A Final Report

ASSESSING THE WATER QUALITY BENEFIT OF POINT SOURCE PHOSPHORUS CONTROL IN THE JAMES RIVER BASIN

Submitted to:

The Soap and Detergent Association
475 Park Avenue South at 32nd Street
New York, NY 10016

Attention: Dr. Keith A. Booman
Technical Director

Submitted by:
Wu-Seng Lung, PhD, PE
Assistant Professor

Report No. UVA/532533/CE85/101

January 1985

SCHOOL OF ENGINEERING AND APPLIED SCIENCE

DEPARTMENT OF CIVIL ENGINEERING

UNIVERSITY OF VIRGINIA
CHARLOTTESVILLE, VIRGINIA 22901

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EXECUTIVE SUMMARY AND CONCLUSIONS

A. Summary

Point source phosphorus control programs have been contemplated for the James River basin in recent years as part of the overall effort to control eutrophication in the Chesapeake Bay. The foremost question raised by any phosphorus control program is: what response, in terms of phytoplankton biomass levels, can be expected as a result of phosphorus control programs?

The present study attempts to put this question into perspective through an analysis of the most recent water quality data and through a series of mathematical modeling simulations designed to show trends in peak phytoplankton biomass levels in the upper James River Estuary as a function of alternative loading scenarios.

The technical effort of this study is therefore focused on several key areas related to the water quality assessment:

- evaluation of the most recent (1983) water quality data currently available on the James,
- quantification of limiting factor(s) on phytoplankton biomass in the upper James River Estuary,
- development of phosphorus reduction scenarios for simulation purposes in terms of various load reduction measures ranging from phosphate detergent bans to phosphorus removal at wastewater treatment plants, and
- use of an existing James River Estuary model, to analyze and present the results of simulations.

Each of these components of the study is directed therefore to providing additional information on the present status of eutrophication in the upper James River Estuary, as well as possible range of responses that might be expected under different scenarios of loading conditions. It should be stressed that the results presented herein are in no way intended to be allocations of phosphorus loads for individual point source discharges in the upper James River Estuary. Rather, the results are comparisons of phytoplankton biomass levels in the upper James River Estuary and are to be viewed as trends and ranges associated with various point source phosphorus control alternatives.

The first element of the study program, that of evaluating present water quality conditions of the upper James River Estuary, was completed through a detailed analysis of two sets of data collected in 1983, and a compilation of available data concerning municipal and industrial discharges direct to the upper James River Estuary. One of the principal results of this task is an understanding of the cause-and-effect relationship between nutrient loads and phytoplankton growth in the upper James River Estuary.

The second element of the study program was conducted through a quantitative analysis of the two data sets using the James River Model (JMSRV). The model calibration and sensitivity analysis identify the key limiting factor for phytoplankton growth in the upper James River Estuary being turbidity (or light).

The results from work element 3 are presented in Figure A where the phosphorus loads associated with various phosphorus control programs are summarized. Phosphate detergent bans are expected to reduce the point source loads from 15% to 25% while phosphorus removal reducing the

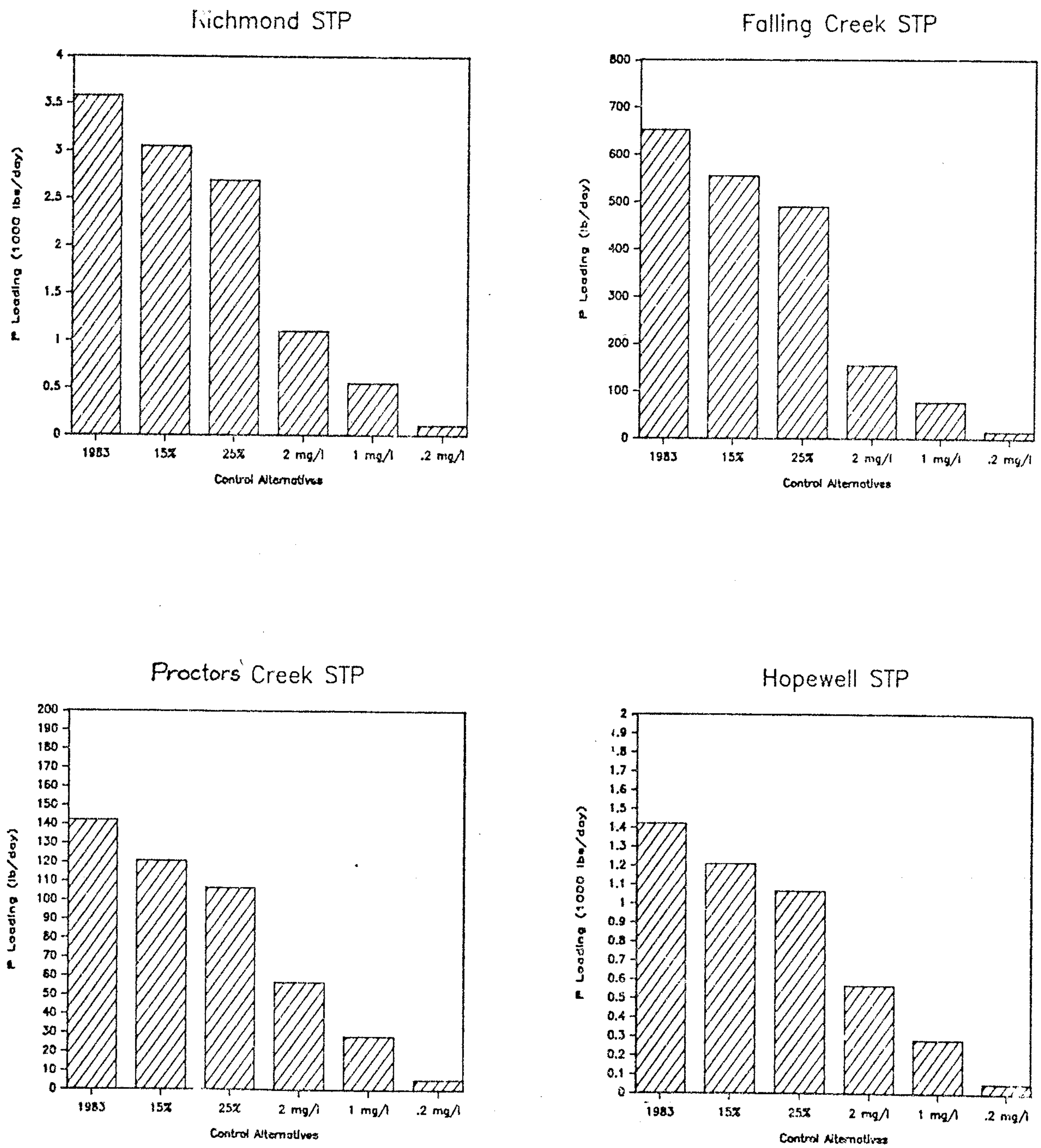


Figure A. POTW Phosphorus Loads to upper James River Estuary effluent concentrations to 2 mg/l, 1 mg/l, and .2 mg/l is expected to achieve load reductions of 63%, 81%, and 96%, respectively.

Figure B presents a summary of computed chlorophyll a concentrations, under the 7-day 10-year low flow conditions in the James River system, associated with various phosphorus control alternatives. The results show that there is some uncertainty that peak chlorophyll a levels will be maintained under the present and phosphate detergent ban scenarios. In general, the phosphate detergent bans would reduce the peak phytoplankton biomass up to 20%. Phosphorus removal at municipal wastewater treatment plants would reduce the peak chlorophyll a level by at least 50% if a phosphorus limit of 2 mg/l is applied. Further reduction in the peak chlorophyll a level may be achieved with effluent limits of 1 mg/l and 0.2 mg/l. If a chlorophyll a target level of 20 μg/l at the 7-day 10-year low flow was established, the 0.2 mg/l effluent limit might be necessary for the upper James River Estuary. However, the peak chlorophyll a level resulting from a 1 mg/l effluent limit would be close to 20 μg/l.

B. Conclusions

The following conclusions are presented, based on the modeling analysis and projection results presented in this study.

1. Phosphorus is not a key limiting factor for phytoplankton growth in the upper James River Estuary, based on the modeling analysis of the 1983 water quality data. Rather, light or turbidity is the major limiting factor. A similar finding was stated by Neilson and Ferry (1978) in an earlier study of the lower James River Estuary.

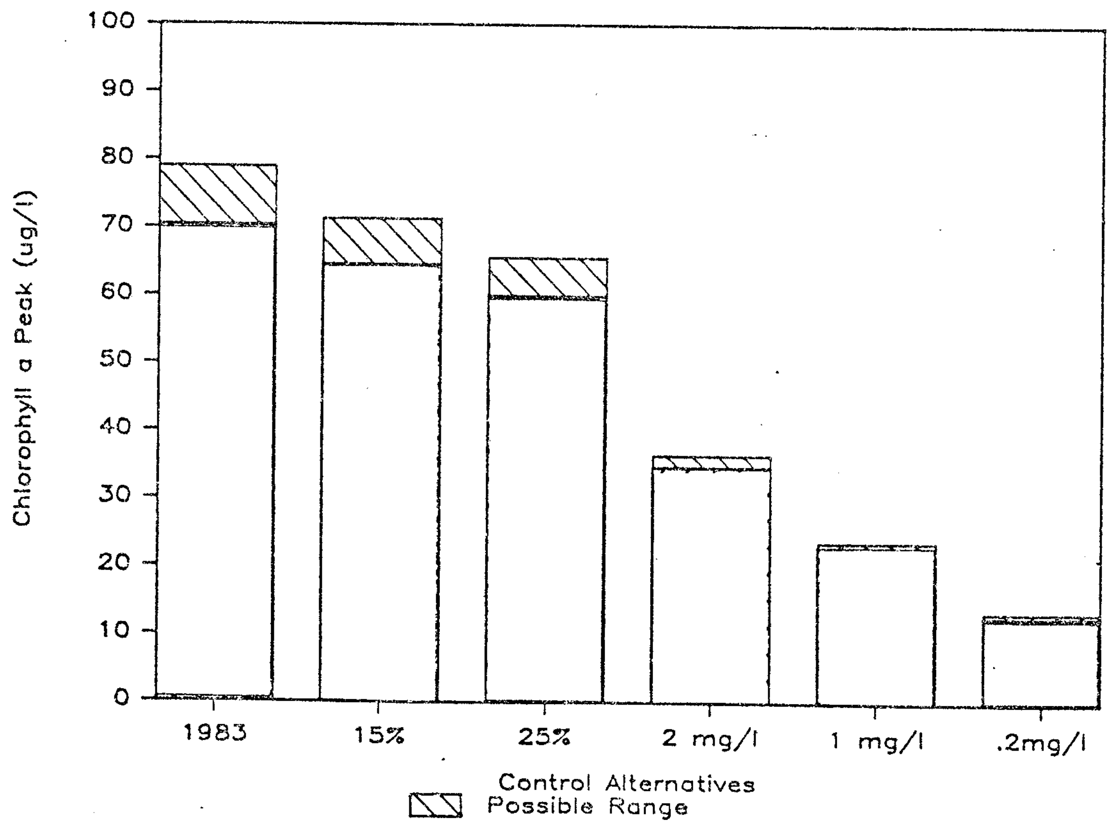


Figure B. Effect of Phosphorus Load Reduction

2. Under low flow conditions, phosphate detergent bans are expected to reduce the peak chlorophyll a levels in the upper James River Estuary from the existing 70-79 μg/l to 60-71 μg/l, still far greater than any acceptable levels (for example, 20 μg/l was once considered for the Potomac).

3. Phosphorus removal at municipal wastewater treatment plants offers further reduction of the chlorophyll a levels. An effluent limit of 0.2 mg/l is expected to achieve a peak chlorophyll a concentration about 13 μg/l.

4. Salinity effect on the reduction of growth rate or the increase in mortality rate of freshwater phytoplankton in the James needs to be investigated on a quantitative basis. Such an effect may have a significant bearing on the phytoplankton biomass under very low flows.

ASSESSING THE WATER QUALITY BENEFIT OF POINT SOURCE PHOSPHORUS CONTROL IN THE JAMES RIVER BASIN

1. Introduction and Purpose

Concerns on accelerated eutrophication in the Chesapeake Bay and its tributary estuaries have been widespread in recent years. One of the control alternatives being considered to reverse eutrophication is reduction of point source phosphorus loads (primarily from municipal wastewaters) to the Bay. At the present time, several major river basins in the Chesapeake Bay region have point source phosphorus control in the form of phosphorus removal at many publicly owned treatment works (POTWs). They include the lower Susquehanna, part of the Western Chesapeake area, the Patuxent and Potomac River basins.

The James River basin in Virginia contributes a significant amount of phosphorus loads to the Bay. Approximately 15% to 30% of the total phosphorus loads to the Bay, depending on the hydrologic conditions, is from the POTWs in the James River basin. One of the reasons that the James River basin contributes such a large portion of phosphorus loads is that none of the POTWs in the basin has phosphorus removal at the present time. In addition, there is no other form of nutrient control existing in the James River basin.

While point source phosphorus control in the basin will reduce the loads to the Bay, it is not clear how much the load reduction (from the James River basin) will impact the water quality of the James River Estuary and the Chesapeake Bay. That is a phosphorus control program may only reduce phosphorus concentrations but not necessarily the phytoplankton biomass in the James River Estuary. The phosphorus effect on phytoplankton, therefore, is a marked contrast to other types of water quality problems where reductions in input load (as in BOD reduction) can generally be considered as being advantageous.

A key question regarding phosphorus control programs for the James River is whether phosphorus is the limiting factor for phytoplankton growth. The present assessment attempts to address this question with mathematical modeling of phytoplankton growth in the upper James River Estuary. The modeling effort, therefore, focuses on the following technical areas:

- quantifying phosphorus limitation effect, if any, on phytoplankton growth in the upper James River Estuary,
- quantifying growth limitation by other factors such as light and salinity, and
- determining the impact of point source phosphorus load reduction on phytoplankton biomass levels in the upper James River Estuary.

To carry out these technical tasks, the study employed an existing water quality model of the upper James River Estuary to assess the water quality impact. The recent water quality data collected in the James during the summer of 1983 were used to calibrate the model. The calibrated model was then used to project the water quality impact of various point source phosphorus control alternatives.

