Tidal Potomac Integrative Analysis Project, A Series of Reports on the Water Quality and Living Resources Responses to Management Actions to Reduce Nutrients in the Potomac River Estuary, Final Draft.
Buchanan, C. [ed.] 1999.
Prepared for the Chesapeake Bay Program.
ICPRB Report 99-4, 268 pp.

APPENDIX B

A HISTORICAL ANALYSIS OF THE EUTROPHICATION OF THE POTOMAC ESTUARY

Norbert A. Jaworski
Retired US EPA
norb.j@att.net

William D. Romano
Maryland Department of Natural Resources
Annapolis, MD
bromano@dnr.state.md.us

A Historical Analysis of the Eutrophication of the Potomac Estuary

By Norbert A. Jaworski and William D. Romano

Introduction

The geology, physiography, and hydrology of the Potomac River Basin have been well-characterized (6), (8), (16), (21). Numerous studies (3), (9), (18) have been conducted on the water quality problems of the Potomac Estuary as part of enforcement programs in the 1950s and 1960s and then as part of the Chesapeake Bay Program. A retrospective study of the water quality issues of the Upper Potomac Estuary was published in 1990 (10). Major water quality assessments and nutrient loading synthesis studies have been recently completed for the entire Chesapeake Bay in 1995 (15) and for the Potomac River Basin in 1996 (2) and 1998 (1).

The Potomac Integrative Analysis Project was recently undertaken to focus on the potential water quality and living resources responses to a 40% reduction in nitrogen and phosphorus in the Potomac Estuary. The project uses as its analysis period the 1985-1996 time frame. The principal goal of this paper is to provide a broader perspective by undertaking a longer historical analysis of the nutrient management issues needed to understand the effects of reduced nutrient load on the eutrophication of the Potomac Estuary. The longer historical analysis period contains the low stream flows of the mid-1960s and the high stream flows of 1996, thus providing the authors a unique opportunity to quantify what changes have occurred over a very wide range of stream flow conditions and enhanced wastewater treatment.

Specific objectives of this paper:

(a) For the period 1900-1995, describe the changes in: (1) the annual landscape nutrient loadings from animal production, crop production, air deposition and domestic wastewater to the upper basin, (2) the water quality, average annual concentrations and riverine export fluxes of the Potomac River above Washington, DC, and (3) the annual nutrient loadings from domestic wastewater directly discharged to the upper estuary and,

(b) For the period 1965-1996, present: (1) the combined (upper basin and estuarine wastewater) monthly nutrient loadings and describe how the control measures affected the loadings, (2) the results of trend analyses in nutrient concentrations of the estuary, and (3) the sampling data to show the consequences of eutrophication i.e., low Dissolved Oxygen (DO) in the bottom waters, elevated levels of chlorophyll and of Total Organic Carbon (TOC), and reduced light penetration (Secchi disk). Finally, conduct an analysis of how well the ambient estuarine nutrient concentrations can be predicted from the combined loading estimates.

Data Sources and Analysis Methods

Data were obtained from numerous sources as presented in Appendix A. All the historical data have been compiled on computerized spreadsheets to facilitate the analysis and to serve as documentation of all data and analysis methods.

The US Department of Agriculture's methods for estimating nutrients available from animal production (23) and used in crop production (14) along with other nutrient conversion data (19), (24) were adopted to determine annual nutrient loadings to the upper basin landscape from agricultural practices. The recent nitrogen landscape loadings from atmospheric deposition were from the National Atmospheric Deposition Program's electronic data base at Colorado State University, Fort Collins, CO. The historic nitrogen loadings were estimated from historical nitrogen emission data (12). In that current wastewater loadings are known, the historical annual loadings from domestic wastewater discharges for the upper basin were assumed to be proportional to the historical population.

The major source of historical water quality data for the Potomac River above Washington, DC, is from the drinking water supply monitoring program of the US Army Corps of Engineers' (USCOE) Delecarlia Treatment Plant. Except for a few years in the 1920s when the data were lost, monthly summaries of weekly chemical analyses of the "raw water" from the Potomac River above Great Falls have been compiled and annual summaries calculated.

In response to continuing degradation of the water quality of the upper estuary, the first Potomac Washington Area Enforcement Conference was convened in 1957 by the US Department of Health, Education, and Welfare (10). In addition to high fecal coliform counts and low dissolved oxygen levels, the upper estuary was highly eutrophic. As a result of the enforcement programs, nutrient water quality monitoring of the Upper Potomac River Basin was established in 1966 by the Federal Water Pollution Control Agency (FWPCA) (8) and in 1969 by the Environmental Protection Agency (EPA) (4). The upgrading of the wastewater treatment facilities to include phosphorus removal and nitrification was a result of the enforcement programs. The District of Columbia's upper estuary monitoring was expanded to include nutrients and annual reports were published by the Metropolitan Washington Council of Governments (MWCOG) (18). A major current water quality monitoring program is a cooperative effort between MWCOG, the US Geological Survey and the State of Maryland's Department of Natural Resources (20).

