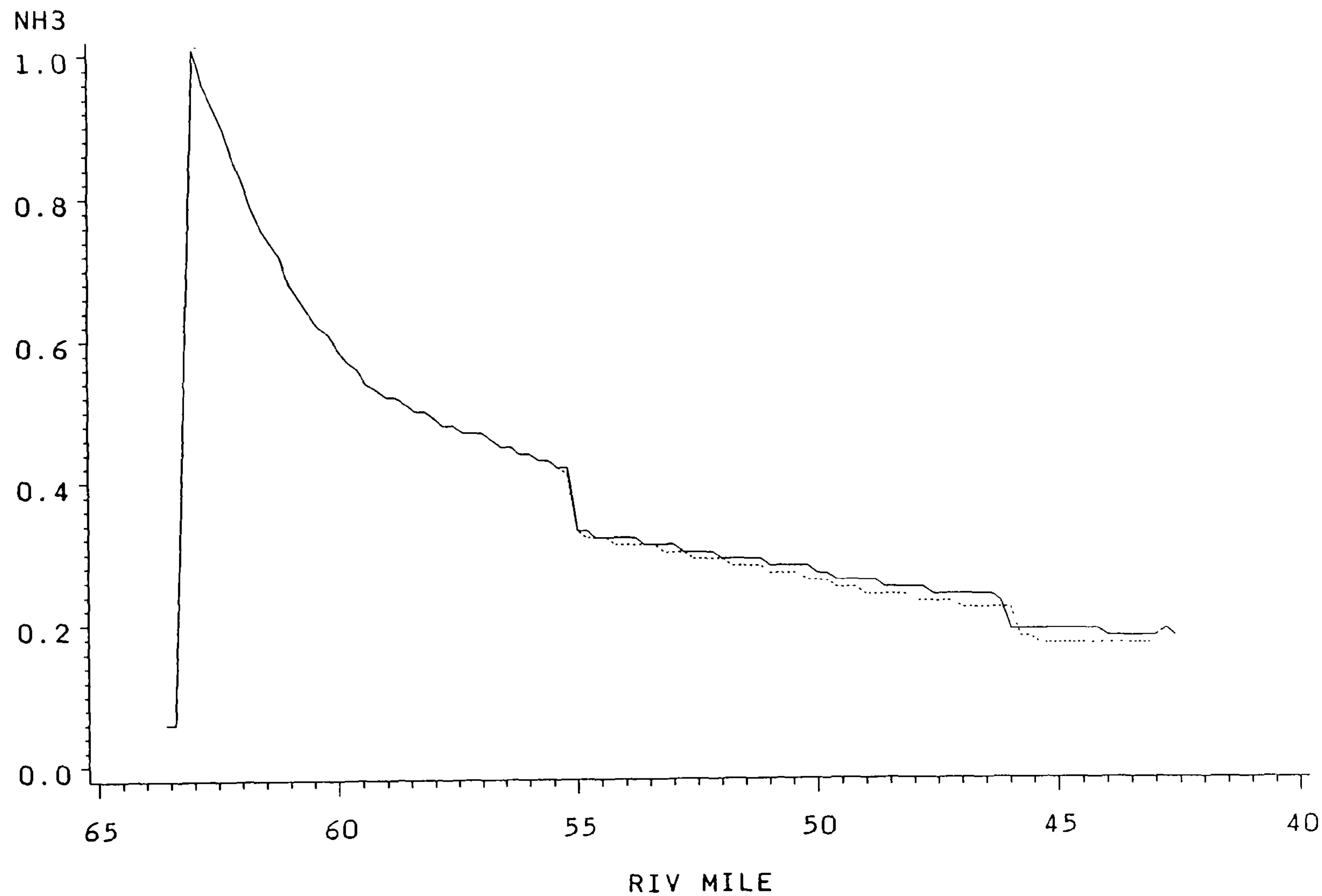


Figure VII-3. The simulated effect of removing the discharges of the Clyde and Waynesville WWTPs on Pigeon River NH_3-N concentrations (Nominal run = __; Scenario = --).

ammonia downstream of Richland Creek (i.e., < 0.1 ppm; Figure VII-3). The removal of the WWTPs from the Pigeon River system has no significant effects on the dynamics of oxygen, BOD, or ammonia in the river.

Scenario #2 - Secondary Treatment at the Waynesville WWTP

The input concentrations for the Waynesville point source discharge were altered to represent secondary treatment maximums for BOD and ammonia (i.e., 30 ppm and 15 ppm respectively) and the model was rerun. These modifications represented a minor decrease in the BOD load associated with the Waynesville facility (i.e., < 3 ppm) and a significant increase in ammonia discharge (i.e, from 0.3 ppm to 15.0 ppm). Figures VII-4 to VII-6 show the effects of secondary treatment at Waynesville WWTP on the dissolved oxygen, BOD, and ammonia concentrations in the Pigeon River, respectively, and Appendix L documents the model run. The increased ammonia load being discharged by Waynesville in this scenario (Figure VII-6) produces an ammonia spike in the river equivalent to that presently produced by the Champion effluent (i.e., about 1.0 ppm). The slightly reduced BOD loading in the scenario does not affect the simulated BOD concentrations in the river. The increase of ammonia, however, does create a simulated dissolved oxygen sag of about 1.0 ppm below the Waynesville discharge for a distance of about 5 miles downstream (Figure VII-4).

Scenario #3 - Reduction of Champion Discharge Rate to 30 MGD

The input discharge rate for the Champion facility was reduced to 30 MGD (i.e., 46.4 cfs) and the model was rerun (Appendix M). This management scenario represents a 55% reduction in the discharge rate of the Champion facility. Reductions in BOD loading from the Champion facility reduced simulated BOD concentrations in the river by about 20 ppm near the Champion discharge (Figure VII-7). Further downstream, dilution acted upon this concentration in the scenario simulation in the same manner as in the nominal simulation, reducing the concentration of simulated BOD from about 35 ppm at the Champion discharge to about 18 ppm at the confluence with Walters Lake. Similarly, simulated ammonia concentrations in the river were reduced by about 20-25% near the Champion discharge, but returned to nominal levels by River Mile 42 (Fig. VII-8). The reduction of the Champion discharge rate had little effect on dissolved oxygen concentrations (Figure VII-9). In fact, reduction of the Champion discharge rate actually lowered oxygen concentrations slightly (< 0.5 ppm) in the vicinity of the discharge. This reduction in DO was due to the proportional reduction in