2. Approach and Methodology

2.1 James River Estuary model (JMSRV)

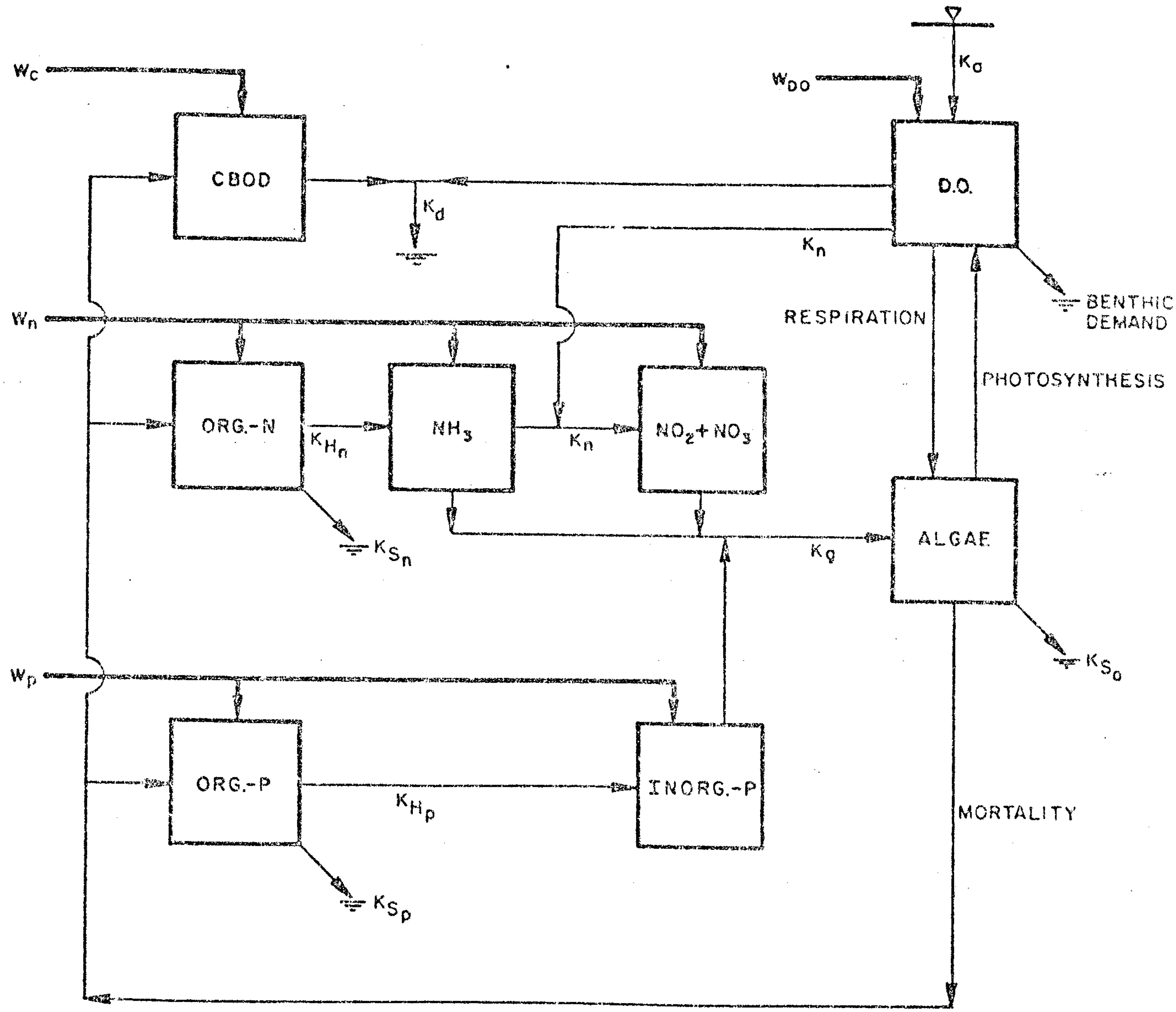
The James River Estuary model (JMSRV), which was developed by Hydroscience, Inc. (1980) for the Virginia State Water Control Board (SWCB), was used in this modeling study. The model is a modified version of an earlier water quality model developed by Virginia

Institute of Marine Science (VIMS). The model was originally intended for use in wasteload allocations (WLA) of BOD loads to meet the dissolved oxygen standard in the James. The kinetic structure of the model is shown in Figure 1. In addition to the BOD/DO kinetics, phytoplankton biomass/nutrient dynamics is also incorporated in the model. As such, the model can be used, in a first-cut analysis, to assess the eutrophication potential and the impact of phosphorus load reduction.

The model was first installed on the University of Virginia's Control Data Corporation (CDC) mainframe computer systems. Recently, it was transferred to microcomputer systems (IBM PC and COMPAQ). The current version is a 50-segment one-dimensional tidally averaged model. Figure 2 shows the model segmentation. With a 8087 math co-processor installed on the COMPAQ computer, the model can be run very efficiently. In fact, each steady-state model run (120-day time variable run to steady-state condition) requires only 11 minutes of total turn-around time (including printing the output). Specially designed software for a Hewlett Packard (HP) personal computer plotter was used to process and present the model results in graphical form.

2.2 Modeling Methodology

The JMSRV model was originally calibrated and verified using the data collected in 1976 and 1978 (Hydroscience, 1980). Although the water quality problem of concern at that time was dissolved oxygen and the emphasis of the modeling analysis was on the verification of BOD and DO concentrations, the modeling analysis also calibrated the kinetic coefficients of phytoplankton/nutrient dynamics in the upper James River Estuary. In this study, these coefficient values were first used in the



W_{DO} = DISSOLVED OXYGEN OF WASTEWATER
W_c = CBOD WASTE LOADS
W_n = NITROGEN WASTE LOADS
W_p = PHOSPHORUS WASTE LOADS
K_a = DISSOLVED OXYGEN REAERATION
K_d = DEOXYGENATION COEFFICIENT
K_n = NITRIFICATION COEFFICIENT
K_{H_n} = HYDROLYSIS RATE OF ORGANIC NITROGEN
K_{H_p} = CONVERSION RATE OF ORGANIC PHOSPHORUS
K_g = GROWTH COEFFICIENT FOR PHYTOPLANKTON
K_{S_a} = SETTLING RATE FOR PHYTOPLANKTON
K_{S_n} = SETTLING RATE FOR ORGANIC NITROGEN
K_{S_p} = SETTLING RATE FOR ORGANIC PHOSPHORUS

Figure 1. James River Model (JMSRV) Kinetics
(from Hydroscience, 1980)

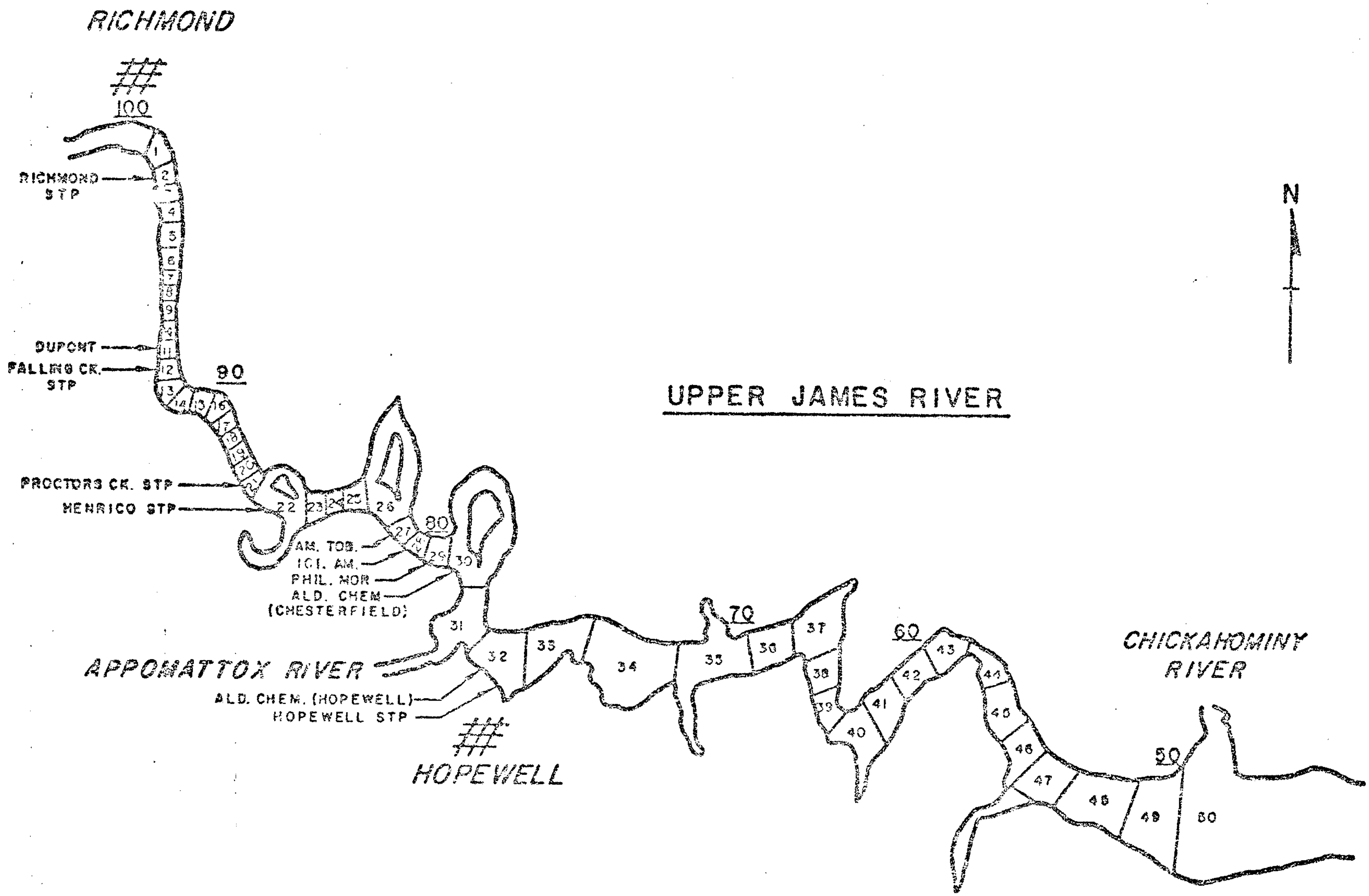


Figure 2. James River Model (JMSRV) Segmentation

(from Hydroscience, 1980)

preliminary model calibration with the most recent data available. Such a model calibration effort is necessary to update the model for changes, if any, in model coefficients (e.g., boundary conditions, loading rates, etc.) and to understand the estuarine system under existing conditions.

The water quality data collected by the Richmond Regional Planning District Commission (RRPDC) in 1983 under the James River Water Quality Monitoring Program (Grizzard and Weand, 1984) were used in this modeling study. Under that monitoring program, seven slack water surveys were performed from July to October, 1983 (Table 1). The receiving water quality data, river flow data, and the associated point source monitoring records were utilized in this study.

Table 1. Slack Water Surveys of the James River Estuary in 1983

Date	Combined Flow near Richmond (cfs)*	Stage Condition
July 28	2380	LWS
August 16	1660	HWS
August 30	1100	LWS
September 20	1140	HWS
September 27	1253	LWS
October 3	1734	HWS
October 12	1071	LWS

* Sum of the flows in the James River near Richmond (USGS Gage 02037500) and in the James River and Kanawha Canal (USGS Gage 02037000). The Canal was closed in 1982 and remained closed until September 21, 1983 for pipeline installation. Thus, during the first 4 surveys, the Canal flow was practically zero (USGS, 1984a, b).

The summer of 1983 was characterized by a prolonged period of warm temperature and low flow. The data collected, therefore, represent the conditions close to critical conditions in the estuary. As indicated in Table 1, the July 28 (low water slack) survey was characterized by the highest freshwater flow among the seven surveys while the September 20 (high water slack) survey was conducted under a relatively lower flow. [Figure 3 shows the combined flow in the James near Richmond, based on the U.S. Geological Survey (USGS) records, during the summer of 1983.] The JMSRV model was used to analyze these two sets of data. In addition, model sensitivity analyses were performed to fine tune the model and to identify the key processes in phytoplankton growth in the upper James River Estuary.

The calibrated model was then used to predict phosphorus and phytoplankton chlorophyll a levels in the upper James River Estuary under various point source phosphorus control alternatives such as phosphate detergent bans and stringent effluent phosphorus limits (2 mg/l, 1 mg/l, and 0.2 mg/l) for POTWs. The projection analysis was based upon a flow condition specified as the 7-day 10-year low flow in the James River system as many receiving water quality standards are written for such a condition. This term is defined as the lowest average flow that occurs for a consecutive 7-day period at a recurrence interval of 10 years.

3. Data Review and Analysis

3.1 September 20, 1983 Survey

On September 20, 1983, the Piedmont Regional Office of the State Water Control Board conducted a water quality survey of the upper James River Estuary. Sample collection was timed to coincide with low slack at each station. Dissolved oxygen and temperature measurements were taken at each station. The following laboratory and field measurements were performed on these samples: total Kjeldahl, ammonia, nitrite plus nitrate and nitrate nitrogen; total and ortho phosphorus;

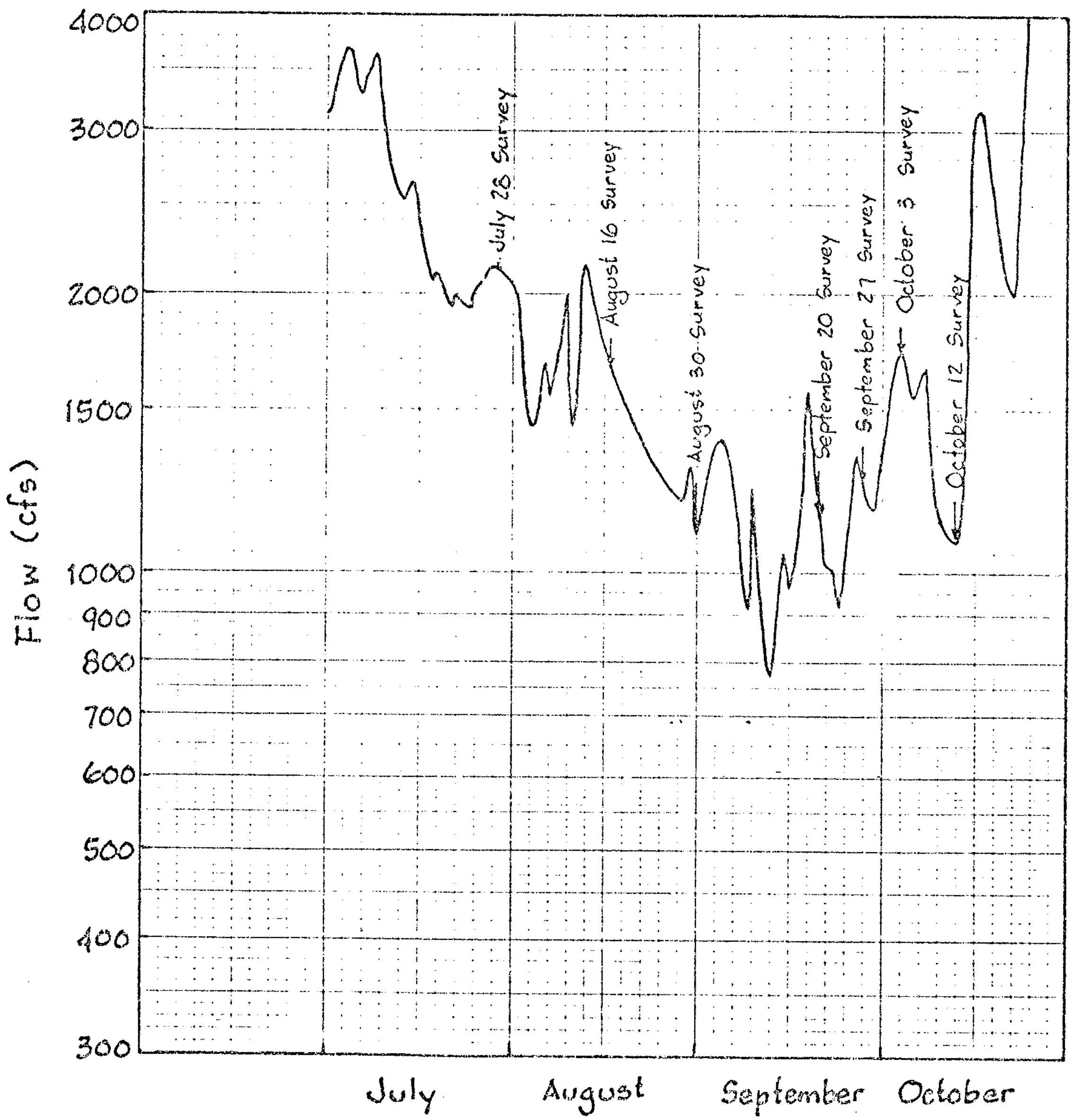


Figure 3. Combined Flow of James River near Richmond, 1983
(USGS Data)

chlorophyll a; long term BOD (40 day series, with and without nitrification suppressant); and pH, alkalinity and conductivity (Grizzard and Weand, 1984).