The historical annual export fluxes of nitrate nitrogen and other chemicals from the upper basin in kilograms per square kilometer per year ($kg/km^2/yr$) have been compiled based on the USCOE's monthly chemical analyses and USGS' river discharge measurements. For the period 1965 to 1977, estimates of monthly nutrient export fluxes were based on predictive models derived using regression analysis, which describe nutrient fluxes-river discharge logarithmic relationships by FWPCA (8) and EPA (4). Using daily USGS river discharge measurements (J.M. Landwehr, personnel communication) and regression relationships, monthly summaries were compiled for the 1964-1977 period. The nutrient export fluxes from 1978 to the present were provided by the USGS as part of the Chesapeake Bay Program. The export fluxes were based on the USGS' ESTIMATOR program which is a statistical load estimation technique (15).

The historical nutrient loadings from wastewater treatment plants discharging directly into the estuary have been compiled from numerous sources (4), (8), (18). For the period 1985-1996, monthly wastewater effluent flow and loadings data were obtained from MWCOG and the Maryland Department of the Environment.

Data for six water quality monitoring stations, which where sampled by various state and federal agency programs since 1965 (See Appendix A), have been compiled for analysis. The six stations and their distances from confluence with Chesapeake Bay are:

Station	Distance
Piscataway	158 kilometers
Indian Head	139 kilometers
Maryland Point	103 kilometer
301 Bridge	64 kilometers
Ragged Point	19 kilometers
Point Lookout	At confluence

Surface water quality data were averaged for each month in which data were obtained except for DO which included both surface and bottom waters. In that the early eutrophication problems addressed were in the upper estuary, the upper three stations have more months which have data than the three stations in the lower estuary. The period of 1978 to 1996 has the most complete water quality data record throughout the 12 months of a given year. Although data from the various monitoring programs have been merged into one spreadsheet for the six stations for +31 years of data, it remains possible to identify the original data sources. The statistical trends were analyzed using the Seasonal Kendall test (7). In merging data from various sources, the authors recognize that there can be differences in analytical methods, especial in the detection limits. The method used by various agencies is being documented.

Changes in the Upper Basin Landscape 1900-1996

Since the turn of the century, the population density of the upper basin has about tripled to a current density of 16.6 people/km^2. During that same period, major agricultural changes have occurred in the upper basin centered around the production of meat (beef, poultry, and pork), eggs, and milk. An example of these changes is in the cattle densities for the states of Maryland (MD) and Virginia (VA). As shown below, the cattle densities (cattle/km^2) for VA have increased dramatically, with beef production resulting in the highest density in 1996.

	VA			MD		
	1900	1955	1996	1900	1955	1996
Dairy	2.6	4.4	1.3	5.8	10.0	4.0
Beef	4.6	8.6	14.7	4.2	11.0	8.0
Total	7.2	13.0	16.0	10.0	21.0	12.0

For MD, both beef and dairy cattle densities were the highest in the 1950s. While the number of dairy cattle have decreased since the 1950s, milk production has gone from about 4,000

lb/yr/cow (22) at the turn of the century to current production levels of approximately 16,000 lb/yr/cow. In that milk production is directly related to animal food requirements, corn silage became a major crop for milk production. To produce the silage corn, large quantities of plant fertilizer were applied at increasing rates following World War II. Since the 1970s, nitrogen fertilizer application rates have leveled off at +2000 kg/km^2/yr for MD and +1000 kg/km^2/yr for VA.

Significant increases in poultry production have occurred, initially in the Shenandoah sub-basin and more recently in the Capapon and South Branch Potomac sub-basins. Even with increased animal food crop production, it has become necessary to import animal feed from the mid-west for meat, eggs, and milk production. It has been estimated that about 900 kg/km^2/yr of TN is imported into the Mid-Atlantic and Northeast USA (13). The nutrients in manure from these animals often exceed the crop nutrient requirements (14).

Since the 1900s, the NOx emissions from combustion sources for the states in which the Potomac Basin lies, have increased from about 500 kg/km^2/yr to a maximum of 2500 kg/km^2/yr in 1970s and have since decreased to about 2100 kg/km^2/yr. The current estimate is that about 1000 kg/km^2/yr of nitrogen is deposited onto the basin from wet and dry atmospheric deposition.