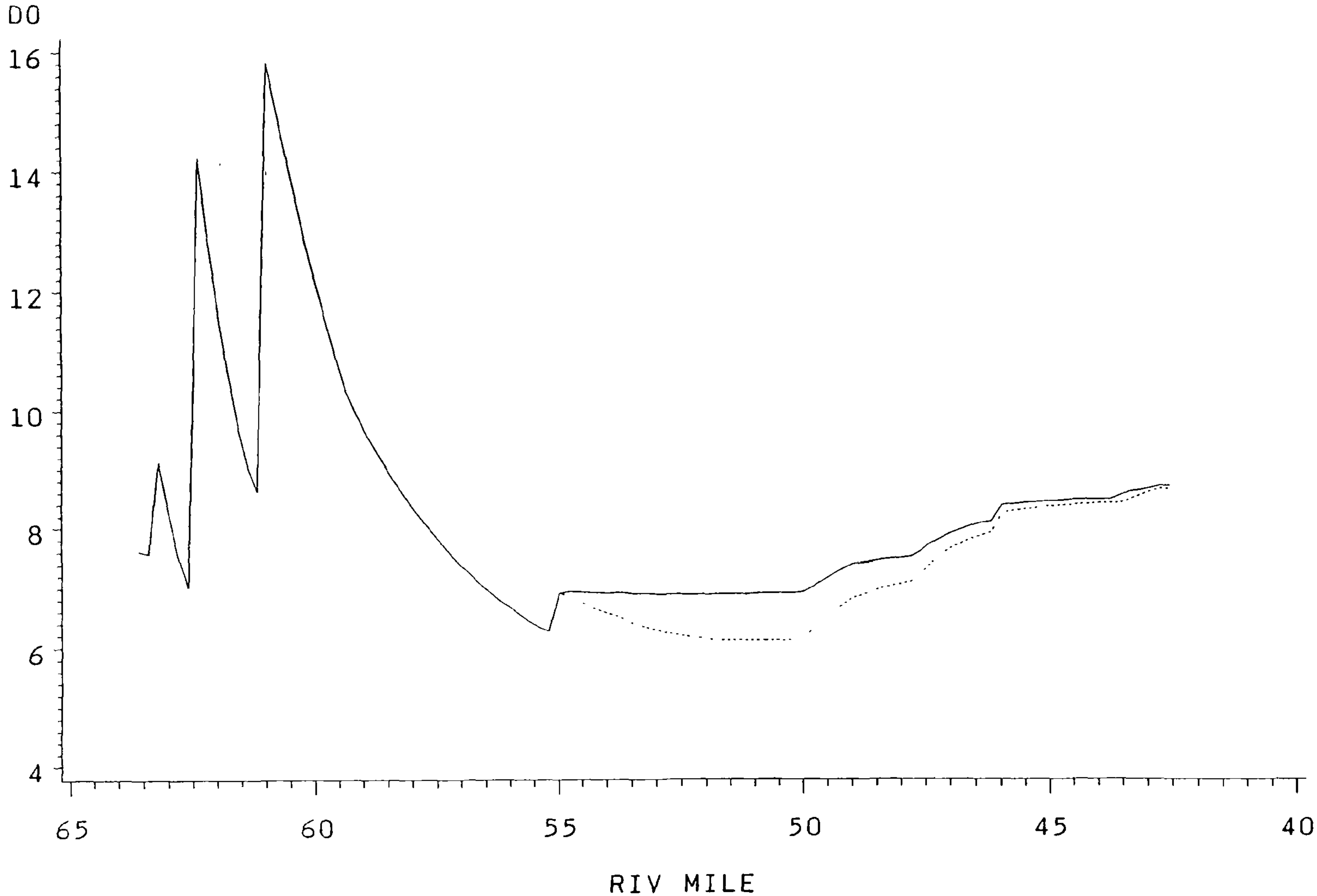


Figure VII-4. The simulated effect of required secondary treatment standards (BOD=30 ppm and NH_3=15 ppm) at the Waynesville STP on Pigeon River dissolved oxygen concentrations (Nominal run = __; Scenario = --).

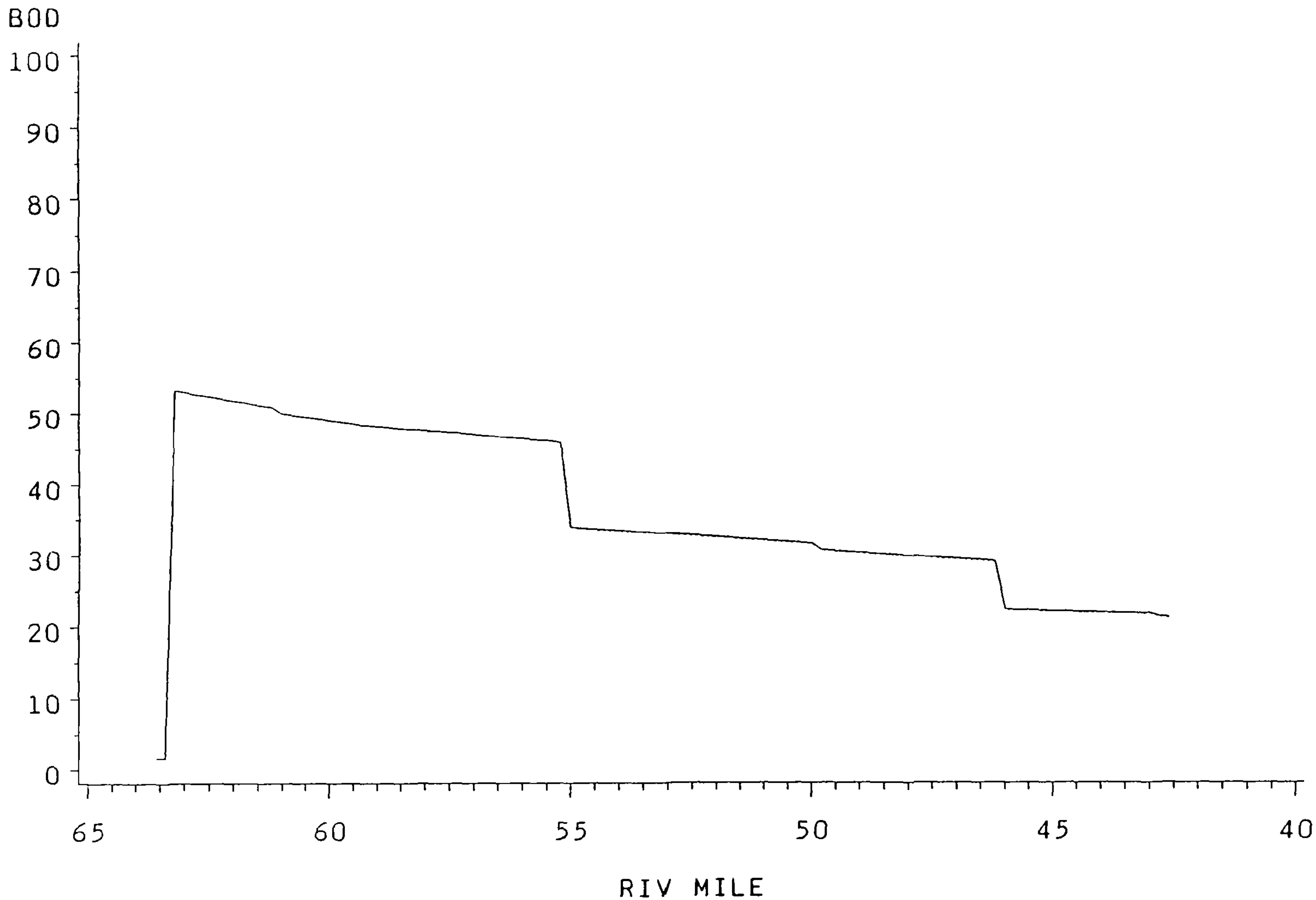


Figure VII-5. The simulated effect of required secondary treatment standards (BOD=30 ppm and NH_3=15 ppm) at the Waynesville STP on Pigeon River UCBOD concentrations (Nominal run = __; Scenario = --).