Wastewater monitoring was conducted at major POTWs and industrial dischargers in conjunction with the receiving water survey. Twenty-four hour composite samples were collected and analyzed for the parameters listed above except for chlorophyll. The wastewater loads associated with this survey are summarized in Table 2.

Table 2. Major Wastewater Loadings (lbs/day) for September 20, 1983 Survey

Discharger	$CBOD_{40}$	Org. N	NH_3	NO_2+NO_3	Total P	Org. P	Inorg. P
Richmond	4512.3	4927.5	3916.7	2332.9	2328.4	144.4	2184.0
DuPont	202.8	230.9	38.9	9.6	5.6	2.8	2.8
Falling Creek	714.7	336.0	116.1	745.2	502.1	111.2	390.9
Proctors Creek	2602.0	208.5	103.4	33.8	179.3	25.2	154.2
Reynolds Metals	1.8	3.9	0.0	2.1	2.3	2.2	0.2
Am. Tobacco	60.8	27.2	1.0	31.2	6.8	0.7	6.2
ICI	31.9	8.0	0.7	4.8	1.4	1.4	0.0
Philip Morris	368.4	27.0	6.7	267.7	106.2	39.4	66.8
Allied-Chester	2480.3	42.9	3.1	61.2	9.2	6.1	3.1
Allied-Hopewell	12680.9	3363.8	2069.0	2349.3	80.1	66.7	13.4
Hopewell	8929.1	7048.3	5904.6	326.8	347.7	205.2	142.5

The results of the receiving water survey are presented in Figure 4. A general assessment of the water quality condition observed during the September 20, 1983 survey is presented below.

- Carbonaceous Biochemical Oxygen Demand (CBOD)

Since these samples contained the concentrations of phytoplankton found in the river, the results reflect two components of oxygen demand. The first is the demand created by oxidation of organic

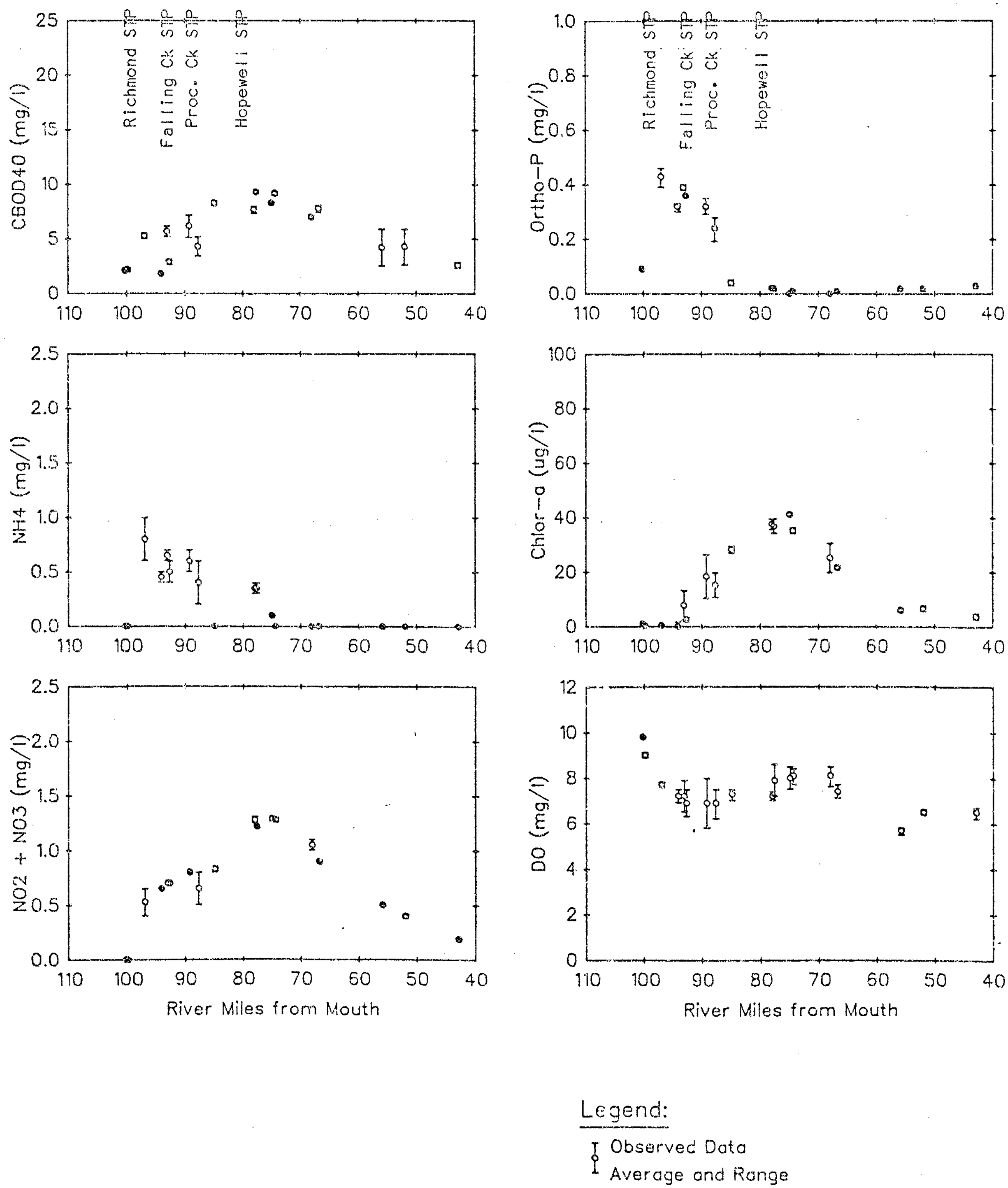


Figure 4. Water Quality of upper James River Estuary (9-20-83)

waste material and the second is the combined demand created by the respiration of living algae and oxidation of dead algae contained in the sample. The significant increase in measured $CBOD_{40}$ between river miles* 70 and 90 is primarily due to the large algae component of oxygen demand in samples taken in this area. This observation is later confirmed by the model results.

- Nitrogen Series

The incremental increase in ammonia nitrogen below Richmond was due to the ammonia discharge from point sources (Richmond wastewater treatment plant and other POTWs as well as industrial facilities). However, the increase did not sustain beyond river mile 90 probably because of nitrification and phytoplankton uptake. Note that the phytoplankton chlorophyll a increased starting this river reach. The slight increase in nitrite plus nitrate gives some indication that both nitrification and algae uptake may be occurring in this area (i.e., between river miles 70 and 90). Both processes (nitrification and algae uptake) will be analyzed quantitatively in model sensitivity analysis.

- Phosphorus

The ortho-phosphorus profile in Figure 4 resembles the ammonia profile closely, suggesting that the marked increase in concentration was due to wastewater discharges from point sources and the sharp decrease in concentration was due to algae uptake (coinciding with

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* The river mile system used in this modeling study and in the figures throughout this report is adopted from the one used in the Hydroscience (1980) report. Note that this system is different from the one used by Grizzard and Weand (1984) in the river between Richmond and Hopewell. The Hydroscience system was determined by tracing the cutoffs whereas the other system was established by tracing around Turkey Island, Curles Neck and Hatchers Island (Bandura and Das, 1984).

the rise of phytoplankton chlorophyll a). The lowest levels of orthophosphorus are about 0.01 mg/l as P which is much higher than the Michaelis-Menton constant (0.001 mg/l) to significantly limit algae growth.

- Phytoplankton Chlorophyll a

Chlorophyll a measurements indicate a rapid growth of phytoplankton above Hopewell followed by a peak immediately below the junction with the Appomattox River (see this trend in Figure 4). The Appomattox River contributed a significant amount of freshwater phytoplankton biomass and may be partially responsible for the chlorophyll a peak in the James (Grizzard and Weand, 1984). The subsequent decline of the phytoplankton biomass was due to significant light limitation below Hopewell (Hydroscience, 1980). In addition, mean channel depths, in general, increase below Hopewell, creating a condition unfavorable for algal growth. Thus, the increase in mean depth and reduction of light penetration may be responsible for the decline of phytoplankton biomass (Hydroscience, 1980). A recent study at Old Dominion University (Filardo, 1984) also suggests that salinity intrusion could increase the mortality of freshwater algae in the James.

- Dissolved Oxygen

The dissolved oxygen profile (Figure 4) exhibits a moderate depression below Richmond followed by a slight increase due to algal photosynthesis in the area (note the diurnal variation reflected in the range of the data) where phytoplankton biomass increases. Below Hopewell, the dissolved oxygen levels decrease again primarily because of the municipal (Hopewell STP) and various industrial wastewater discharges. The dissolved oxygen levels remained above 5 mg/l throughout the River sampled. In general, the dissolved oxygen profile for this survey reflects the existence of a healthy biological environment and the presence of moderate amounts of oxidizable materials.

3.2 July 28, 1983 Survey

The water quality conditions observed in this survey (Figure 5) resembled the conditions observed in the September 20 survey. The freshwater flow, however, was higher in July than in September. As such, the nutrient concentrations (NH_3, NO_2 + NO_3, and ortho-P) were slightly lower in July than in September (resulting in more pronounced peaks of concentrations of NH_3, NO_2 + NO_2, and ortho-P under low flows). The peak of phytoplankton chlorophyll a moved slightly downstream in July than in September, reflecting higher freshwater flows. The dissolved oxygen profile in July indicates less severe depressions below Richmond and below Hopewell when compared with the September profile, resulting from shorter detention time created in the system by higher freshwater flows in July.

Table 3 presents the point source loads from major POTWs and industrial dischargers measured in the July 28 survey. These loading rates are relatively close to those measured in the September 20 survey (see Table 2).

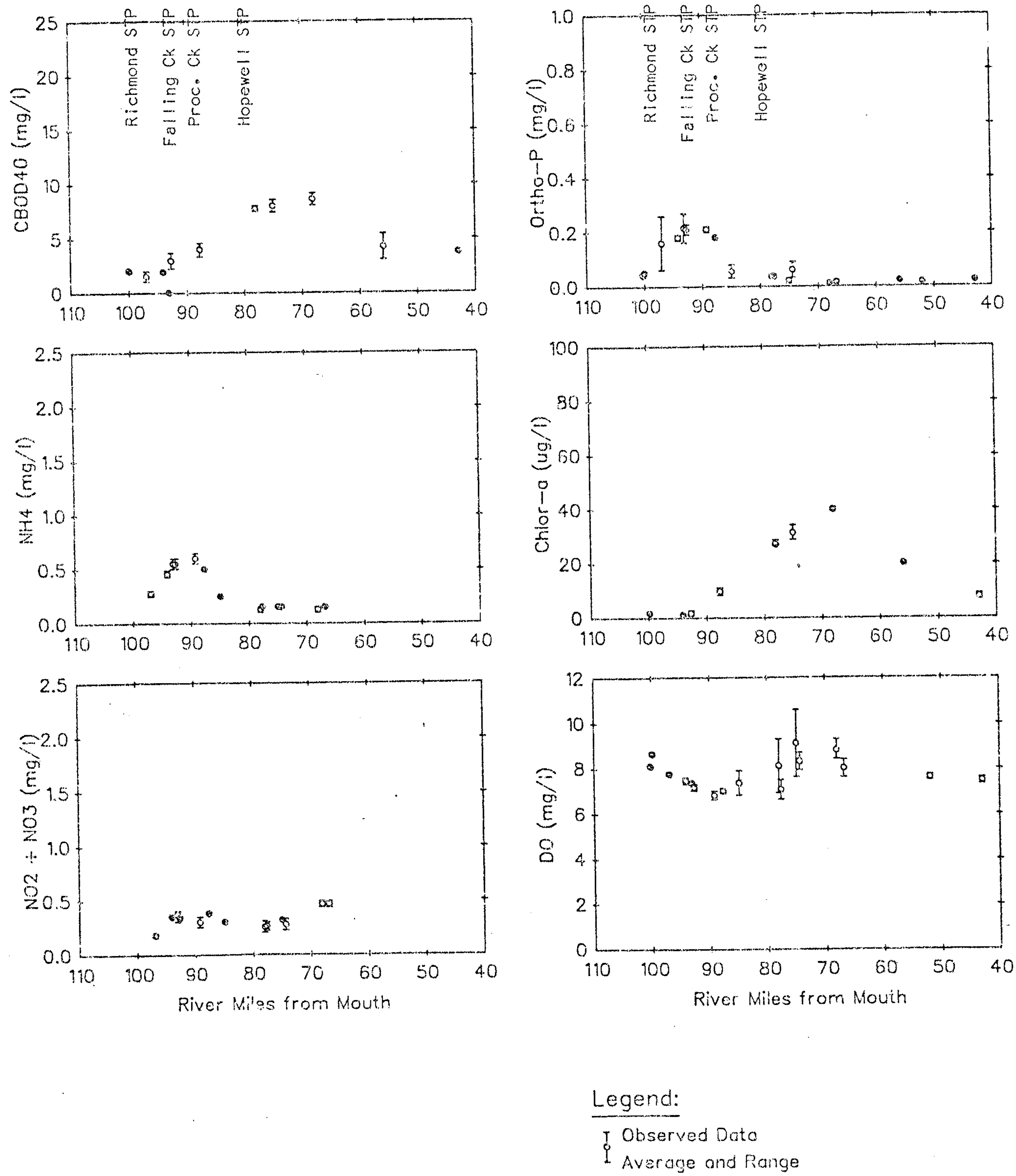


Figure 5. Water Quality of upper James River Estuary (7-28-83)