The landscape loadings from the above mentioned sources for all three major terrestrial nutrients i.e., nitrogen, phosphorus and potassium, have significantly increased since the turn of the century (Figure 1). Nitrogen loadings have increase by a factor +5.0, from 800 to 4000 kg/km^2/yr. Likewise, potassium has increased by a factor of +3.3 and phosphorus, +7.3. For the period 1965-1996, the TN landscape loadings have increased by approximately 37%.

Impact on Riverine Water Quality and Export Fluxes

The impacts of man's activities in the upper basin on the water quality above DC have been dramatic (Figure 2). The chloride and nitrate riverine concentrations have increased about 10 fold. The total residue, which is a measure of dissolved and particulate matter, has doubled. The river water, which is the major source of drinking water for the DC area, has also become harder and more alkaline.

The amount of nutrients, chlorides, and sulfates, in flux units of kg/km^2/yr that were exported from the upper basin to the upper estuary, are presented in Figure 3. The nitrate export has increased from about 100 kg/km^2/yr in the 1900s to over 500 kg/km^2/yr in the 1990s. Potassium and chlorides export fluxes have increased by a factor of 10. Since the 1920s, sulfate export fluxes, for which acid rain is a significant source, doubled by the 1970s and later began to decrease, primarily in response to a reduction in atmospheric deposition of SOx. The phosphorus export fluxes peaked about 1975-1985 and began to decrease in response to reductions in fertilizer use and the implementation of the various phosphate detergent bans (17). The large TP export fluxes in 1996 were a result of high stream flows.

Upper Potomac Estuary Wastewater Historical Loadings

Most of the domestic wastewater from the 4.6 million inhabitants of the DC Metropolitan Area receives advanced treatment from numerous facilities in DC, VA, and MD, and is subsequently discharged into the fresh water portion of the upper estuary. While the first sewers were built in the 1870s, there was no wastewater treatment until 1930s, when the Blue Plains plant started to provide primary treatment. The historical loading data (Table 1) show that the flow volume and nitrogen loading have increased over 10 fold since 1913. The TOC and TP loadings reached a maximum in the 1970s and have been reduced by about 90% and 98%, respectively, by the implementation of advanced wastewater treatment. While the advanced wastewater treatment plants included nitrification, which converts the ammonia to nitrates, only a small amount of the total nitrogen was removed from the wastewater discharges. In October 1996, the Blue Plains plant added the denitrification process and began to remove nitrogen.

Total Nutrient Loadings to Upper Estuary for the period 1965-1996

The contributions from the upper basin and from the upper estuary wastewater treatment plants are presented for TN, TP, and TOC in Figures 4, 5, and 6, respectively. Currently about 50% of the TN is from the upper basin and the remaining 50% from the wastewater treatment plants. With the application of advanced wastewater treatment technology, the 1990s TOC and TP loadings from the estuary discharges were 5% and 8%, respectively of the loadings from the upper basin. Prior to 1972, about two-thirds of the TP load was from wastewater discharges in the DC area. The low loadings observed in 1966, 1969, 1981, 1992 and 1995 occurred during drought conditions whereas the high loadings observed in 1973, 1980, 1985, 1994 and 1996 occurred during high stream flow periods.

The TN, TP, and TOC monthly loadings in kg/month from both the upper basin and upper estuary wastewater discharges for the first and last 6-year periods of the 1965-1996 time frame are summarized below:

	TN	TP	TOC
1965-1970	1,899,200	414,300	4,654,800
1991-1996	3,681,400	181,700	6,016,400
% Change	+94%	-56%	+29%

Excluding the loadings for 1996, which was a very high flow year, the loading changes were +68%, -70%, and +20% for TN, TP, and TOC respectively.

The TN, TP, and TOC "Point-of Entry" concentrations were estimated using the combined upper estuary wastewater and the upper basin export loadings to assess the effects on the biological communities (Figure 7). Given that the upper estuary has a short retention time, three month moving-average Point-of-Entry concentrations were calculated using the combined wastewater and fall-line loadings and the combined wastewater flow and river discharge data.

Over the +31 year period, the estimated upper estuarine ambient TP Point-of-Entry concentrations (Figure 7) went from an average of about 0.943 mg/l in the 1960s (dry period) to about 0.116 mg/l in the 1990s (wet period) for a reduction of 88%. The estimated ambient TOC levels were reduced by about 40%. During the +31 year period, the estimated ambient TN Point-of-Entry concentrations increased by about 12%.

Estuarine Nutrient Concentration Trends 1965-1996

The water quality trends for all six stations for TN, dissolved inorganic nitrogen (DIN), TP, TOC, chlorophyll, bottom DO and Secchi disk were analyzed using the Seasonal Kendall test and are presented in Table 2. Inorganic phosphorus was not included because there were significant chemical analysis changes in 1990, which precluded examining the entire record.