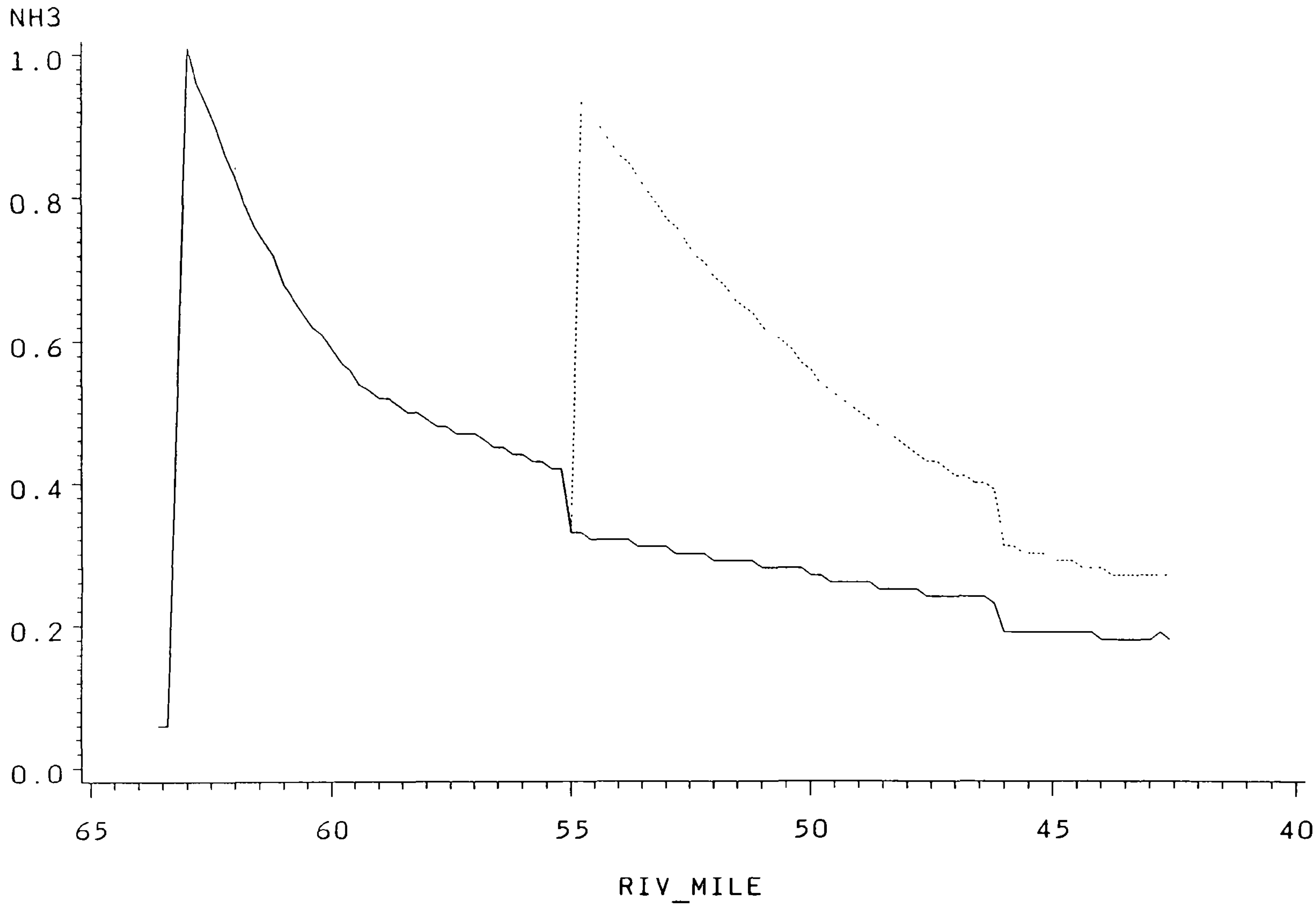


Figure VII-6. The simulated effect of required secondary treatment standards (BOD=30 ppm and NH_3=15 ppm) at the Waynesville STP on Pigeon River NH_3-N concentrations (Nominal run = __; Scenario = --).

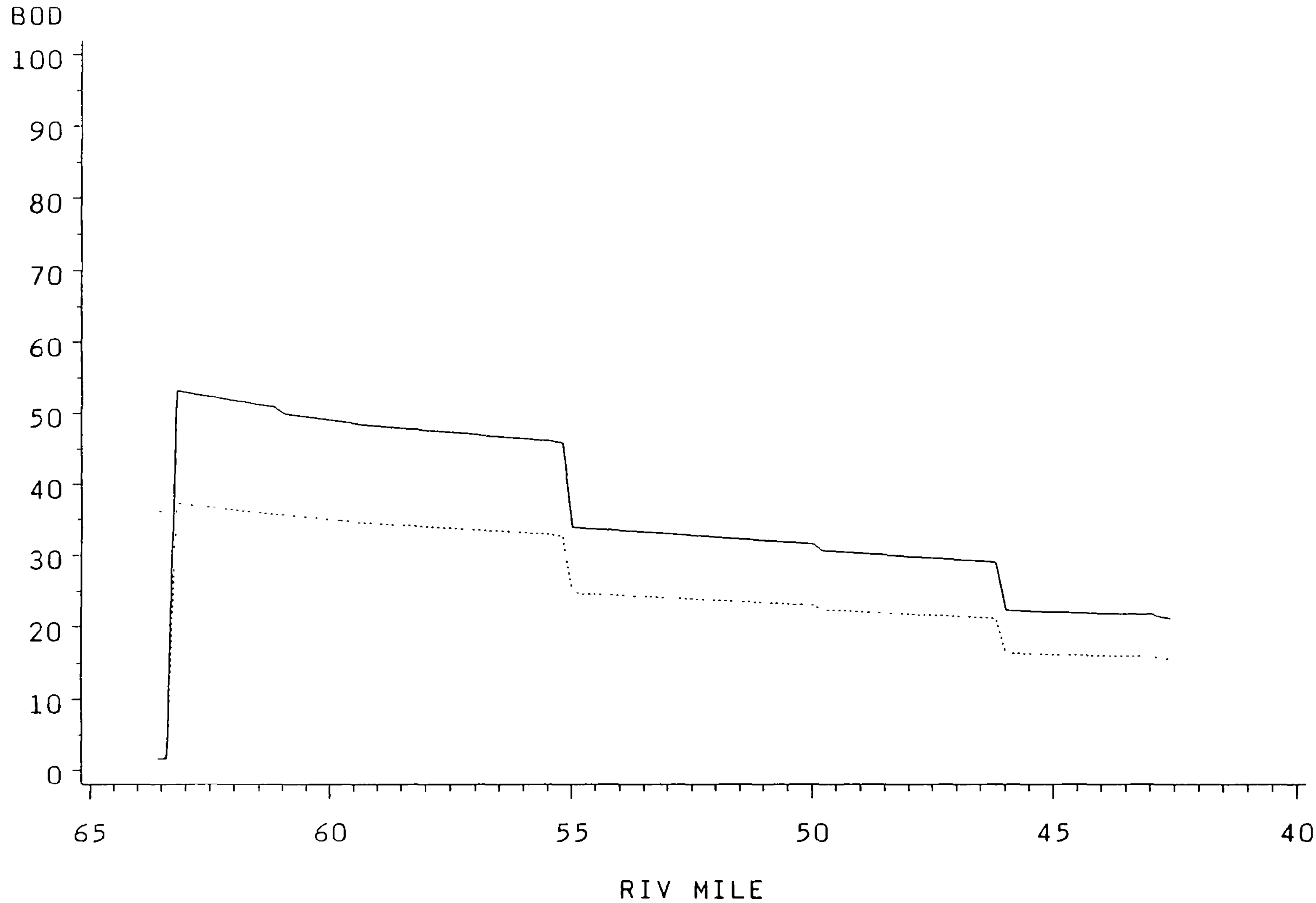


Figure VII-7. The simulated effect of reducing the Champion discharge to 30 MGD while maintaining present effluent concentrations on Pigeon River UCBOD concentrations (Nominal run = __; Scenario = --).