Table 3. Major Wastewater Loadings (lbs/day) for July 28, 1983 Survey

Discharger	$CBOD_{40}$	Org. N	NH_3	NO_2+NO_3	Total P	Org. P	Inorg. P
Richmond	5642.1	1282.7	3216.5	1379.2	2314.7	144.7	2170.0
DuPont	427.5	217.3	0.0	63.1	12.6	6.3	6.3
Falling Creek	1067.2	398.0	328.8	311.5	461.5	109.6	351.9
Proctors Creek	312.5	312.5	45.3	36.2	156.2	64.3	91.9
Reynolds Metals	3.3	0.7	0.0	0.9	0.6	0.4	0.2
Am. Tobacco	16.3	60.1	14.3	3.1	40.3	17.6	22.7
ICI	17.9	8.0	0.6	4.6	1.4	1.4	0.0
Philip Morris	485.7	26.7	8.8	351.4	140.0	52.0	88.0
Allied-Chester	3859.1	46.5	3.6	35.7	0.0	0.0	0.0
Allied-Hopewell	16502.0	1163.3	1055.1	1514.9	60.9	47.3	13.5
Hopewell	10347.6	5046.9	6989.5	429.5	322.1	119.1	203.0

4. Preliminary Model Calibration

4.1 Model Results for September 1983 Condition

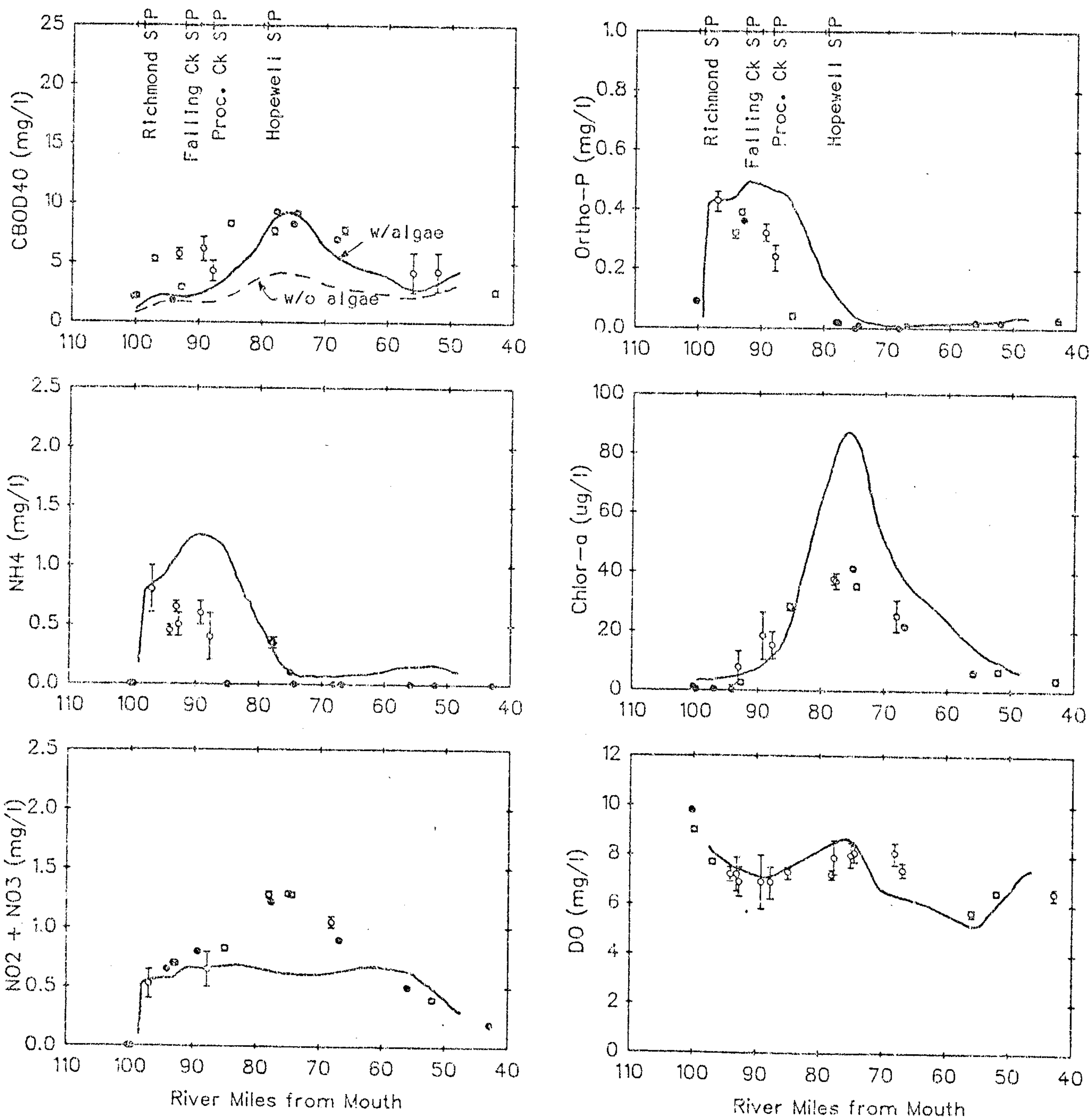
The JMSRV model was incorporated with the hydrologic and environmental conditions of the James River associated with the September 20 survey. The point source loads ($CBOD_{40}$, organic nitrogen, NH_3, NO_2 + NO_3, organic phosphorus, and ortho-phosphorus) shown in Table 2 were also incorporated into the model. The kinetic coefficients and other model coefficients which were calibrated for the September, 1978 conditions (Hydroscience, 1980) were used.

The modeling analysis assumes that the estuarine system is under an intertidal steady-state condition. In reality, however, a steady-state condition rarely exists, nor does a steady dry weather river flow (see Figure 3). In fact, the flow fluctuated widely on a day-to-day basis. To better approximate a steady water quality condition observed on September 20, it is necessary to use an average river flow over a period of at least 7 to 10 days prior to the survey. An average flow of 1100 cfs was used to best represent the flow near Richmond.

The results of the preliminary calibration using the September data are summarized in Figure 6 for $CBOD_{40}$, NH_3, $NO_2 + NO_3$, ortho-P, chlorophyll _a_, and dissolved oxygen. The calculated ultimate CBOD ($CBOD_u$) concentrations are compared with the observed 40-day CBOD ($CBOD_{40}$) data. The long term BOD analysis indicates complete decay of the organic materials in the river samples by 40 days. Thus, the measured $CBOD_{40}$ values closely represent the ultimate CBOD and can be compared with the calculated $CBOD_u$ without serious errors.

Figure 6 indicates that the preliminary model calibration results reproduce the observed trends of the water quality parameters. The addition of CBOD recycled from phytoplankton biomass (the CBOD curve labeled as 'with algae') matches the observed data reasonably well. Note that the CBOD curve without algae is consistently below the observed data. Thus, it is important to include the oxygen demand of decayed phytoplankton biomass in the area where phytoplankton growth is significant.

However, there are discrepancies between data and model calculations for some parameters. The model overestimates the ammonia nitrogen levels and accordingly underestimates the nitrite plus nitrate concentrations in the estuary. Similarly, the calculated ortho phosphorus concentrations are slightly higher than the observed data. In addition, the calculated phytoplankton chlorophyll _a_ peak (about 85 μg/l) based on a saturated growth rate of 3.0/day (Hydroscience, 1980) is significantly higher than the data.



Freshwater Flow near Richmond: 1100 cfs
Water Temperature: 26°C

Legend:
Observed Data
Average and Range
— Model Results

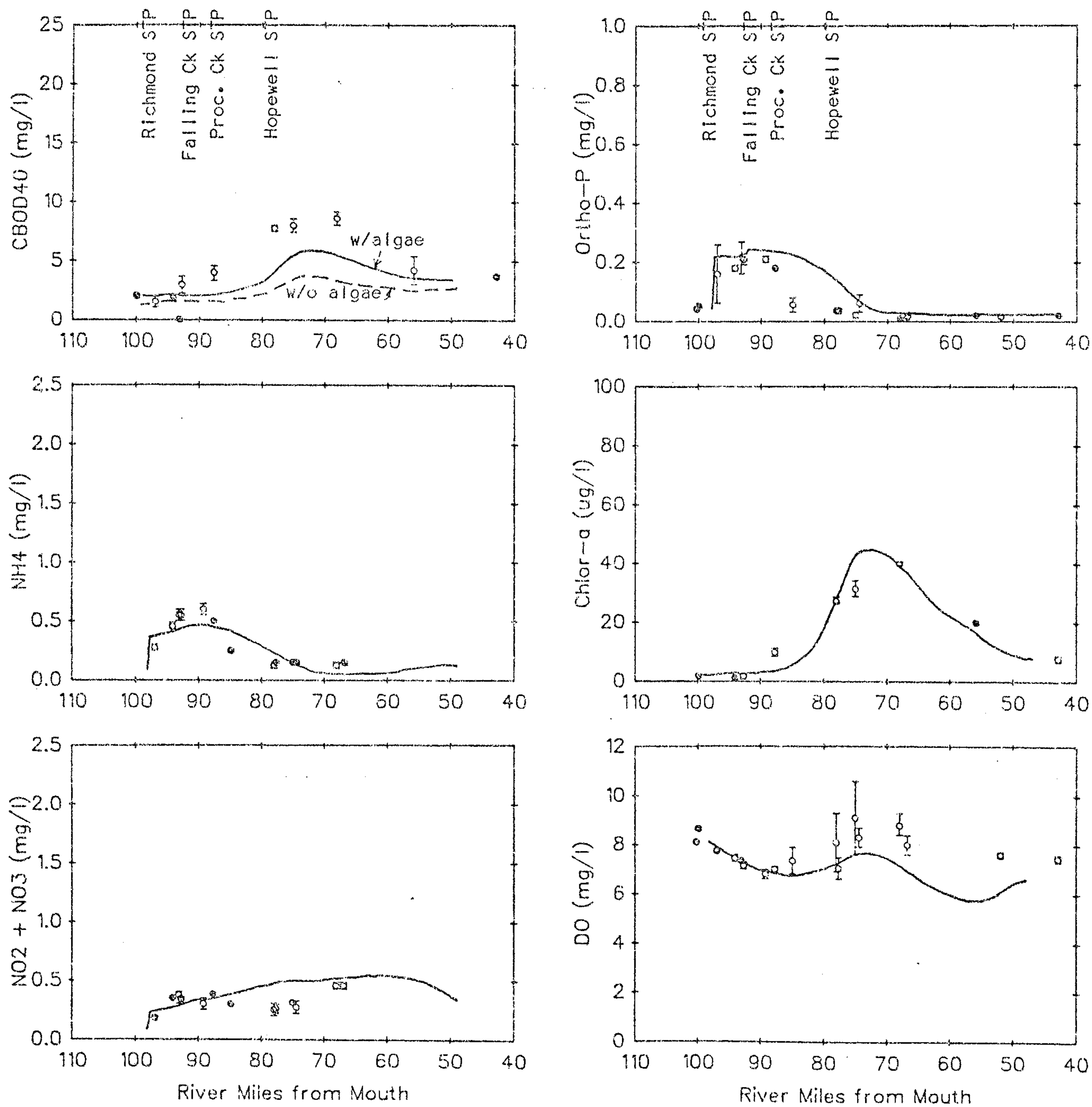
Figure 6. Preliminary Model Calibration Results (9-20-83)

Note that the maximum difference between the observed and calculated nitrite plus nitrate concentrations is about 0.7 mg/l which is much greater than the equivalent difference between the observed and calculated chlorophyll _a_ concentrations, based on the biomass stoichiometry. This result suggests that some nitrogen is missing or certain degree of nitrification is occurring in the area between river miles 100 and 79. [The original modeling analysis by Hydroscience does not include nitrification between river miles 100 and 79.] That is, should the model prediction on chlorophyll _a_ concentrations match the observed peak (say, 40 µg/l), the calculated peak of $NO_2 + NO_3$ concentrations would be about 0.9 mg/l, a level far below the observed peak of $NO_2 + NO_2$ concentrations.

4.2 Model Results for July 1983 Condition

The JMSRV model was also applied to analyze the July 28, 1983 data set. Specific hydrologic (combined flow near Richmond = 2,200 cfs averaged over a week prior to the survey) and environmental conditions were incorporated along with the point source loads (Table 3) into the model. The model kinetic coefficients and other stoichiometry constants developed by Hydroscience for the July 1976 condition were used in this calibration analysis.

The results of the preliminary calibration are summarized in Figure 7. The model calculations match the observed data reasonably well. Note that the relatively higher flow in July slightly reduces the nutrient concentrations while compared with the September concentrations. However, the chlorophyll _a_ levels remain about the same between the two surveys. Further, the results do not suggest nitrification in the river immediately below Richmond for the July condition. Based on the kinetic coefficients developed by Hydroscience (1980), the model does not



Freshwater Flow near Richmond: 2200 cfs
Water Temperature: 28°C

Legend:
Observed Data Average and Range
Model Results

Figure 7. Preliminary Model Calibration Results (7-28-83)

indicate nutrient limitation on algal growth. Instead, light limitation is the cause for the decline of phytoplankton biomass in the lower estuary.

5. Model Sensitivity Analysis

The use of the model coefficient values originally developed by Hydroscience (1980) did not generate results which fit the data (September survey) completely as discussed in the preceding section. In addition, the modeling analysis has indicated some technical aspects which need further investigation. They include nitrification rate and phytoplankton growth rate. The sensitivity analysis was designed to vary these coefficients to reproduce the data and, therefore, would enable us to better understand the phytoplankton growth mechanisms. The final product of the sensitivity analysis is a fine tuned model which would reproduce the two data sets using a consistent set of model coefficients. The September survey data were used in the sensitivity analysis.

5.1 Nitrification

The model assumed no nitrification in the James River from Richmond to Hopewell (the first 30 model segments) according to Hydroscience (1980). Downstream from Hopewell, a nitrification rate of 0.15/day was used. There are, however, widespread discussions on whether nitrification is occurring in the James between Richmond and Hopewell. Nitrifying bacteria data collected in 1983 (Grizzard and Weand, 1984) could not provide a firm answer. Additional field studies to quantify the growth potential of nitrifiers are underway but their results are not available at the present time.