In Figures 8 and 9, surface TP and TN concentration data for the period 1965-1996 are presented for three Potomac Estuary sampling stations: Indian Head, 301 Bridge and Point Lookout. At Indian Head, the TP levels have dropped from the late 1960s concentrations of 0.2-0.4 mg/l to 1990s levels of 0.08 to 0.1 mg/l (Figure 8). Statistically significant reductions occurred at the upper five stations. It is not clear if there has been a significant reduction at Point Lookout in that the early data reflects mainly low river discharge conditions and that station may be more influenced by the ambient levels in the Chesapeake Bay. The increased levels of TP in the early 1980s at all three stations were not due to the increased wastewater or riverine input. In fact, the two loadings decreased during this period (Table 1 and Figure 6). The increases in concentrations were from the sediments mainly in upper and middle reaches due to a loss in buffering capacity(9).

Statistically significant increasing trends in TN were detected at all stations except Piscataway Creek and Point Lookout (Table 2); trends at Piscataway and Point Lookout were not statistically significant. At Indian Head, Maryland Point, 301 Bridge, and Ragged Point the trends were statistically significant with increases of 21%, 22%, 38%, and 73%, respectively. There were also statistically significant upward trends in DIN at the four upper stations, which ranged from 41% to 80%. The larger increase of 80% at the 301 Bridge station rather than the +40% increases at upper three stations was probably due to lower alga uptake in the upper estuary and greater down stream transport. A statistically significant decrease of 42% was observed in DIN at Point Lookout, which may be more influenced by Chesapeake Bay water quality than by changes in the upper estuary. During the high stream flows that occurred during all of 1996, the TN levels at the upper five stations were relatively constant at approximately 2.5 mg/l.

Consequences of Eutrophication

We selected indicators of the consequences of over enrichment to be increased chlorophyll and TOC levels, reduced light penetration, and reduced dissolved oxygen concentrations in the bottom waters. The trend analysis results for these indicators are presented in Table 2 for all six stations and plots of the data are presented in Figures 10, 11, 12, and 13 for Indian Head, 301 Bridge, and Point Lookout.

The TOC concentrations (Figure 10 and Table 2) have also statistically significantly decreased at the five upper stations by 26% to 61%, in a fashion similar to TP. Since 1985, the TOC levels at all stations were very similar ranging from 3 to 6 mg/l or about two fold greater than at the fall line. The cause of the elevated levels of TOC in the late 1970s and early 1980s is unknown in that the wastewater and riverine inputs were not higher than normal.

Statistically significant decreases in chlorophyll were detected at all stations except Point Lookout. Chlorophyll concentrations for the upper five stations have decreased by an average of 60% (Table 2).

Statistically significant improving trends in bottom dissolved oxygen were observed at Piscataway Creek and Indian Head. A statistically significant degrading trend in bottom DO was detected at 301 Bridge; DO was unchanged at Maryland Point, Ragged Point, and Point Lookout. As a result of reduced TP concentrations, chlorophyll levels decreased and there were fewer occurrences of noxious alga blooms (10). As described earlier, the higher levels of chlorophyll in the late 1970s and early 1980s appear to have occurred in response to elevated levels of TP.

Although the changes were not statistically significant, light penetration in the upper estuary has improved from approximately 20 inches to 30 inches, except during 1996 when light penetration fell below 20 inches (Figure 12). The decrease in light penetration observed during 1996 may have resulted from elevated levels of suspended particles in the upper basin, which occurred during high stream flow periods. Improved light penetration in the upper basin is attributed to advanced wastewater treatment.

At 301 Bridge and Ragged Point, light penetration also appeared to have improved, again except for 1996. At Point Lookout, light penetration declined by a statistically significant 30%. The reduced light penetration at most of the stations during the 1975-1985 period appears to have been in response to increased chlorophyll levels.

The bottom water DO levels in the upper estuary at the Piscataway Creek and Indian Head stations have improved mainly in response to the greater removal of Biochemical Oxygen Demand (BOD) in the wastewater treatment plants (Figure 13 and Table 2). The bottom water DO concentrations for the 301 Bridge, Ragged Point, and Point Lookout stations have not improved over the 1965-1996 time period and were often less than 2.0 mg/l during summer time conditions. At the Piscataway Creek station, there is a more complete picture of surface DO for the 31 year period as shown in Figure 14. The improvement in DO was not only due to the greater removal of carboneous BOD, but also resulted from the reduction of the nitrogenous BOD when the wastewater treatment plants began to nitrify as part of the advanced treatment process. This additional treatment process increased the DO at Piscataway Creek by about 2.0 mg/l. Since 1985, except for one month, the DO has been over 5.0 mg/l.