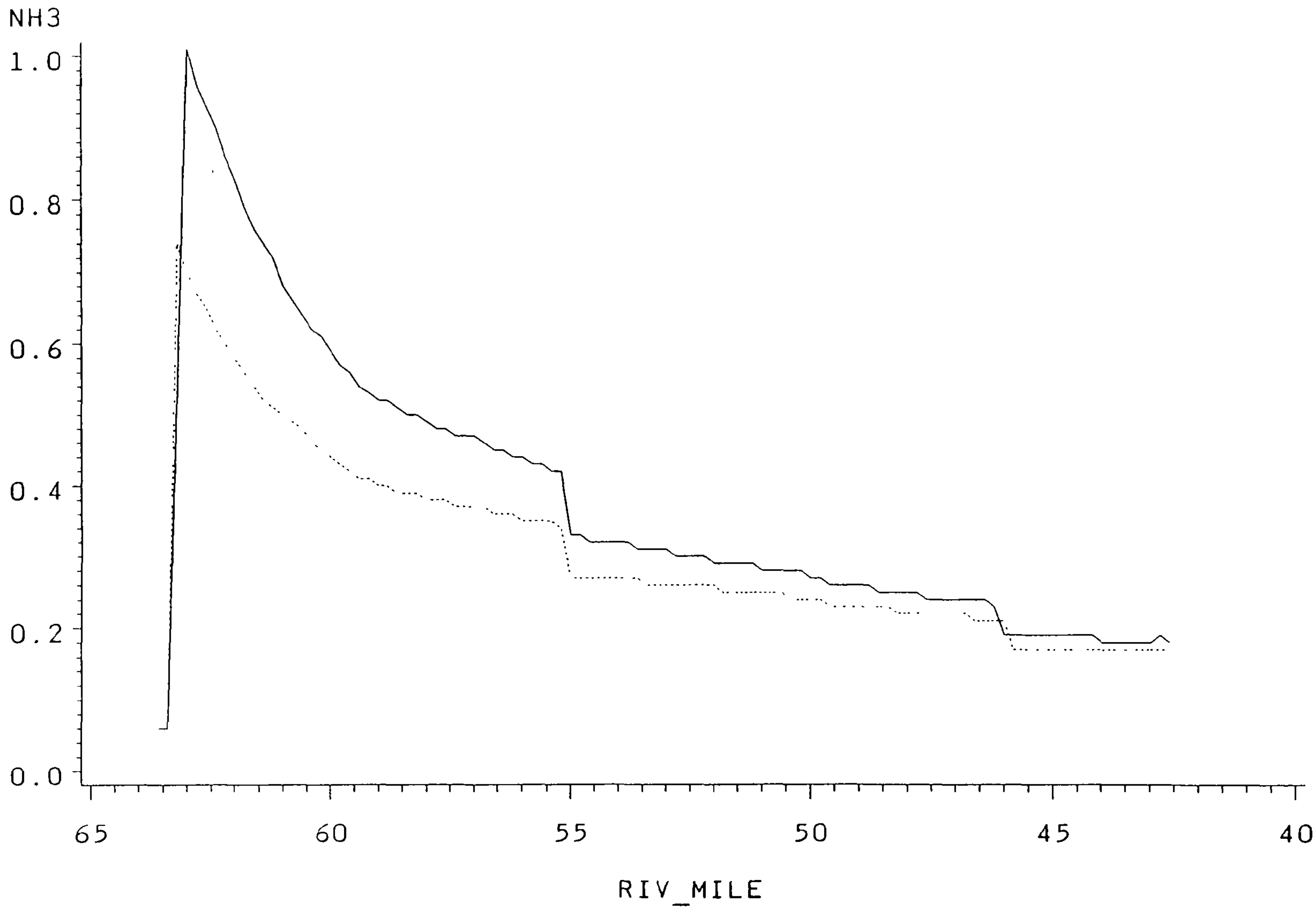


Figure VII-8. The simulated effect of reducing the Champion discharge to 30 MGD while maintaining present effluent concentrations on Pigeon River NH_3-N concentrations (Nominal run = __; Scenario = --).

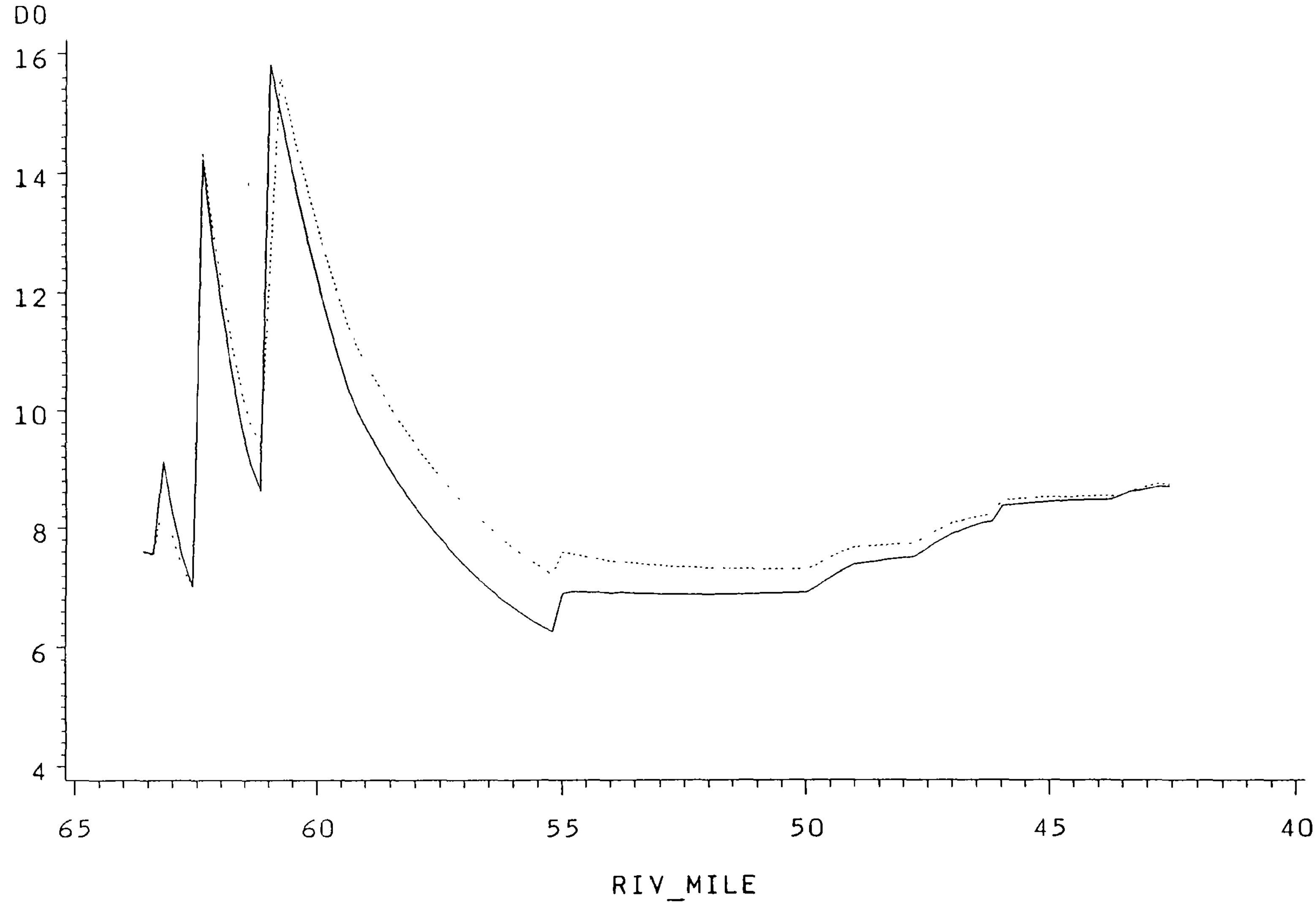


Figure VII-9. The simulated effect of reducing the Champion discharge to 30 MGD while maintaining present effluent concentrations on Pigeon River dissolved oxygen concentrations (Nominal run = __; Scenario = --).

artificial oxygenation at the point of discharge. However, dissolved oxygen concentrations were increased above the nominal condition by the first downstream oxygenator, and due to decreased ammonia loads (Figure VII-8) and to some extent reduced BOD loads(Figure VII-7), the rate of decrease in dissolved oxygen between the final oxygenator and Richland Creek was slowed. This resulted in a simulated increase of about 1 ppm at the confluence with Richland Creek. Subsequent reaeration resulted in returning the dissolved oxygen levels in Pigeon River under this scenario to the same concentration observed in the nominal simulation at the river's entrance to Walters Lake (Figure VII-9).

Scenario #4 - Reduced Champion Discharge and Secondary Treatment at Waynesville WWTP

The input discharge rate for Champion was reduced to 30 MGD (i.e., 46.4 cfs) and the input concentrations for the Waynesville WWTP were altered to maximum secondary treatment levels (i.e., 30 ppm for BOD, and 15 ppm for ammonia) and the model was rerun. As described above, the modification in the ammonia effluent for the Waynesville WWTP represents a substantial increase over the nominal simulation. Figures VII-10 to VII-12 show the effects of this management scenario on the dissolved oxygen, BOD, and ammonia concentrations in the Pigeon River, respectively, and the model run is documented in Appendix M. Under this management scenario, both simulated BOD and ammonia concentrations are changed in the river; BOD is reduced primarily due to the reduced Champion discharge (Figure VII-11), and ammonia is increased due to the increased loading from the Waynesville WWTP (i.e., 15 ppm NH_3 compared to 0.3 ppm in the nominal simulation; Figure VII-12). These changes in BOD and ammonia result in an increase in simulated dissolved oxygen in the region between the Champion discharge and River Mile 54 and a decrease in simulated dissolved oxygen between River Mile 54 and River Mile 47 (Figure VII-10). Simulated dissolved oxygen in this scenario returns to the nominal level by the Piegon River's confluence with Walters Lake (Figure VII-10).