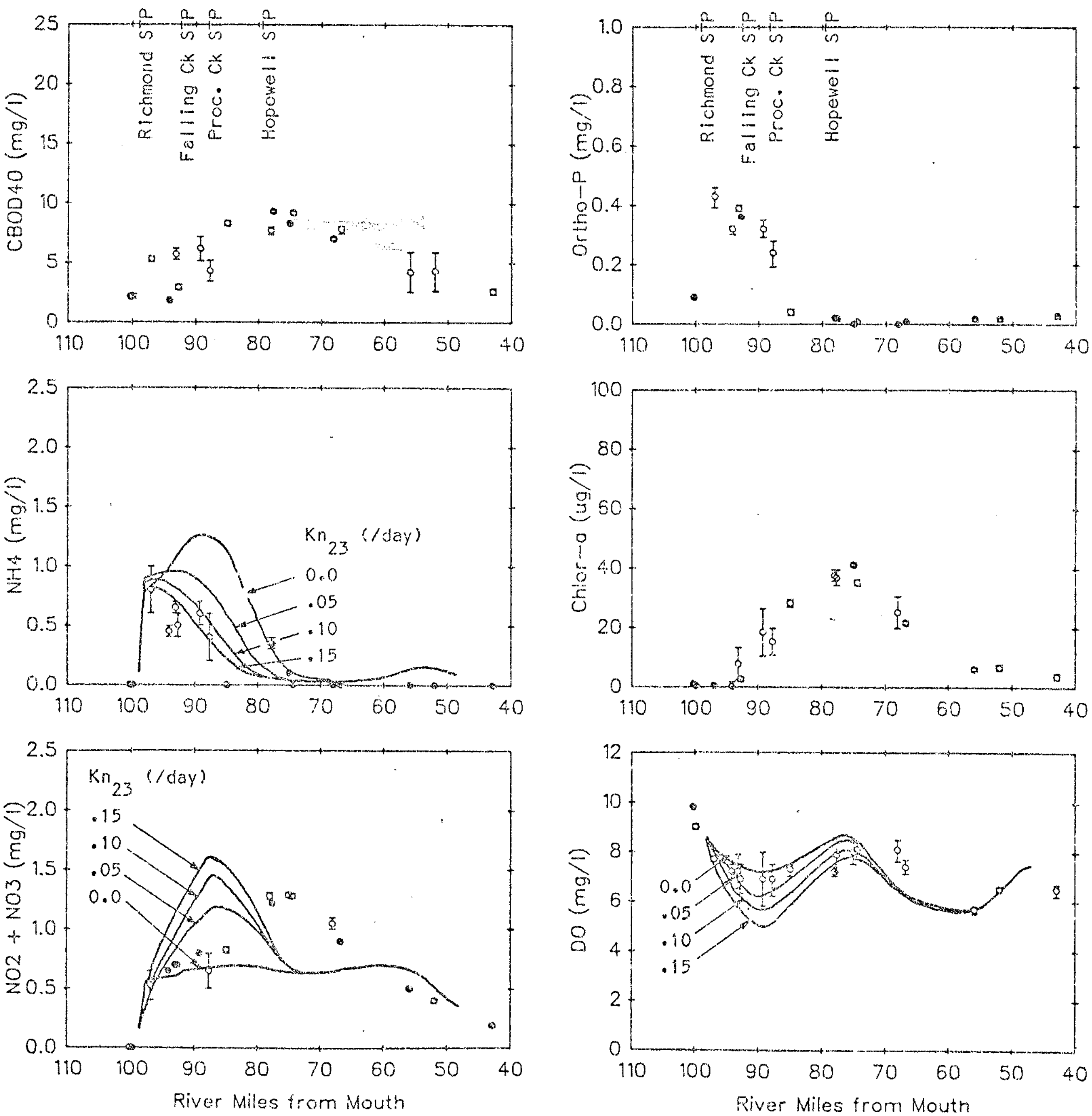
The results from our preliminary modeling analysis of the September 1983 data implies some degree of nitrification based on nitrogen balance in the James. Thus, a number of nitrification rates ranging from 0.05/day to 0.15/day were incorporated into the model for segments 1-30 (from Richmond to Hopewell). The results of the sensitivity analysis are presented in Figure 8. The nitrification rate of 0.05/day (at 20°C) gives the best fit to the data among the rates tested, considering the reproduction of the NH_3, $NO_2 + NO_3$, and DO data.

5.2 Phytoplankton Growth Rate

Based on the modified nitrification pattern, the model was then tested with different growth rates of phytoplankton ranging from 2.0/day to 3.0/day in order to improve the model calculation of chlorophyll a concentrations. The results are shown in Figure 9. At a lower algal growth rate of 2.2/day, nitrogen is shifted from the phytoplankton biomass to $NO_2 + NO_3$, resulting in lower chlorophyll a level and slightly lower dissolved oxygen concentrations in the area between river miles 70 and 90. On the other hand, a growth rate of 3.0/day produces a chlorophyll a peak about 85 μg/l. A growth rate of 2.2/day seems to produce a close fit of the September data (Figure 9).

5.3 Salinity Effect on Freshwater Phytoplankton Biomass

There is a general consensus that in the low salinity waters, riverborne phytoplankters, which are advected into the higher salinity waters, exhibit a characteristic decrease in biomass (Morris et al., 1978, 1982; Sharp et al., 1982; Pennock, 1983). One of the hypothesis that has been suggested to account for the decline in biomass in the James River Estuary is the following: The freshwater halophobic phytoplankters cannot withstand the osmotic changes that are presented in a



Freshwater Flow near Richmond: 1100 cfs
Water Temperature: 26°C

Legend:
Observed Data
Average and Range
Model Results

Figure 8. Model Sensitivity Results — Nitrification

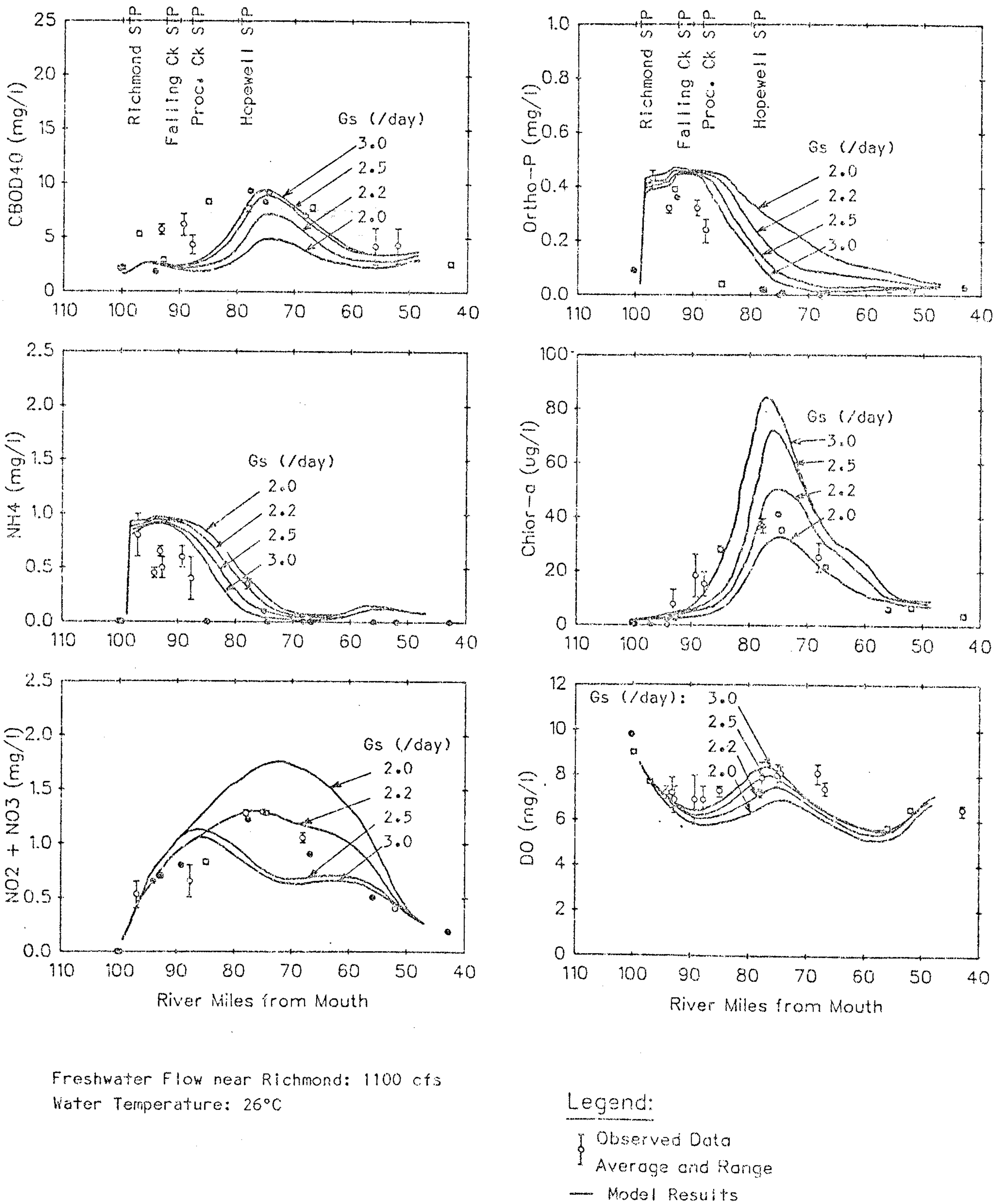


Figure 9. Model Sensitivity Results — Phytoplankton Growth Rate

narrow band of salinity, say, between 0‰ to 2‰ (Filardo, 1984). The laboratory and field studies conducted by Filardo on the James have confirmed that biomass along the 0-2‰ salinity area decreases during certain periods of the year.

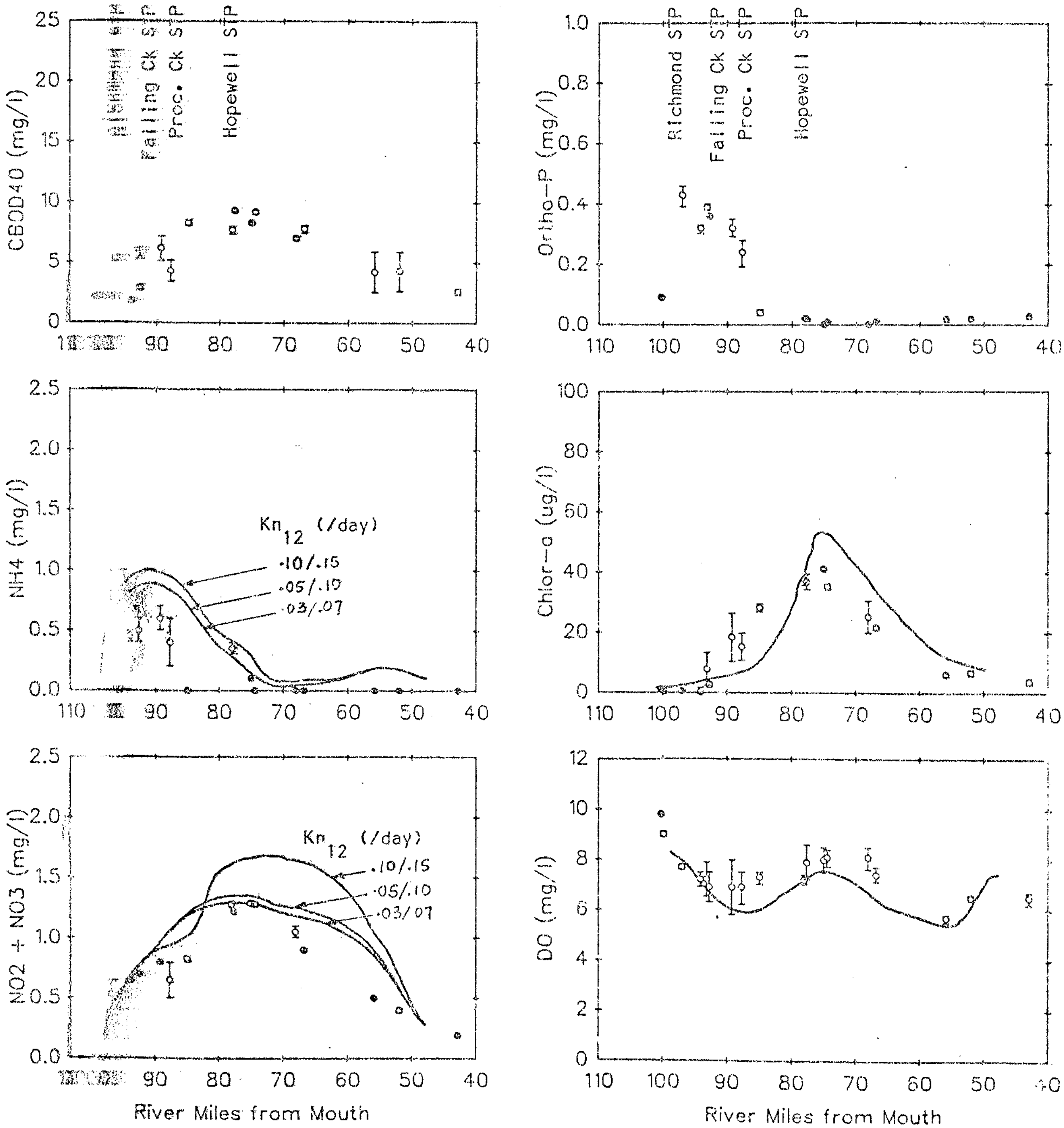
The study conducted by Filardo provides a qualitative explanation of phytoplankton biomass reduction but does not supply data to quantify the reduction in growth rate or increase in mortality rate. Further, a close examination of the conductivity measurements in the upper James River Estuary in 1983 indicates that freshwater condition existed in the area where the peak of chlorophyll a occurred. Thus, it is not expected that salinity intrusion significantly affected phytoplankton growth and the associated peak levels of biomass in the upper James River Estuary in the summer of 1983.

5.4 Nutrient Hydrolysis

Slightly lower hydrolysis rates for organic nitrogen and organic phosphorus than the rates presented by Hydroscience (1983) seem to match the ammonia nitrogen and orthophosphorus data better (see Figure 10). These lower rates are within the reported ranges of literature values.

5.5 Nutrient Uptake by Aquatic Weeds

Hydroscience (1980) suggested that the losses of ammonia nitrogen and ortho-phosphorus between river miles 90 and 80 may be due to inorganic nutrient uptake by rooted aquatic weeds in the marshes and oxbows in this stretch of river. Since no data is available to confirm this hypothesis, an empirical approach is taken in this analysis to incorporate a loss rate of ortho-phosphorus (0.5 ft/day) into the model. Such a loss rate may include not only the uptake by aquatic weeds, but



Freshwater Flow near Richmond: 1100 cfs
Water Temperature: 26°C

Legend:
Observed Data
Average and Range
— Model Results

Figure 10. Model Sensitivity Results -- Nutrient Hydrolysis Rate

also some other mechanisms such as phosphorus adsorption by sediments. Figure 11 shows that incorporating such a loss rate brings the calculated ortho-phosphorus concentrations closer to the data.

5.6 Discussions

The JMSRV model is now calibrated reasonably well (Figures 7 and 12) with a consistent set of model coefficients using two data sets from 1983. The model coefficients are summarized in Tables 4 and 5 for the September and July surveys, respectively. The only difference between Table 4 and Table 5 is the saturated growth rate of phytoplankton (2.2/day for the September condition and 2.0/day for the July condition). Additional insights into the estuarine system can be summarized from the model calibration and sensitivity analysis results. First, the location of the phytoplankton biomass peak moves up and down the estuary with the freshwater flow. Between the two water quality surveys, the July condition (associated with a freshwater of 2200 cfs in Richmond) produced a phytoplankton biomass peak near river mile 70. On the other hand, the lower freshwater flow of 1100 cfs in the September survey moved the peak upestuary to river mile 75.

The question of nutrient limitation can be further explored from the model results. Figure 13 shows the degrees of nutrient limitation (nitrogen and phosphorus) on phytoplankton growth in July and September, 1983. Both nitrogen and phosphorus are not limiting the growth rate as the Michaelis-Menton limitation ratios are close to 1.0 (no reduction in growth rate).