Comparison of Observed Estuarine Nutrient Concentrations with the Calculated Combined Loading Point-of Entry Concentrations.

Estimates were made of the TN, TP, and TOC levels of the upper estuary for the combined wastewater and upper basin export loadings (Figure 7). These Point-of-Entry concentrations, which were calculated from the combined fall-line and upper basin loadings and from the combined wastewater flow and river discharge data, represent the nutrient content of an upper estuary prior to tidal dilution and dispersion. The Point-of-Entry concentrations (Figure 7) are compared to the observed estuarine nutrient concentrations at Piscataway Creek (Figures 15, 16, and 17).

The observed and calculated Point-of-Entry estuarine concentrations at Piscataway Creek for all three nutrients were remarkably similar for the +31-year study period. The predicted TOC (Figure 15) and TP (Figure 16) levels reflect the improvements in wastewater treatment except for the 1975-1985 period where the predicted TP concentrations were much higher than the observed and the TOC concentrations were lower. This period was when many of the advanced wastewater treatment units went on line and some may have had start-up difficulties (9).

For TN (Figure 17), the observed and calculated estuarine concentrations at Piscataway Creek were also remarkably similar, except during low stream flow periods when the predicted concentrations were much higher throughout the +31 years. When one examines the nitrate concentrations at Piscataway Creek and at Great Falls (Figure 18), it can be seen that prior to the initiation of nitrification at most major wastewater plants, which occurred around 1979-80, the nitrate levels were around 1.0 mg/l. Since the early 1980s, with higher nitrate concentrations being discharged from the treatment facilities and from the upper basin, the nitrate level at Piscataway Creek has more than doubled to +2.5 mg/l .

A scatter plot showing the relationship between the predicted Point-of-Entry TN concentration data at the Piscataway Creek station and the observed levels has a slope of 0.37 and an intercept of 1.4 (Figure 19). This suggests that if the concentration of the combined inputs was reduced by 1.0 mg/l, the concentration at Piscataway Creek, after dilution and tidal dispersion, would be reduced by approximately 0.37 mg/l. Thus, the regression relationship can be used to gain some insight as to how the concentration of TN at Piscataway Creek might respond to either upper basin or wastewater management of nitrogen.

Summary

Landscape loadings to the upper Potomac River Basin have increased over the past +90 years. TN loadings having increased by a factor of +5.0 during this period. More recently, for the 1965-1996 period, the TN landscape loadings have increased by approximately 37%.

Water quality at Great Falls on the upper Potomac River as measured by total residue, hardness, alkalinity, chlorides, and nitrates, has significantly degraded over the past +90 years. The total residue has doubled and the river water has become harder and more alkaline. The chloride and nitrate riverine concentrations have increased by approximately +8 fold.

Riverine export of nitrates and potassium from the upper basin into the upper estuary has increased +8 fold. Currently about 50% of the TN is from the upper basin and the remaining 50% is from the wastewater treatment facilities whose discharges are to the upper estuary.

Major improvements in wastewater treatment in the mid-1970s and early 1980s have significantly reduced the TP and TOC loadings from municipal wastewater treatment plants discharging into the upper estuary. TN loadings for the +31 year period from the treatment plants increased as wastewater flows increased.

Since 1965, with the treatment improvements, the total loadings of TP and TOC to the upper estuary have decreased by 56% and 29%, respectively. However, TN loadings from all sources to the upper estuary have increased by approximately 95% over the +31 year period.

In response to reductions in total loads, TP and TOC concentrations for the upper five stations in the estuary decreased during the 1965-1996 period by an average of 70% and 50%, respectively. Although a statistically significant decrease of 12% in TOC was observed at Point Lookout, the trend in TP, although decreasing, was not significant. Statistically significant increases were observed for DIN at the upper four stations, which changed on average by 54% during the 1965-1996 period. DIN decreased by 42% at Point Lookout.

The chlorophyll levels at all stations except Point Lookout have decreased in response to wastewater treatment plant improvements. Chlorophyll concentrations for the upper five stations have decreased by an average of 60%.

Light penetration increased in the upper estuary except for 1996, but has decreased in the middle and lower zones during the 1965-1996 period. There was a statistically significant 30% decrease in light penetration at Point Lookout.

Bottom DO concentrations have improved in the upper estuary with the Piscataway Creek station levels usually above 5.0 mg/l during the summer months. However, the DO in the bottom waters of the deep channels of the lower estuary during the 1965-1996 period were hypoxic with summer time concentrations often near 0 mg/l. At Point Lookout, there has been no discernible change in DO in the bottom water of the deep channels during the past +31 years.