Scenario #5 - Removal of Sidestream Oxygenators

The inputs of the nominal Pigeon River model were altered to eliminate the two downstream oxygenators by reducing their withdrawal and discharge rates to zero, and by increasing the Tsivoglou-Wallace reaeration coefficients for the reaches associated with the sidestream oxygenators. In this scenario, these reaches were given values equivalent to those assigned to the remainder of the river. Figures VII-13 to VII-15 show the

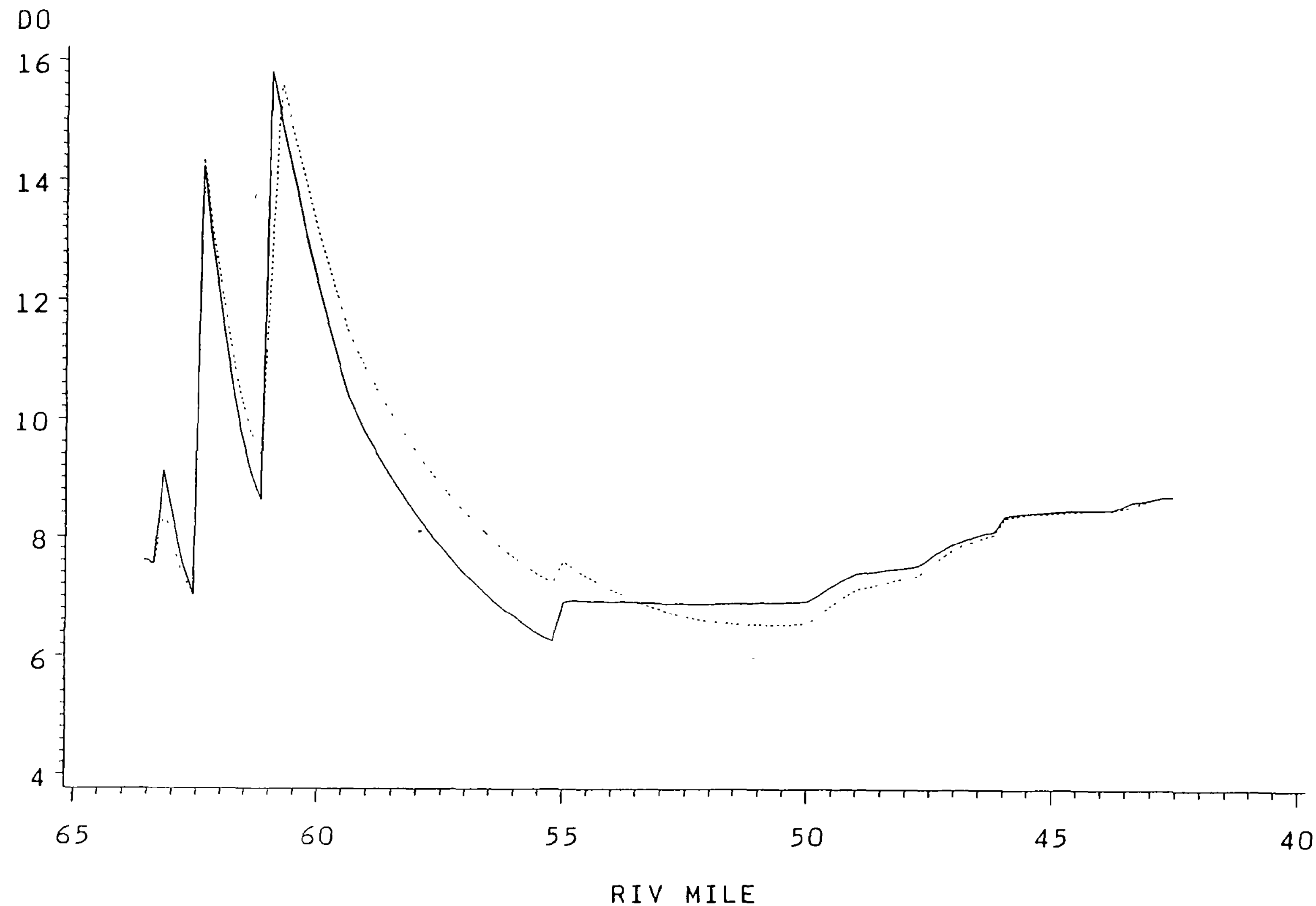


Figure VII-10. The simulated effects of reducing the Champion discharge to 30 MGD and requiring secondary treatment standards at the Waynesville STP on Pigeon River dissolved oxygen concentrations (Nominal run = __; Scenario = --).

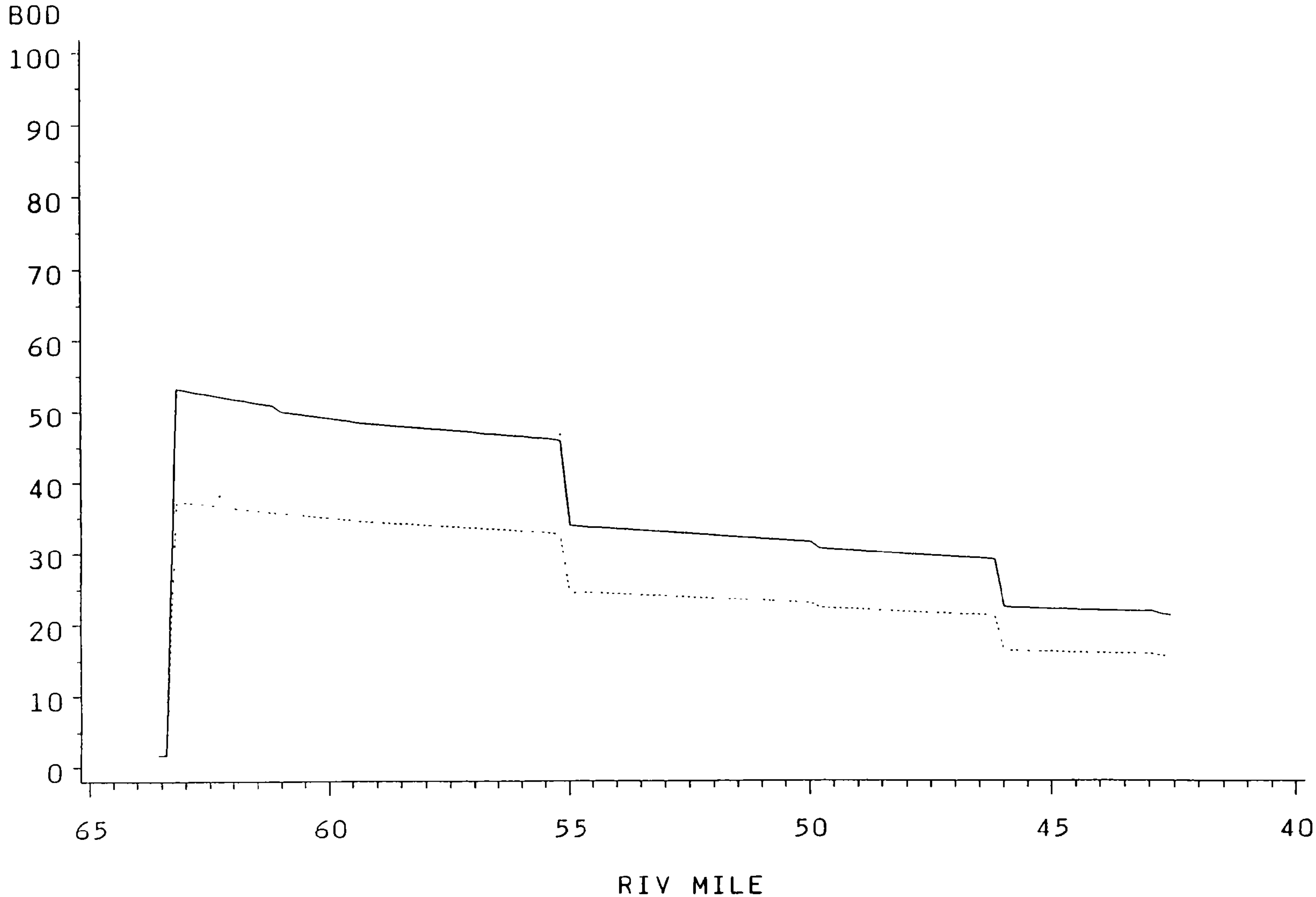


Figure VII-11. The simulated effects of reducing the Champion discharge to 30 MGD and requiring secondary treatment standards at the Waynesville STP on Pigeon River UCBOD concentrations (Nominal run = __; Scenario = --).