Further, light appears to be a major factor in reducing the growth rate. Figure 14 shows the light extinction coefficients used in the model which are justified by the values derived from the measured

Table 4. James River Model Parameters
September 1983 Calibration

Kinetics Coefficients (Base e @ 20°C)

Oxyger Transfer	ft/day	3.00
Deoxygenation	1/day	0.10
Nitrification	1/day	0.05 (Segments 1-30) 0.15 (Segments 31-50)
Hydrolysis - N	1/day	0.10 (Segments 1-30) 0.15 (Segments 31-50)
- P	1/day	0.05 (Segments 1-30) 0.10 (Segments 31-50)
Setting - N	ft/day	0.75
- P	ft/day	0.75
- Chl 'a'	ft/day	0.75
Growth	1/day	2.20
Respiration	1/day	0.10
Death	1/day	0.10
Extinc. Coef.	1/meter	1.4 (Segments 1-10) 2.0 (Segments 11-31) 2.3 (Segment 32) 3.0 (Segments 5-6)
Hrs. of Daylight	hrs	12.0
Benthic Demand	gm/m^2-day	0.5 (Segments 1-30) 1.5 (Segments 31-50)

Stoichiometry & Constants

Temperature	°C	26.0
C/CHL Ratio	mg/µg	0.025
N/CHL Ratio	mg/µg	0.007
P/CHL Ratio	mg/µg	0.001
O_2/C Ratio	mg/mg	2.67
Half. Sat.		
Conc. - N	mg/l	0.005
-P	mg/l	0.001
Sat. Light	langleys/day	300.
Avail. Light	langleys/day	600.

Table 4. James River Model Parameters
September 1983 Calibration

Kinetics Coefficients (Base e @ 20°C)

Oxygen Transfer	ft/day	3.00
Deoxygenation	1/day	0.10
Nitrification	1/day	0.05 (Segments 1-30) 0.15 (Segments 31-50)
Hydrolysis - N	1/day	0.10 (Segments 1-30) 0.15 (Segments 31-50)
- P	1/day	0.05 (Segments 1-30) 0.10 (Segments 31-50)
Setting - N	ft/day	0.75
- P	ft/day	0.75
- Chl 'a'	ft/day	0.75
Growth	1/day	2.20
Respiration	1/day	0.10
Death	1/day	0.10
Extinc. Coef.	1/meter	1.4 (Segments 1-10) 2.0 (Segments 11-31) 2.3 (Segment 32) 3.0 (Segments 5-6)
Hrs. of Daylight	hrs	12.0
Benthic Demand	gm/m^2-day	0.5 (Segments 1-30) 1.5 (Segments 31-50)

Stoichiometry & Constants

Temperature	°C	26.0
C/CHL Ratio	mg/µg	0.025
N/CHL Ratio	mg/µg	0.007
P/CHL Ratio	mg/µg	0.001
O_2/C Ratio	mg/mg	2.67
Half. Sat.		
Conc. - N	mg/l	0.005
-P	mg/l	0.001
Sat. Light	langleys/day	300.
Avail. Light	langleys/day	600.

Table 5. James River Model Parameters
July 1983 Calibration

Kinetics Coefficients (Base e @ 20°C)

Oxygen Transfer	ft/day	3.00
Deoxygenation	1/day	0.10
Nitrification	1/day	{0.00 (Segments 1-30) 0.15 (Segments 31-50)
Hydrolysis - N	1/day	{0.10 (Segments 1-30) 0.15 (Segments 31-50)
- P	1/day	{0.05 (Segments 1-30) 0.10 (Segments 31-50)
Setting - N	ft/day	0.75
- P	ft/day	0.75
- Chl 'a'	ft/day	0.75
Growth	1/day	2.00
Respiration	1/day	0.10
Death	1/day	0.10
Extinc. Coef.	1/meter	1.4 (Segments 1-10) 2.0 (Segments 11-31) 2.3 (Segment 32) 3.0 (Segments 33-50)
Hours. of Daylight	hrs	14.5
Benthic Demand	gm/m^2-day	0.5 (Segments 1-30) 1.5 (Segments 31-50)

Stoichiometry & Constants

Temperature	°C	27.0
C/CHL Ratio	mg/µg	0.025
N/CHL Ratio	mg/µg	0.007
P/CHL Ratio	mg/µg	0.001
O_2/C Ratio	mg/mg	2.67
Half. Sat. Conc. - N	mg/l	0.005
- P	mg/l	0.001
Sat. Light	langleys/day	300.
Avail. Light	langleys/day	450.

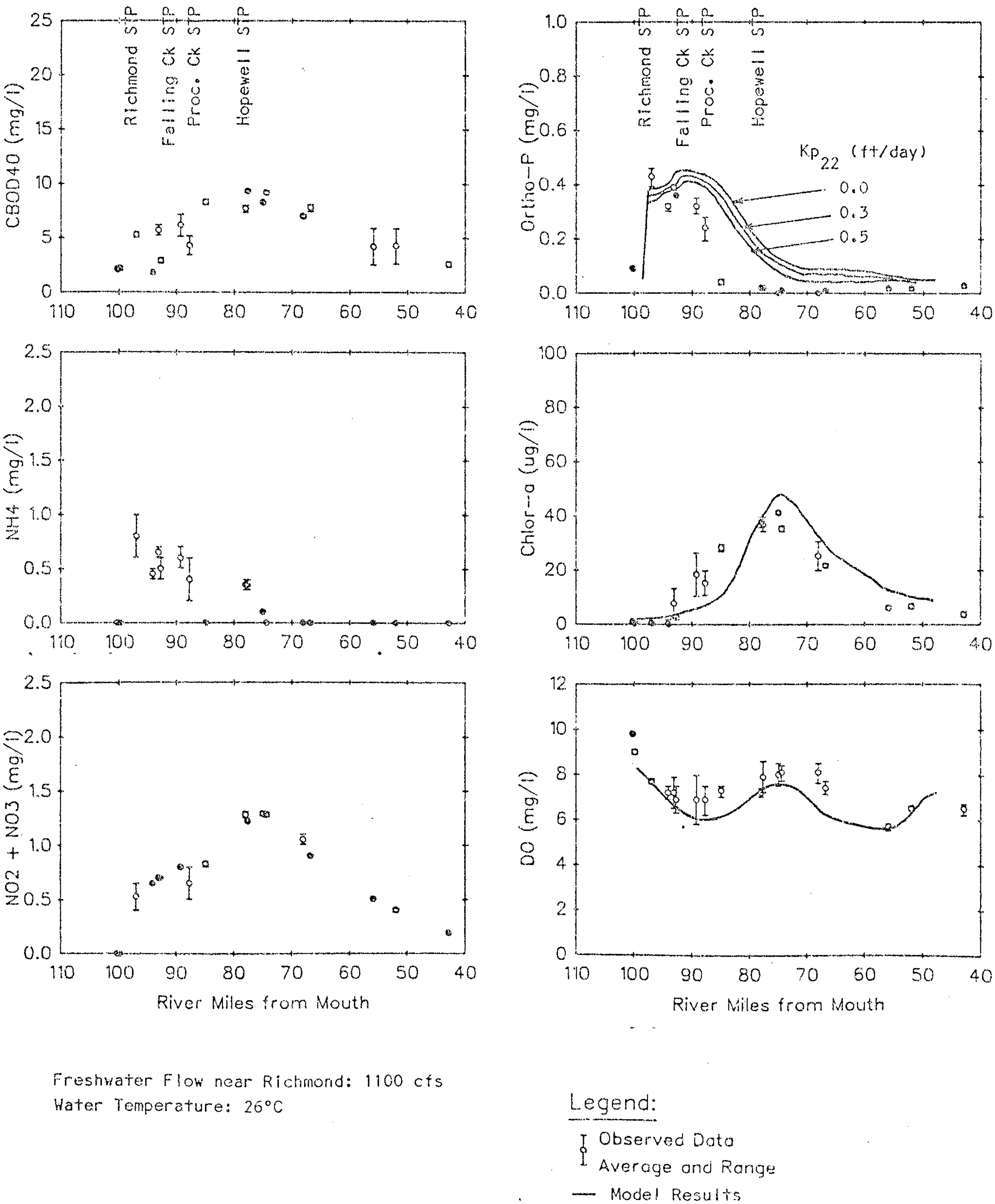
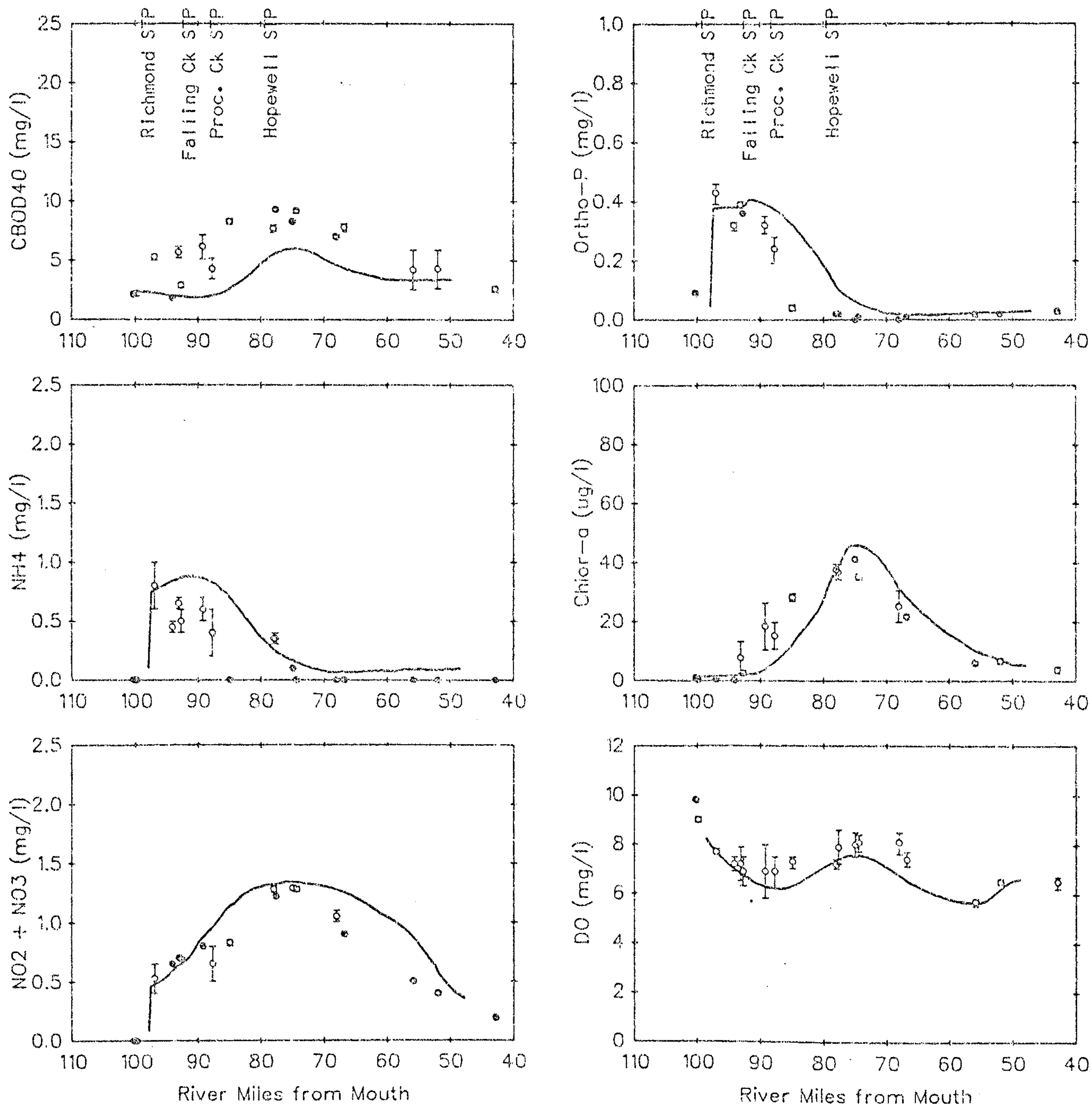