The comparison of the nitrate nitrogen concentrations at Piscataway Creek with those at Great Falls for the +31 years reflects the initiation of nitrification at most major wastewater treatment plants, which was around 1979-80. The nitrate levels were around +1.0 mg/l. Since the early 1980s, with higher nitrate concentrations being discharged from the treatment facilities and from the upper basin, the nitrate levels at Piscataway have more than doubled to +2.5 mg/l.

Estimates were made of the TN, TP, and TOC Point-of-Entry of the upper estuary from the combined wastewater and upper basin export loadings compared favorably to the observed estuarine nutrient concentrations at Piscataway Creek.

The relationship between the calculated Point-of-Entry concentrations of the combined TN inputs and the observed levels at the Piscataway Creek station illustrates the effect of dilution and tidal dispersion. This statistical relationship can be used to gain some insight as to how the concentration of TN in the upper estuary at Piscataway Creek may respond to changes in either upper basin and/or upper estuary wastewater nitrogen loadings.

References

1. Ator, S.W., et al, (1998), Water Quality in the Potomac River Basin, Maryland, Pennsylvania, Virginia, West Virginia, and the District of Columbia, 1992-96, US Geological Survey Circular 1166.
2. Blomquist, J.D., et al, (1996), Water-Quality Assessment of the Potomac River Basin: Basin Description and Analysis of Available Nutrient Data, 1970-1990, US Geological Survey Water-Resources Investigations Report 95-4221.
3. Boynton, J., J. Garber, R. Summers, and W.M Kemp, (1995). Inputs, transformations and transport of nitrogen and phosphorus in Chesapeake Bay and selected tributaries. *Estuaries*. Vol. 18, No. 1B, p. 285-314.
4. Clark, L. J., V. Guide, et al. (1974). Summary and Conclusions: Nutrient Transport and Accountability in the Lower Susquehanna River Basin, Annapolis, U.S. Environmental Protection Agency, Region III .Annapolis Field Office.
5. Eckles, C.H., (1935). *Dairy and Milk Production,* Macmillan Company, London.
6. Interstate Commissions on the Potomac River Basin, (1978), The Fresh Water Potomac: Aquatic Communities and Environmental Stress, Proc. Symp. College Park, MD.
7. Gilbert, R.O., (1987). *Statistical Methods for Environmental Pollution Monitoring*, Van Nostrand Reinhold, New York.
8. Jaworski, N. A. (1969). Nutrients in the Upper Potomac River Basin, U.S. of the Interior, Federal Water Pollution Control Administration, Middle Atlantic Region, Chesapeake Technical Support Laboratory.
9. Jaworski, N.A., et al, (1971). A Water Resources-Water Supply Study of the Potomac Estuary, US EPA, Technical Report 35.
10. Jaworski, N.A. (1990). Retrospective study of the water quality issues of the upper Potomac estuary. *Aquatic Sciences*, Vol. 3/Issue 1, pp. 11-40.
11. Jaworski, N.A., P.M. Groffman, A.A. Keller, and J.C. Prager. (1992). A watershed nitrogen and phosphorus balance: The upper Potomac River basin. *Estuaries,* 15:83-95.
12. Jaworski, N.A., et al (1997). Atmospheric Deposition of Nitrogen Oxides onto the Landscape Contributes to Coastal Eutrophication the Northeast Untied States, *ES&T,* 31,, 1995-2004.
13. Jordan, T.E. and D. E. Wheller, (1996), Human Contributions to Terrestrial Nitrogen Flux, *Bioscience*, 46: 655-664.
14. Lander, C.H., and Moffitt, D., (1996) Nutrient Use in Cropland Agriculture (Commercial Fertilizers, and Manure): Nitrogen and Phosphorus, Working Paper 14, RCAIII, USDA, NRCS.
15. Langland, M.J., et al, (1995) Synthesis of Nutrient and Sediment Data for the Watersheds Within the Chesapeake Bay Drainage Basin, US Geological Survey Water-Resources Investigations Report 95-4233.
16. Lippson, A.J., et al, (1979) Environmental Atlas of the Potomac Estuary, Prepared for the Maryland's DNR Power Plant Sitting Program.
17. Michael, B.D., (1989). Upper Potomac Estuary: An Historical Perspective, Technical Report # 105, Maryland Department of Environment, Baltimore, MD.
18. MWCOG, (1985-1990), Potomac River Water Quality: Conditions and Trends in Metropolitan Washington, DC Area, Annual Reports.