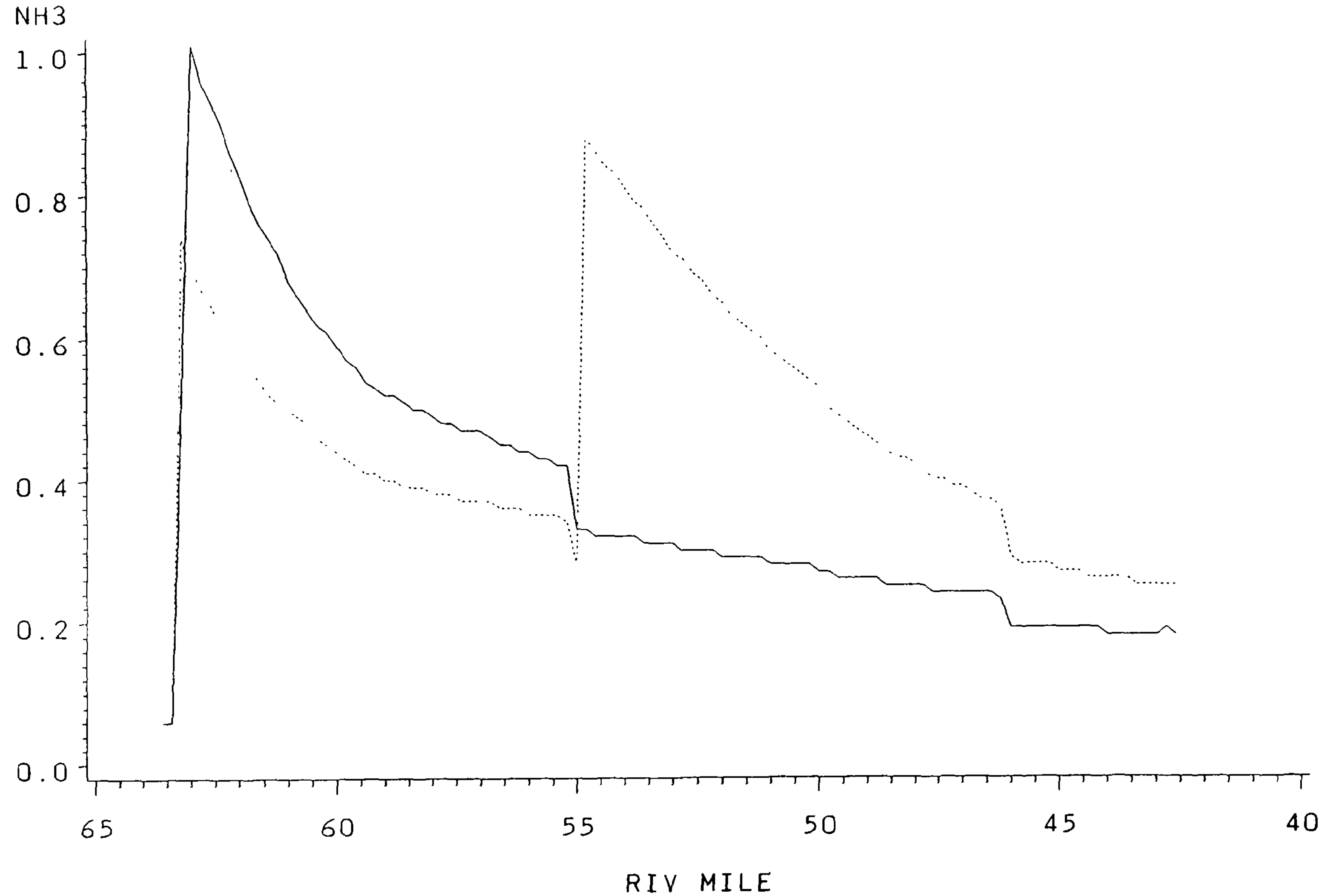


Figure VII-12. The simulated effects of reducing the Champion discharge to 30 MGD and requiring secondary treatment standards at the Waynesville STP on Pigeon River NH_3-N concentrations (Nominal run = __; Scenario = --).

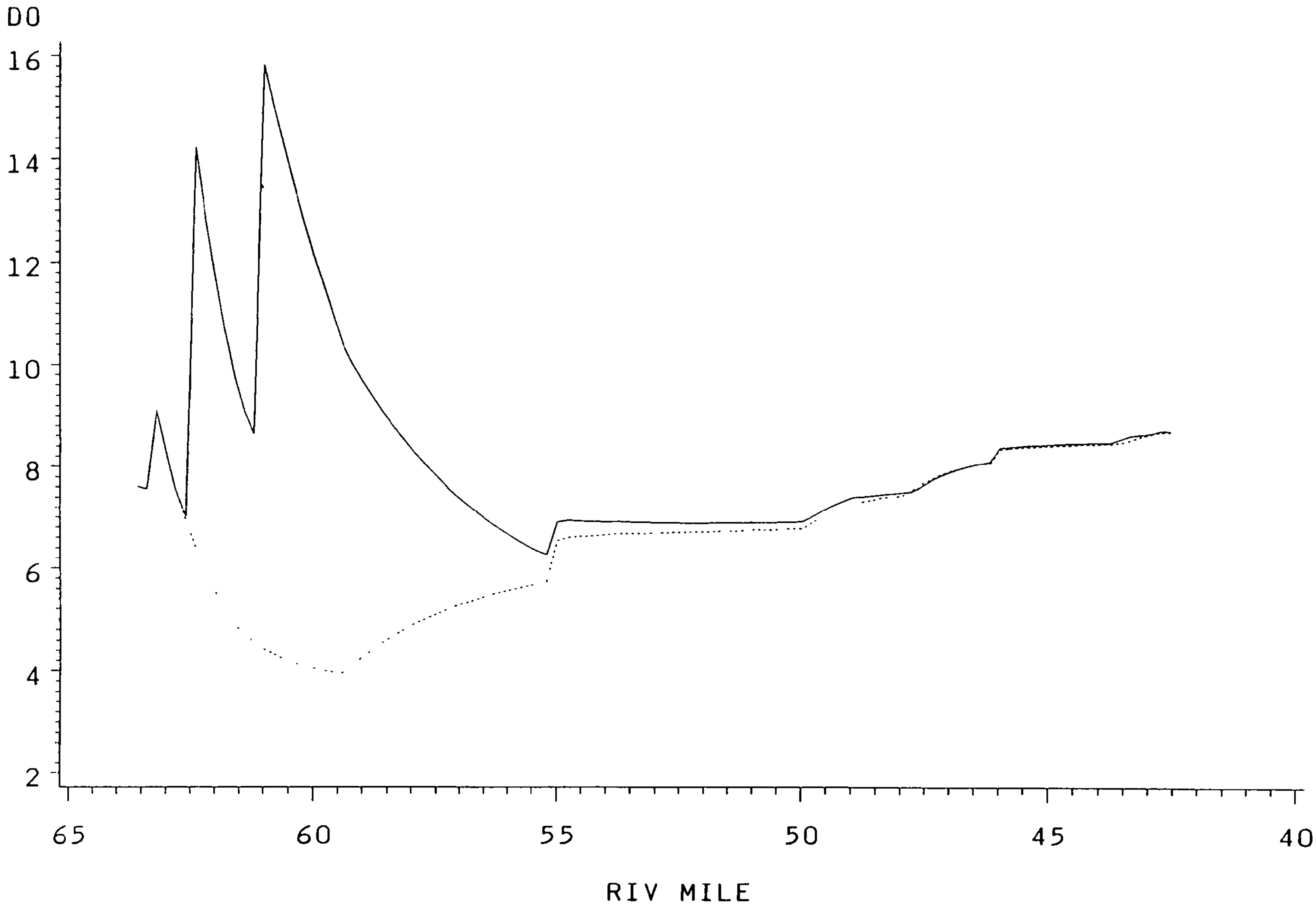


Figure VII-13. The simulated effects of removing the two downstream oxygenators on Pigeon River dissolved oxygen concentrations (Nominal run = __; Scenario = --).