Figure 11. Model Sensitivity Results — Nutrient Uptake by Weeds



Freshwater Flow near Richmond: 1100 cfs
Water Temperature: 26°C

Legend:
Observed Data
Average and Range
Model Results

Figure 12. Model Calibration of September 20 Survey

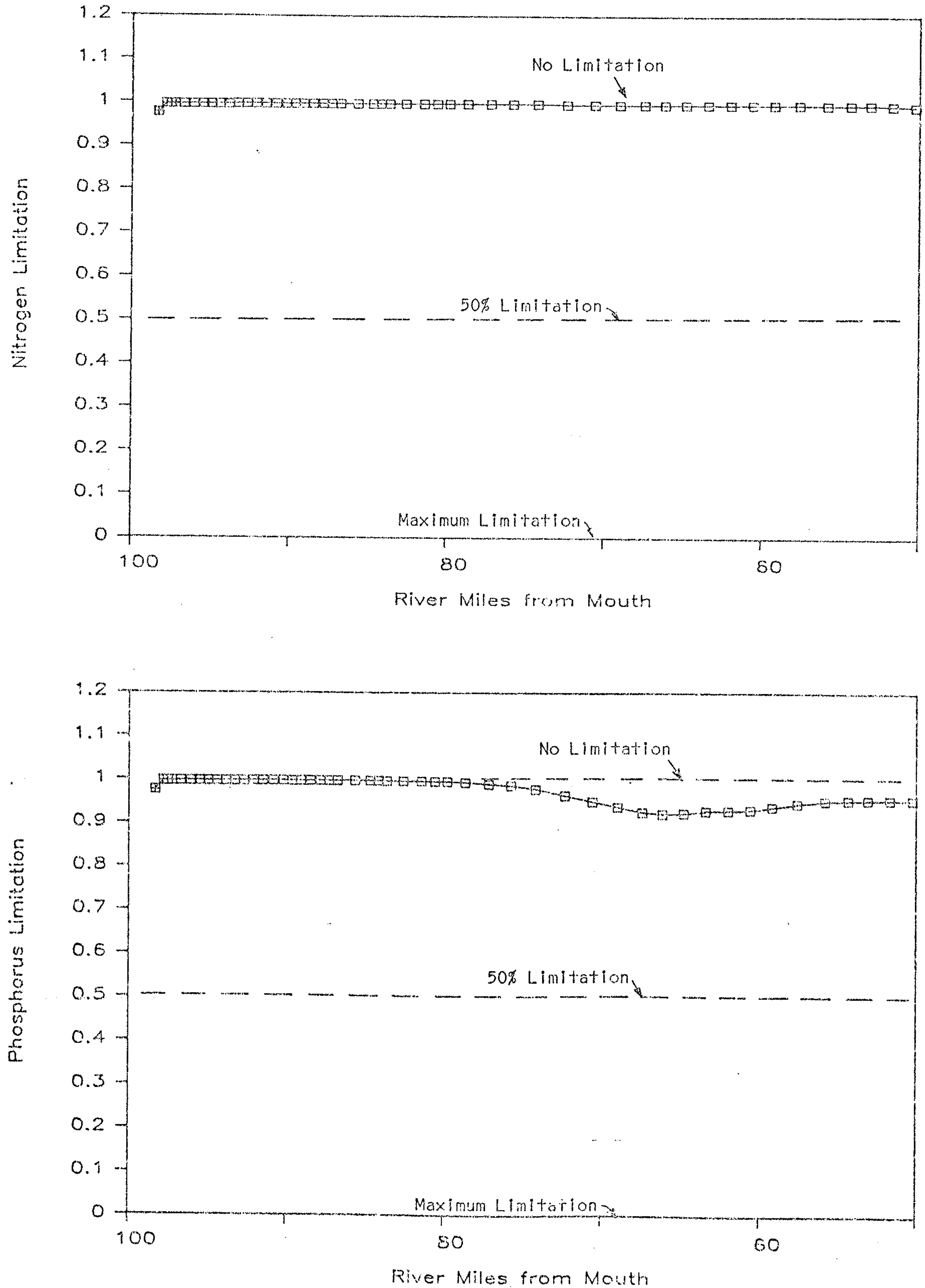


Figure 13. Degree of Nutrient Limitation

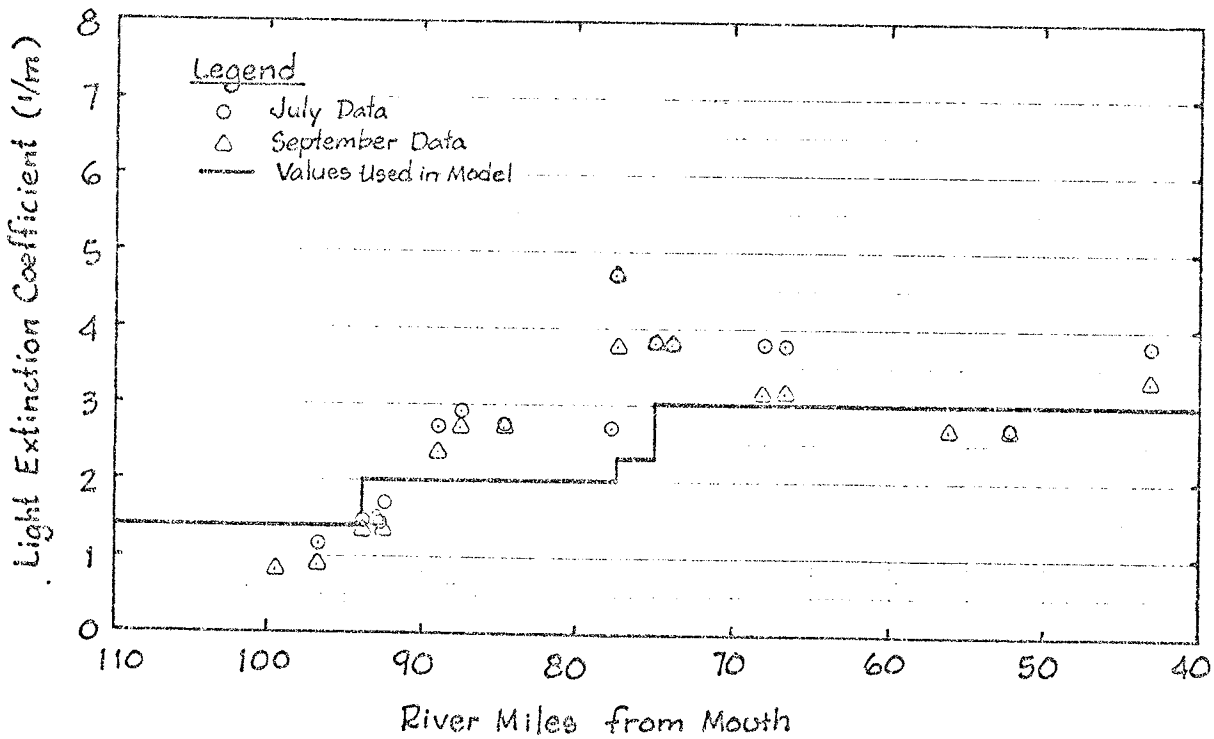


Figure 14. Light Extinction Coefficients in upper James River Estuary

Secchi depths in July and September, 1983. Figure 15 shows that the specific growth rates of phytoplankton (/day) are significantly reduced in the turbid water along the estuary in September, 1983. In an earlier study on the lower James River Estuary, Neilson and Ferry (1973) suggested that factors (other than nutrients), such as turbidity, mixing, and zooplankton grazing, are likely to control phytoplankton growth.

6. Projection Analysis

6.1 Phosphorus Load Reductions

A number of phosphorus control alternatives for the POTWs in the James River basin are evaluated using the calibrated model. They include phosphate detergent bans, phosphorus removal to produce effluents with total phosphorus concentrations of 2 mg/l, 1 mg/l, and 0.2 mg/l at POTWs. The control alternatives and their associated total phosphorus loads at major POTWs in the James River basin are presented in Table 6. Phosphate detergent bans would have a range of load reduction from 15% to 25%. Out of the 21 major POTWs in Table 6, only 4 (Richmond, Falling Creek, Proctors Creek, and Hopewell) are direct dischargers into the James within the model boundaries. Others are in the upper basin above the fall line or in the lower estuary near the Chesapeake Bay. Between the POTWs and industrial facilities, the POTW loads dominate the phosphorus input to the James (see Tables 2 and 3).

6.2 Model Projections

The model projection runs were conducted at the 7-day 10-year low flow condition. The 7-day 10-year low flow in Richmond is 680 cfs (Engineering-Science Co., 1974). A high water temperature of 28°C was incorporated into the model. All other model parameters and coefficients were kept the same as those used in the model calibration

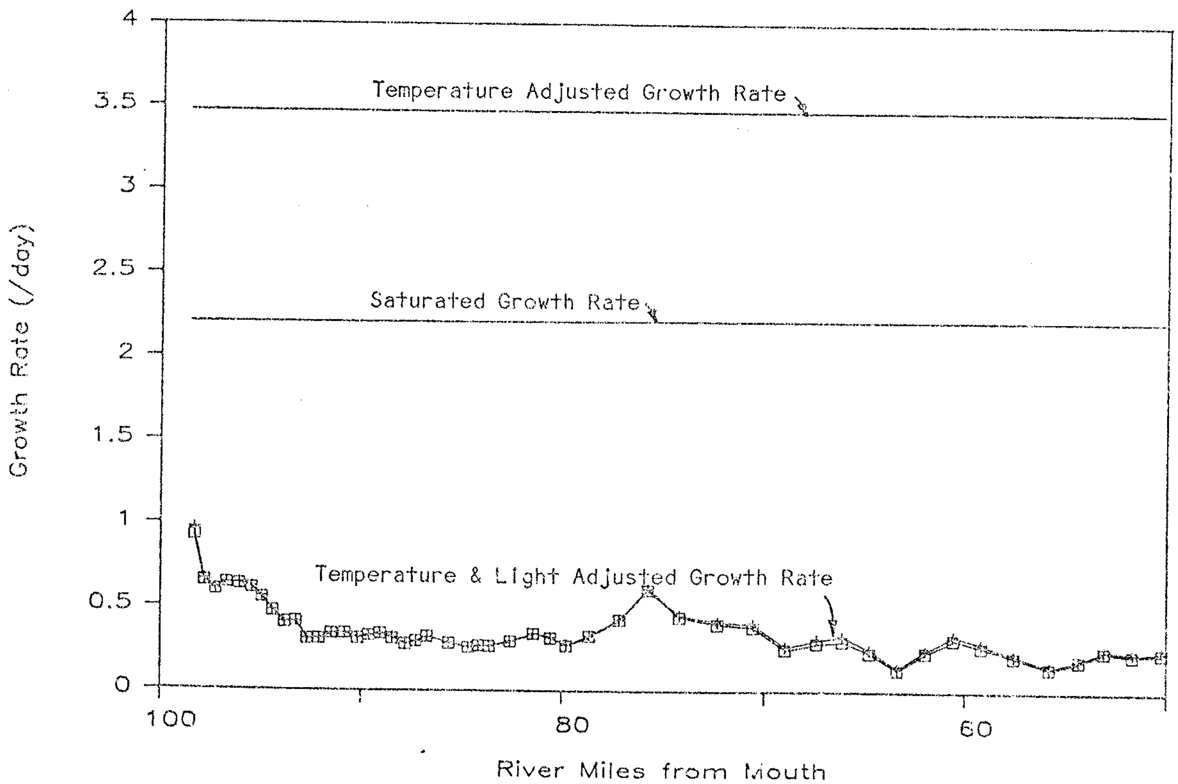


Figure 15. Specific Growth Rate of Phytoplankton

analysis. The model was run for 6 different phosphorus loading levels: the 1983 average (considered as existing) loads, the phosphate detergent ban loads (15% and 25% load reduction from the 1983 loads), and the phosphorus loads associated with effluent phosphorus limits of 2 mg/l, 1 mg/l, and 0.2 mg/l. Two sets of simulations with phytoplankton growth rates of 2.2 mg/l and 2.0 mg/l were conducted.

Table 6. Phosphorus Loads from Major POTWs in the James River Basin in Terms of Various Control Measures

Facility	1983 Flow(mgd)	Avg Load (lb/day) 1983	P Bans	2 mg/l	1 mg/l	.2 mg/l
Above Fall Line						
Buena Vista	1.85	77.1	65.6/57.9	30.9	15.4	3.1
Clifton Forge	1.42	59.2	50.3/44.4	23.7	11.8	2.4
Covington	1.73	72.1	61.3/54.1	28.9	14.4	2.9
Farmville	0.31	12.9	11.0/9.7	5.2	2.6	0.5
Lexington	1.03	43.0	36.5/32.2	17.2	8.6	1 7
Lynchburg	13.04	543.8	462.2/407.8	217.5	108.8	21.8
Moores Creek	9.80	408.7	347.4/306.5	163.5	81.7	16.4
Petersburg	10.38	692.4	588.7/519.4	173.1	86.6	17.3
Upper Estuary						
Falling Creek	9.32	652.9	555.0/489.7	155.5	77.7	15 6
Hopewell	34.16	1424.5	1211.0/1068	569.8	284.9	57.0
Proctors Creek	3.42	142.6	121.2/107.0	57.0	28.5	5.7
Richmond	66.2	3588.7	3053.0/2694	1104.2	552.1	110.4
Lower Estuary						
Army Base	13.89	538.7	457.6/404.3	231.7	115.8	23.2
Boat Harbor	18.21	770.1	654.6/577.1	303.7	151.9	30.4
Chesapeake	21.39	1081.1	918.7/811.7	356.8	178.4	35.7
Ft. Eustis	1.56	65.1	55.3/48.8	26.0	13.0	2.6
James River	14.72	669.1	568.4/502.1	245.5	122.8	24.6
Lamperts Point	23.86	523.4	445.7/392.0	398.0	199.0	39.8
Nansemond	5.22	312.6	265.6/234.7	87.1	43.5	8.7
Pinners Point	9.06	468.5	398.2/351.4	151.1	75.6	15.1
Williamsburg	8.18	122.8	104.4/92.1	122.8	68.2	12.3
Total	268.9	12269	10432/9205	4414	2241	441
		Load Reduction	15%/25%	63%	81%	96%

The results of the model projections are summarized and presented in Figure 16. The ortho-phosphorus and chlorophyll *a* concentrations are shown for each simulation scenario. The peak levels of chlorophyll *a* under the 1983 average (existing) loading rates at the POTWs range from 70 µg/l to 79 µg/l, depending on the algal growth rates. Phosphate detergent bans would reduce the chlorophyll *a* peak to a range between 60 µg/l and 71 µg/l, depending on the rate of load reduction (25% or 15% reduction from 1983 loads). Note that the effect of algal growth rate difference becomes less pronounced in the calculated chlorophyll *a* concentrations at reduced phosphorus levels. If phosphorus removal is practiced at the POTWs, the chlorophyll *a* levels would decrease more significantly to about 36 µg/l and 25 µg/l under phosphorus limits of 2 mg/l and 1 mg/l, respectively. The orthophosphorus levels in the upper James River Estuary would be reduced substantially from the existing levels and the sign of phosphorus limiting (ortho-phosphorus concentrations lowered to about 0.001 mg/l between river miles 75 and 70) starts to show. Further reduction of the POTW effluent phosphorus concentration to 0.2 mg/l would generate a peak chlorophyll *a* level about 13 µg/l.

Figure 17 presents the synthesized results in a bar chart showing the projected chlorophyll *a* peaks associated with all scenarios. Phosphate detergent bans would provide at most a 20% reduction in chlorophyll *a* peak levels from the existing conditions. Phosphorus removal at POTWs would reduce the peak chlorophyll *a* level by about 50% with an effluent phosphorus limit of 2 mg/l. The 0.2 mg/l phosphorus limit is considered the lowest effluent limit currently written in many NPDES permits for the POTWs in the Chesapeake Bay region, with the