19. Morrison, F.B., (1959), *Feeds and Feeding: A Handbook for Students and Stockman,* Morrison Publishing Company, Ithaca, NY.
20. Summers, R. (1993). Maryland Department of the environment Chesapeake Bay water quality monitoring river input monitoring component: Level 1 data summary report: 1993. Maryland Department of the Envir. Chesapeake Bay and Watershed Mgt. Administration.
21. Tiner, R.W., et al, (1994), Recent Wetland Status and Trends in the Chesapeake Watersheds (1982-1989), US Fish and Wildlife Service, Hadley, MA.
22. USDA, (1932). *Yearbook of Agriculture* 1932, United States Department of Agriculture, Washington. DC.
23. Van Dyne, D.L., and Gilbertson, C.B., (1978), Estimating US Livestock and Poultry Manure and Nutrient Production, USDA, ESCS-12.
24. Van Horn, H.H. and W. Powers, (In Preparation 1998), Properties and Characteristics of Animal Waste, University of Florida, Gainesville, Fl.

Data Sources

Blanchard, S.F., and D.C. Hahl, (1981) Water Quality of the Tidal Potomac River and Estuary: Hydrologic Data Report, 1979 Water Year, US Geological Open File Report 81-1074.

Blanchard, S.F., et al. (1982). Water Quality of the Tidal Potomac River and Estuary: Hydrologic Data Report, 1980 Water Year, US Geological Open File Report 82-152.

Clark, L. J., V. Guide, et al. (1974). Summary and Conclusions: Nutrient Transport and Accountability in the Lower Susquehanna River Basin, Annapolis, U.S. Environmental Protection Agency, Region III. Annapolis Field Office.

Coupe, R.H. and W. E. Webb. (1984). Water Quality of the Tidal Potomac River and Estuary: Hydrologic Data Reports Supplement, 1979 Through 1981 Water Year, US Geological Open File Report 84-132.

District of Columbia's Upper Potomac Estuary Monitoring Program, 1974-1976.

Feister, C. and M. Karweit (1973). Data Bank Report 2 , Data Bank Inventory Volume II Chesapeake Bay, Edition 1, 1949 through 1970. Annapolis, Chesapeake Bay Institute The Johns Hopkins University.

Guide, V. and J. Orterio Villa (1972). Chesapeake Bay Nutrient Input Study. Philadelphia, U.S. Environmental Protection Agency, Region III, Annapolis Field Office.

Jaworski, N. A. (1969). Nutrients in the Upper Potomac River Basin, U.S. of the Interior, Federal Water Pollution Control Administration, Middle Atlantic Region, Chesapeake Technical Support Laboratory.

Jaworski, N. A. and J. Orterio Villa, et al. (1969). Nutrients in the Potomac River Basin, U.S. Department of the Interior, Federal Water Pollution Control Administration, Middle Atlantic Region.

Jaworski, N. A. and L. J. Hetling (1970). Relative Contributions of Nutrients to the Potomac River Basin from Various Sources, Rochester, NY, U.S. Department of the Interior, Federal Water Pollution Control Administration, Middle Atlantic Region, Cornell Agricultural Waste Management Conference.

Lear, D. and J. W. Marks (1966). Water Quality Survey of the Potomac Estuary. Annapolis, Chesapeake Technical Support Laboratory, Middle Atlantic Region, Federal Water Pollution Control Administration, U.S. Department of the Interior.

Marks, J. W. and J. Orterio Villa (1967). Water Quality Survey of the Potomac Estuary,

Annapolis, Chesapeake Technical Support Laboratory, Middle Atlantic Region, Federal Water Pollution Control Administration, U.S. Department of the Interior.

Marks, J. W. and J. Orterio Villa (1968). Water Quality Survey of the Potomac Estuary, Annapolis, U.S. Department of the Interior, Federal Water Pollution Control Administration, Middle Atlantic Region.

Marks, J. W., J. Orterio Villa, et al. (1969). Water Quality Survey of the Potomac Estuary Phosphate Tracer Study. Annapolis, U.S. Environmental Protection Agency, Region III, Annapolis Field Office.

Marks, J. W., J. Orterio Villa, et al. (1969). Water Quality of the Potomac Estuary Transects, Intensive and Southeastern Water Laboratory Cooperative Studies. Annapolis, U.S. Environmental Protection Agency, Region III, Annapolis Field Office.

Marks, J. W., J. Orterio Villa, et al. (1970). Water Quality Survey of the Piscataway Creek Watershed, 1968-1969-1970. Annapolis, U.S. Environmental Protection Agency, Region III, Annapolis Field Office.

Marks, J. W., J. Orterio Villa, et al. (1970). Water Quality of the Potomac Estuary Transport Survey. Annapolis, U.S. Environmental Protection Agency, Region III, Annapolis Field Office.