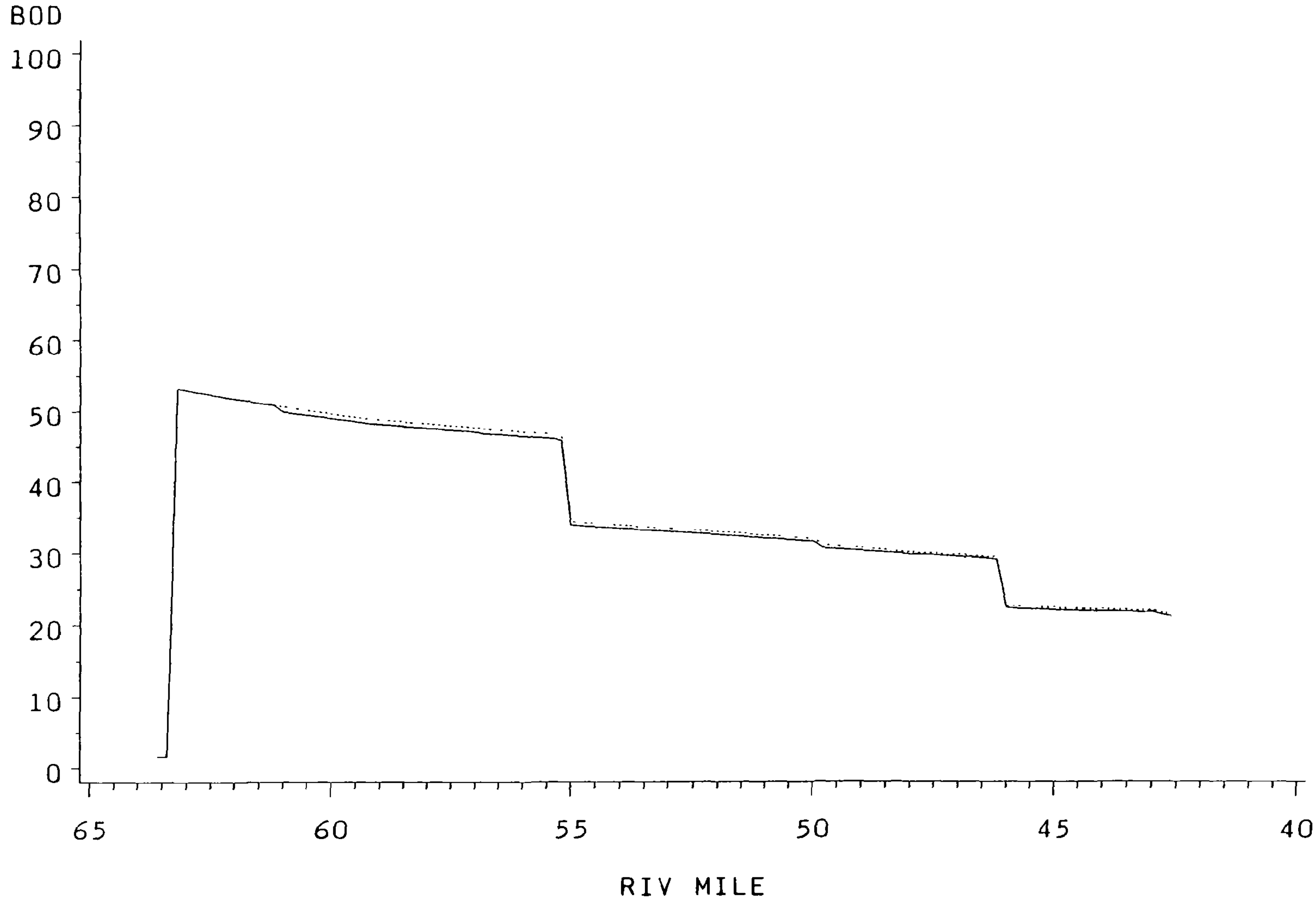


Figure VII-14. The simulated effects of removing the two downstream oxygenators on Pigeon River UCBOD concentrations (Nominal run = __; Scenario = --).

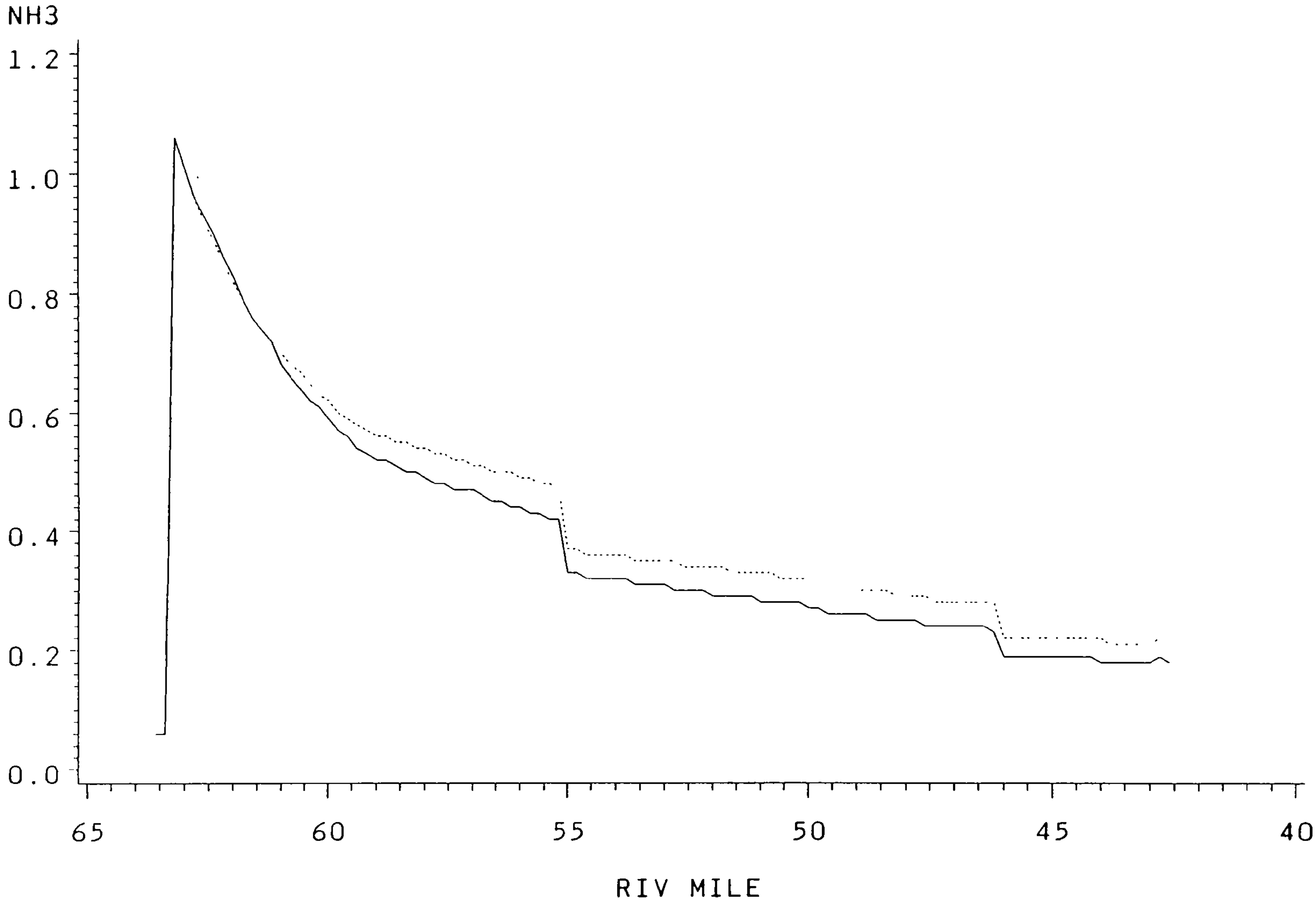


Figure VII-15. The simulated effects of removing the two downstream oxygenators on Pigeon River NH_3-N concentrations (Nominal run = __; Scenario = --).

effects of sidestream oxygenator removal on dissolved oxygen, BOD, and ammonia concentrations, respectively, and the model run is documented in Appendix N. The removal of the oxygenators produces a small increase in the simulated values of BOD (Figure VII-14) and ammonia (Figure VII-15). These increases are due to reductions in the simulated oxidation rate of these compounds resulting from low-level inhibition processes for BOD degradation and nitrogen oxidation. In the QUAL2E model, low-level inhibition is initiated when dissolved oxygen levels fall below 5.0 ppm. The major parameter affected by the removal of the oxygenators is dissolved oxygen. After initial oxygenation to about 9.0 ppm at the Champion discharge, the reduction of oxygen is controlled by deaeration, oxidation of nitrogen, and microbial activity until simulated dissolved oxygen reaches a minimum concentration of slightly less than 4.0 ppm at River Mile 60 (Figure VII-13). Due to increased elevation gradient, some reaeration occurs between River Mile 60 and 55, and after the inflow from Richland Creek enhances the simulated DO concentrations in the river, there is little difference between the scenario and the nominal simulation.