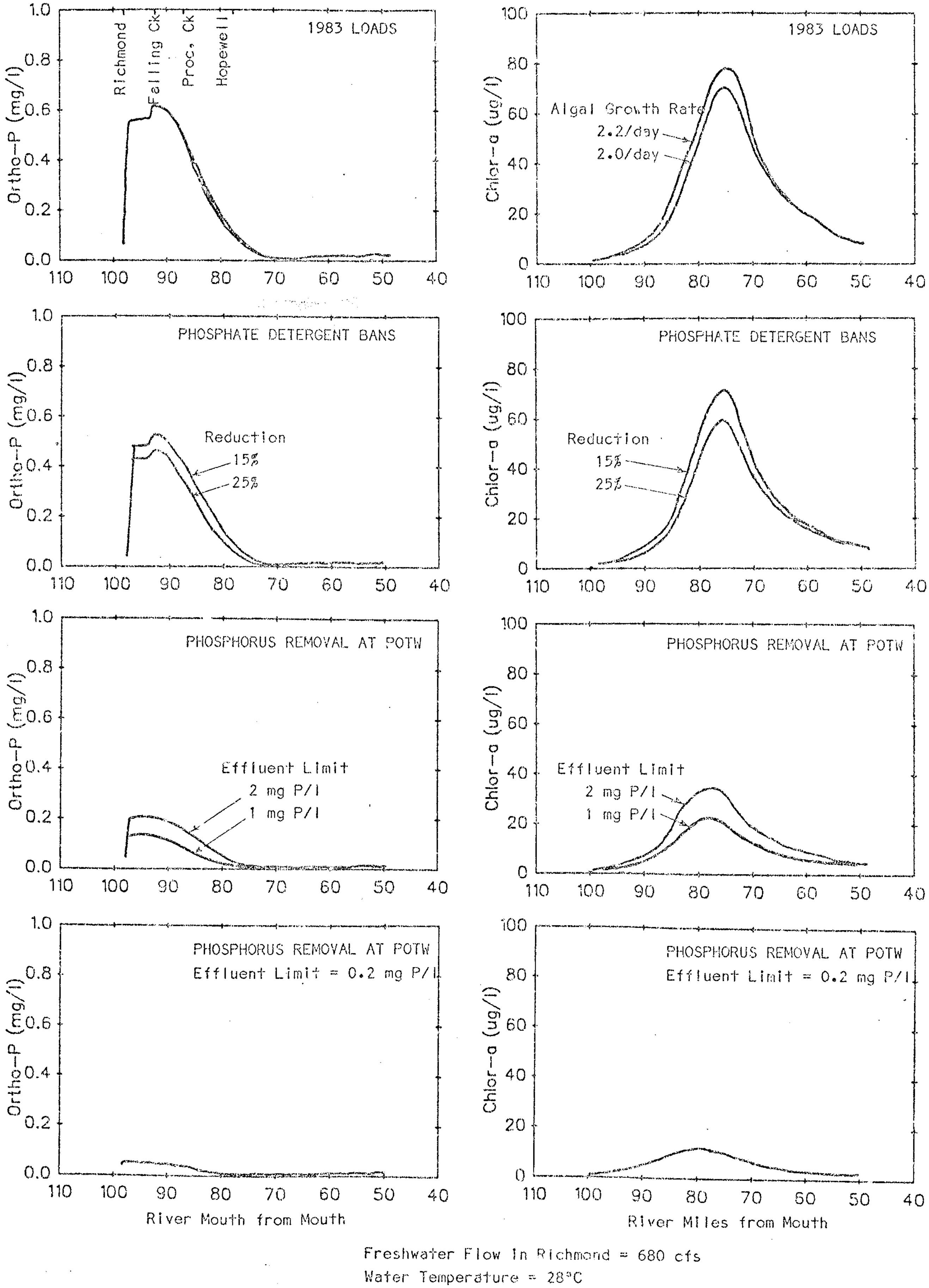


Figure 16. Model Projections at 7-Day 10-Year Low Flow

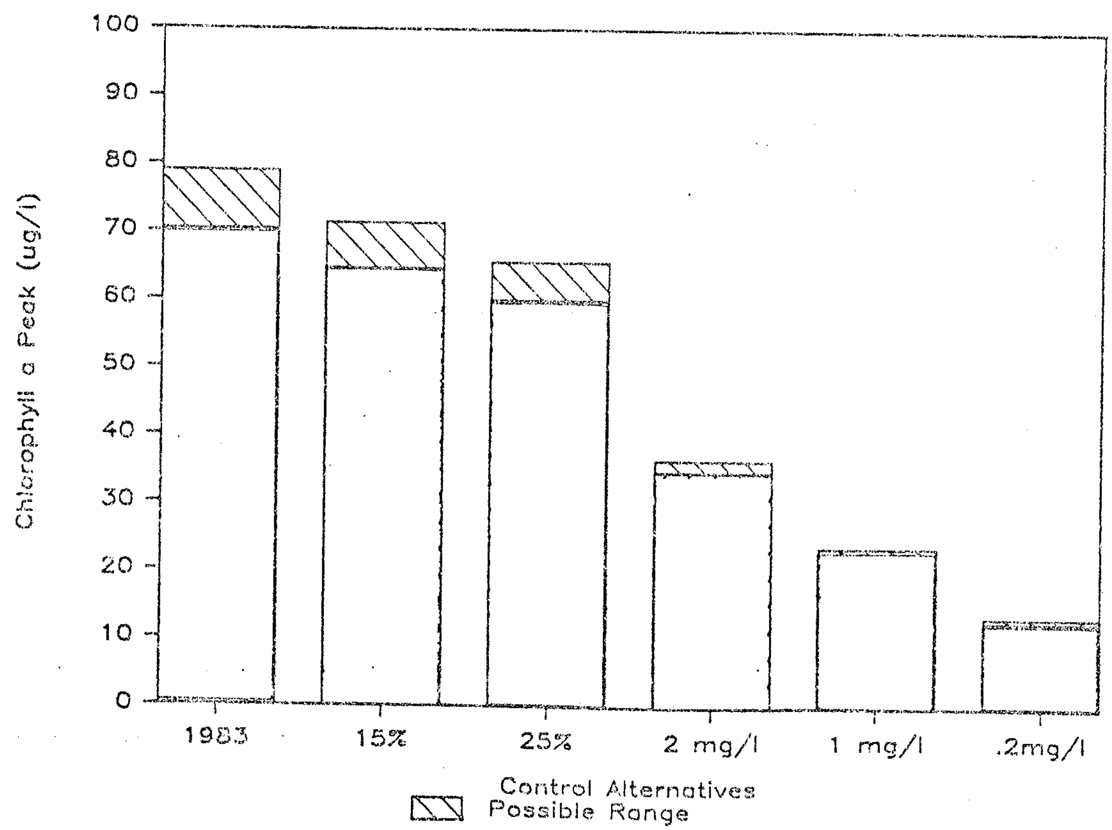


Figure 17. Effect of Phosphorus Load Reduction

exception of the Upper Occoquan plant in the Potomac River basin (0.1 mg/l). Such a phosphorus limit would provide a 85% reduction in the chlorophyll _a_ peak. It is believed that any additional reduction in chlorophyll _a_ levels (say, below 10 μg/l) in the upper James River Estuary under low flow conditions would come from the control of nonpoint phosphorus input in the upper basin.

The salinity effect on phytoplankton growth and mortality is judged minimal under the 1983 conditions as explained in the model calibration and sensitivity analyses. It is not clear, however, how salinity intrusion would affect phytoplankton growth rate and mortality rate under low flow conditions. At the 7-day 10-year low flow of 680 cfs in Richmond, salinity level reaches 1% at river mile 70 (Engineering-Science Co., 1974). Further studies on this aspect are needed to provide quantitative answers to this question.

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Fate and Transport of Nutrients in the James River Estuary

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Fate and Transport of Nutrients in the James River Estuary

Wu-Seng Lung

Introduction

Results from a recent modeling study of point source phosphorus control in the James River basin indicate that while the present nutrient levels in the *upper* James River Estuary are adequate to support algal growth, reduction of nutrient inputs by removing phosphorus at publicly owned treatment works (POTWs) would lead to a phosphorus-limiting condition and thereby lower the phytoplankton biomass levels (Lung 1986a). The study results also indicate that inorganic nitrogen (NH_4, NO_2, and NO_3) not utilized by the algae due to possible phosphorus removal at POTWs can be transported into the *lower* estuary and possibly into the Chesapeake Bay. Additional modeling effort is underway to expand the analysis into the lower estuary to address a question: how much phosphorus originating from the upper estuary will enter the lower estuary under various phosphorus-control scenarios? Finally, the amount of nutrients from the James River basin contributing to the bay eutrophication will be quantified.

Phosphorus Loads from the James River Basin

The James River Basin contributes a significant amount of phosphorus loads to the bay, ranging from 24 to 36% depending on the hydrologic conditions (Lung 1986b). Such a high phosphorus input is because none of the POTWs in the basin currently practice phosphorus removal. In addition, no other form of nutrient control exists in the James River Basin. As a result, approximately 15 to 30% of the total phosphorus loads to the bay, again depending on the hydrologic condition, are from the POTWs in the James River Basin. More importantly, POTWs account for about 55 to 75% of the total phosphorus loads from the James River Basin with the majority coming from sources below the fall line (Lung 1986b).

Phytoplankton-Nutrient Dynamics in the Upper James River Estuary

To understand the fate and transport in the James River Estuary, one needs first to quantify the phytoplankton-nutrient dynamics and its cause-and-effect relationship in the *upper* estuary. A modeling study was conducted for the upper estuary using recent water quality data (Lung 1986a). Model calculation results from that study are shown in Figure 1 for two separate data sets in 1983. In general, the increase in ammonia nitrogen below Richmond was due to ammonia discharge from point sources such as the Richmond wastewater treatment plant and other POTWs and industrial facilities. However, the increase did not sustain beyond river mile 90 because of phytoplankton uptake and nitrification. Note that the phytoplankton chlorophyll *a* concentration increased starting at this river reach. The orthophosphate profile in Figure 1 closely resembles the ammonia profile. Again, the sharp increase in orthophosphate concentration was because of wastewater discharges from point sources. Subsequent decrease in concentration was the result of algal uptake. The lowest level of orthophosphate is about 0.01 mg/l of P, which is much higher than the Michaelis-Menton constant (0.001 mg/l) limiting the algal growth in the model.

Effect of Point-Source Phosphorus Control

Given the above quantitative phytoplankton-nutrient dynamics, the calibrated model was used to assess the effect of point-source phosphorus control. A number of phosphorus control alternatives for the POTWs in the basin were evaluated. They ranged from phosphate detergent bans to phosphorus removal at POTWs. Although phosphate detergent bans would provide small reductions in phytoplankton (chlorophyll *a*) biomass, phosphorus removal at POTWs would offer more promising results in reducing chlorophyll *a* levels. That is, phosphorus limitation starts to show under the phosphorus removal scenarios (Lung 1986a).

Under the phosphorus removal scenarios, inorganic nitrogen (NH_4, NO_2, and NO_3) would increase in the downstream direction because they would not be utilized by the reduced algal biomass (Figure

2). This result raises an interesting question: would phosphorus removal cause nitrogen increase and associated algal growth in the lower estuary and the Chesapeake Bay?

Fate and Transport of Nutrients In the Lower Estuary

Additional modeling effort is underway to expand the analysis into the *lower* estuary to address the above question. The objective of the ongoing work is to determine how much nutrients originating from the upper estuary will enter the lower estuary? It is known that nutrient releases from the sediments in the James Estuary would contribute a significant amount of nutrients into the water column under favorable conditions. Recent data on nutrient release and sediment oxygen demand rates are available (Cerco 1985) and being incorporated into the expanded model.

The above analyses were performed by assuming that 100% of the phosphorus loads from the James River enters the Chesapeake Bay. However, it is known that once leaving the James River, the bulk of the loads does not move in an upstream direction along the bay. Rather, it flows into the Atlantic Ocean. Would the nutrients (phosphorus and nitrogen) from the James River enter the Bay and affect the algal growth in the bay? If not, exactly how much nutrient from the James River is contributing to the bay eutrophication? To provide answers to these questions, a water quality model is being developed to quantify the interactions between the James River and the bay. The study results will be used to determine the fate and transport of nutrients from the James River Basin into the Chesapeake Bay.

Citations

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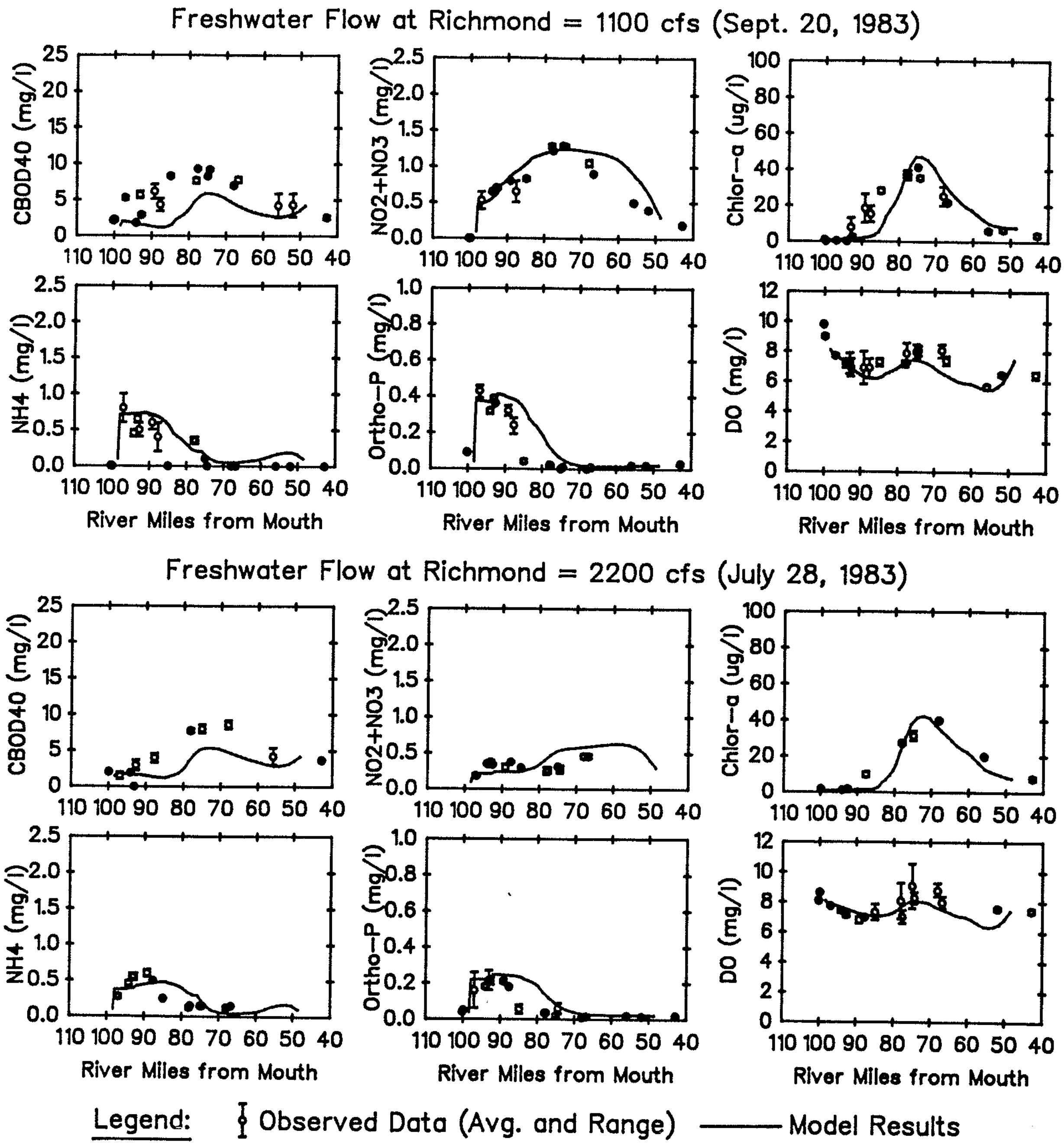

Figure 1. Fate and transport of nutrients in upper James River Estuary

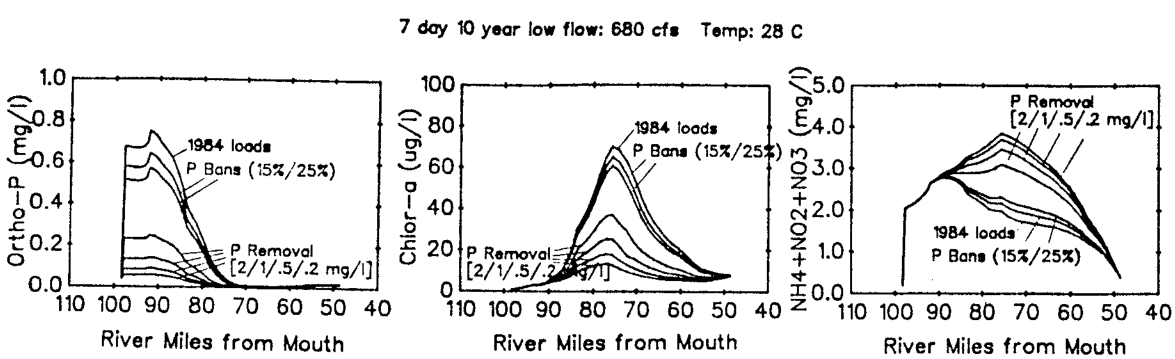

Figure 2. Effect of phosphorus control on water quality