VIII. DISCUSSION

Under loading conditions prevailing during the time of our study, the Champion Mill effluent had a greater effect in determining the lowest oxygen concentrations in the river than discharges from either the Waynesville or Clyde WWTPs. The lowest DO value we found occurred upstream of Richland Creek. Given its location, it is unlikely that the dissolved oxygen minimum results from the WWTPs effluents. Most of the decline below saturation had already occurred before the effluent from the Clyde WWTP entered the river, and recovery was apparent prior to introduction of the effluent from the Waynesville WWTP.

Our modeling simulations confirmed the relative importance of Champion Mill effluent on oxygen dynamics. When the modeled effluents from the Champion Mill were reduced by 55%, simulations indicated there would be more than a 1 ppm improvement in dissolved oxygen concentration in the river near Richland Creek. When the inputs from the Waynesville and Clyde WWTPs were totally removed from the model, there was no detectable change in river concentration of dissolved oxygen. The dominance of the Champion effluent was also evident from the relative insensitivity of dissolved oxygen to other inputs in the uncertainity analyses. These findings are not surprising given the relative volumes of the effluents observed in our studies. Loadings of nitrogen and ultimate BOD were 40 and 10 times higher, respectively, in the Champion Mill discharge than in the discharge from the two WWTPs combined.

The model run in which the Champion effluent was reduced by 55% identified that most of the improvement in downstream oxygen conditions was as a result of reductions in nitrogen inputs. This finding was consistent with the uncertainty analysis which found the model to be significantly affected by changes in nitrogen loading. Presumably the importance of nitrogen is a result of oxidation of ammonia (i.e., consuming 4.57 ppm of oxygen for every ppm of ammonia).

Ammonia concentrations discharged from all three effluents during the study period were substantially less than their yearly average concentrations (Table VIII-1). This may be the reason oxygen values were never found to be less than 6 ppm during our study. Oxygen values less than 5 ppm have been frequently seen during previous low flow summer conditions. Additional simulations in which the ammonia concentrations of the Champion and WWTP effluents were increased to twice their annual average value suggested that most of the depletion associated

Table VIII-1. BOD and ammonia concentrations in the three effluents on 27 September 1988 compared to most recently available yearly average effluent concentrations.

	BOD_5			Ammonia		
	This Study	Yearly Average	Yearly Maximum	This Study	Yearly Average	Yearly Maximum
Champion[a] Mill	4.3	12.8	47.6	1.1	2.2	9.8
Clyde WWTP[b]	3.0	8.8	19.0	1.8	2.8	12.8
Waynesville[c] WWTP	3.4	14.1	36.0	0.3	2.4	8.0

Source of yearly data: [a] 1986 permit application
[b] 1988-89 self monitoring data
[c] 1988-89 self monitoring data

with low oxygen conditions result from quality of the Champion Mill effluent. When ammonia concentration in the WWTP effluents were increased, there was no significant change in oxygen concentration in the river. However, simulated increases in ammonia concentration from the Champion Mill effluent resulted in a further decrease of almost 2 ppm in DO levels near the mouth of Richland Creek to a simulated dissolved oxygen level of 4.7 ppm.

Although the discharge of the Champion Mill contained an ultimate carbonaceous BOD of greater than 50 ppm, very little of this material was found to degrade within our study area. The low rate of degradation recorded for the discharge ($BOD_5 < 5$ ppm) and the rapid travel time to reach the mouth of Walters Lake (~ 2 days) were the primary reasons for the lack of degradation within the study area.

In most low gradient lotic systems, algal photosynthesis and respiration, as well as respiration of benthic biota, play an important role in regulating instream DO patterns. In the Pigeon River, however, these factors were found to be relatively unimportant. Measured sediment oxygen demand values were low and had little effect on the model predictions. However, the values we measured were consistent with that from a previous study of sediment oxygen demand in the Pigeon River (Weston 1983). Primary production was negligible in our study, reflecting the low chlorophyll numbers (< 10 mg/l) seen throughout the study area. This was confirmed by the almost total absence of diurnal variation in the parameters that are normally affected by photosynthesis. Presumably the low primary productivity in the presence of abundant nitrate results from the reduced light penetration associated with the Champion effluent.

The two sidestream oxygenation units had a substantial influence on oxygen content of the river between the Champion Mill and Richland Creek. Simulations removing the oxygenation units identified that dissolved oxygen content would fall to less than 4 ppm near River Mile 60, consistent with values of less than 4 ppm that were observed in monitoring efforts prior to installation of these units. However, the model run also showed that the oxygenation units had no measurable effect on the river downstream of Richland Creek, where reaeration and dilution by tributaries were the dominant factors controlling recovery from the depletion zone. The model also identified that most (60-70%) of the oxygen added by the units is lost to the atmosphere, and has little effect on decay rate of carbonaceous BOD from the mill. Given that the oxygen infusion rate that was supplied to Versar is an apparent underestimate (measured DO values immediately downstream of the units were higher than would be produced given the infusion rate), the percentage loss to the atmosphere is likely to be an underestimate. Since, the observed DO decline is mimiced by the model, and the decay rates (both CBOD and NBOD) have sufficient oxygen to continue uninhibited at the simulted oxygen levels, the increase in infused oxygen would simply be lost to the atmosphere. This would increase the atmospheric deaeration to about 80-85% of total infused oxygen. Thus, it appears the major effect of the oxygenation units is to maintain DO levels between Champion and Richland Creek above State water quality standards.

Since the sidestream oxygenation units do not substantially add to consumption within the river of the carbonaceous BOD load being added by the Champion effluent, it follows that this BOD load is being transported to the lake. A mass balance approach comparing empirical data from the Champion effluent (E1) and the station at the headwaters of Walters Lake (S11) shows that most of the difference in concentration of ultimate BOD at these stations can be attributed to dilution from tributaries; when weighted by flow there is less than a 20% difference in BOD mass at these sites. Our model, which leads to the same conclusion that less than 20% of the BOD loads are being consumed in the river, provides a semi-independent confirmation of this finding since it is based on point source loadings and process rates, rather than on downstream concentrations. The model conclusion relies heavily on the high ultimate carbonaceous. BOD inputs the UCBOD to 5-day BOD ratio was 12:1, higher than average for paper mill effluents (NCASI 1982). However, the fact that this ratio exceeds 10:1 for the mill effluent was confirmed by a monitoring sample from the Champion effluent that was collected by the NCDEM on the same day as our study (Table VIII-2). This high ratio may be a reflection of the lignocellulosic content and relatively large size of fiber particles observed suspended in the water column downstream of the Champion Mill effluent.

Very little information is available to examine the effect of this source contribution to the lake, but what data are available suggest that the lake is severely impacted. Data collected in 1973 (STORET) and in 1982 (Herlong et al. 1982) both show that DO levels near the surface were less than 2 ppm in late summer/early fall. Values near the bottom of the reservoir are even lower. Since Walter's Lake is used as a source for a hydroelectric facility which has its intake located near the bottom of the reservoir, there is reason to be concerned that water being discharged from that facility fails to meet State standards. Future modeling efforts that extend the downstream boundary of the present study are recommended to better describe the ultimate fate of carbon inputs from the three Pigeon River discharges.

Table VIII-2. Results of UBOD analyses from an undiluted Champion Mill effluent sample collected by NCDEM on 27 September 1988 at 1015

Day	Total BOD (mg/l)	NH_3-N	TKN-N	NOX-N	Total N
0		1.1	3.1	0.01	3.1
5	6.8				
10	11.6				
15	16.1				
20	20.3				
25	24.5				
30	30.2				
35	35.4				
40	37.9				
50	41.6				
60	44.8				
70	47.7	0.03	0.8	1.7	2.5
83	51.1				
95	53.5				
106	55.5				
118	57.8				
140	61.5				
155	64.2				
175	67.1				
201	70.2				
223	72.2				

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