Marks, J. W., J. Orterio Villa, et al. (1970). Water Quality Survey of the Potomac Estuary Embayments and Transects. Philadelphia, U.S. Environmental Protection Agency, Region III, Annapolis Field Office.

Marks, J. W., J. Orterio Villa, et al. (1970). Special Water Quality Surveys of the Potomac River Basin; Anacostia Estuary 1970, Wicomico River, St. Clement and Breton Bays, Philadelphia, U.S. Environmental Protection Agency, Middle Atlantic Region III Annapolis Field Office.

Marks, J. W., O. Villa, et al. (1970). Water Quality of the Potomac Estuary, Gilbert Swamp and Allen's Fresh and Gunston Cove. Annapolis, U.S. Environmental Protection Agency, Region III Annapolis Field Office.

Marks, J. W., J. Orterio Villa, et al. (1970). Consolidated Water Quality Survey of the Potomac Estuary, Annapolis, U.S. Environmental Protection Agency, Region III, Annapolis Field Office.

Maryland' Department of Natural Resources Potomac Estuary Monitoring Program, 1978-1996. Metropolitan Washington Council of Governments' Monthly Wastewater Quantity and Quality Electronic Data Base.

National Atmospheric Deposition Program's Electronic Data Base.

US Army Corps of Engineers' (USCOE) Delecarlia Treatment Plant Drinking Water Monitoring Program Data Files, 1905-1996.

US Department of Agriculture, National Agriculture Statistical Services and State Statistical Offices Electronic Information & Data, 1900-1996.

US Geological Surveys, Surface Water and Water-Quality Water Resources Data for the Potomac River, 1964-1996.

Whaley, R. C., J. H. Carpenter, et al. (1966). Data Summary Potomac River Nutrient Cruises 1965-1966, Annapolis, Chesapeake Bay Institute, The Johns Hopkins University.

Table 1. Upper Potomac Estuary Wastewater Loadings

Year	Waste Flow	TOC	TN	TP
	(million liters/day)	(kg/day)	(kg/day)	(kg/day)
1913	158	17620	2900	50
1932	283	31360	5270	1000
1944	630	60900	10400	2000
1960	737	33430	14400	4500
1965	1020	40250	22960	9220
1970	1180	44800	27040	10930
1975	1410	23040	26500	2890
1980	1730	29268	25670	2480
1985	1750	4200	26080	320
1990	1890	5940	29190	260
1995	1970	4350	32430	160
1996	2030	7080	30200	230

Table 2. Water Quality Trends for Six Estuarine Sampling Stations, 1965-1996

Station		Total Nitrogen mg/l	Inorganic N mg/l	Total Phosphorus mg/l	T Organic Carbon mg/l	Chlorophyl ug/l	Bottom DO mg/l	Secchi Disk inches
Piscataway	Initial Median	2.389	1.47	0.169	5.8	36.4	5.7	18
(XFB2470)	% Change	9	**46**	**>-95**	**-50**	**-30**	**60**	0
	p-value	0.0404	0.0000	0.0000	0.0000	0.0000	0.0000	0.3843
Indian Head	Initial Median	1.8	1.368	0.168	5.86	32	5.7	21.2
(XEA6596)	% Change	**21**	**48**	**-83**	**-61**	**-50**	**20**	10
	p-value	0.0004	0.0000	0.0000	0.0000	0.0000	0.0003	0.1891
Maryland Point	Initial Median	1.477	1.05	0.065	5.24	6.2	6.8	30
(XDA1177)	% Change	**22**	**41**	**-69**	**-60**	**>-95**	0	-10
	p-value	0.0005	0.0000	0.0001	0.0000	0.0000	0.5727	0.0750
301 Bridge	Initial Median	0.926	0.393	0.099	5.06	15.3	5.9	40
(XDC1706)	% Change	**38**	**80**	**-36**	**-57**	**-60**	**-20**	0
	p-value	0.0007	0.0000	0.0000	0.0000	0.0000	0.0025	0.1904
Ragged Point	Initial Median	0.504	0.081	0.093	5.45	13.2	5.2	79.5
(MLE2.2)	% Change	**73**	86	**-24**	**-26**	**-50**	0	-20
	p-value	0.0002	0.0441	0.0018	0.0070	0.0066	0.7631	0.0357
Point Lookout	Initial Median	0.394	0.174	0.031	10.57	5.8	5.9	120
(MLE2.3)	% Change	22	**-42**	-10	**-12**	20	-10	**-30**
	p-value	0.3652	0.0035	0.1693	0.0004	0.4698	0.1374	0.0000

Note: All trends are based on 31.58 years of data except for TOC which has 27.9 years except for Point Lookout which has 14.5 years.
Bold type indicates trends are statistically significant

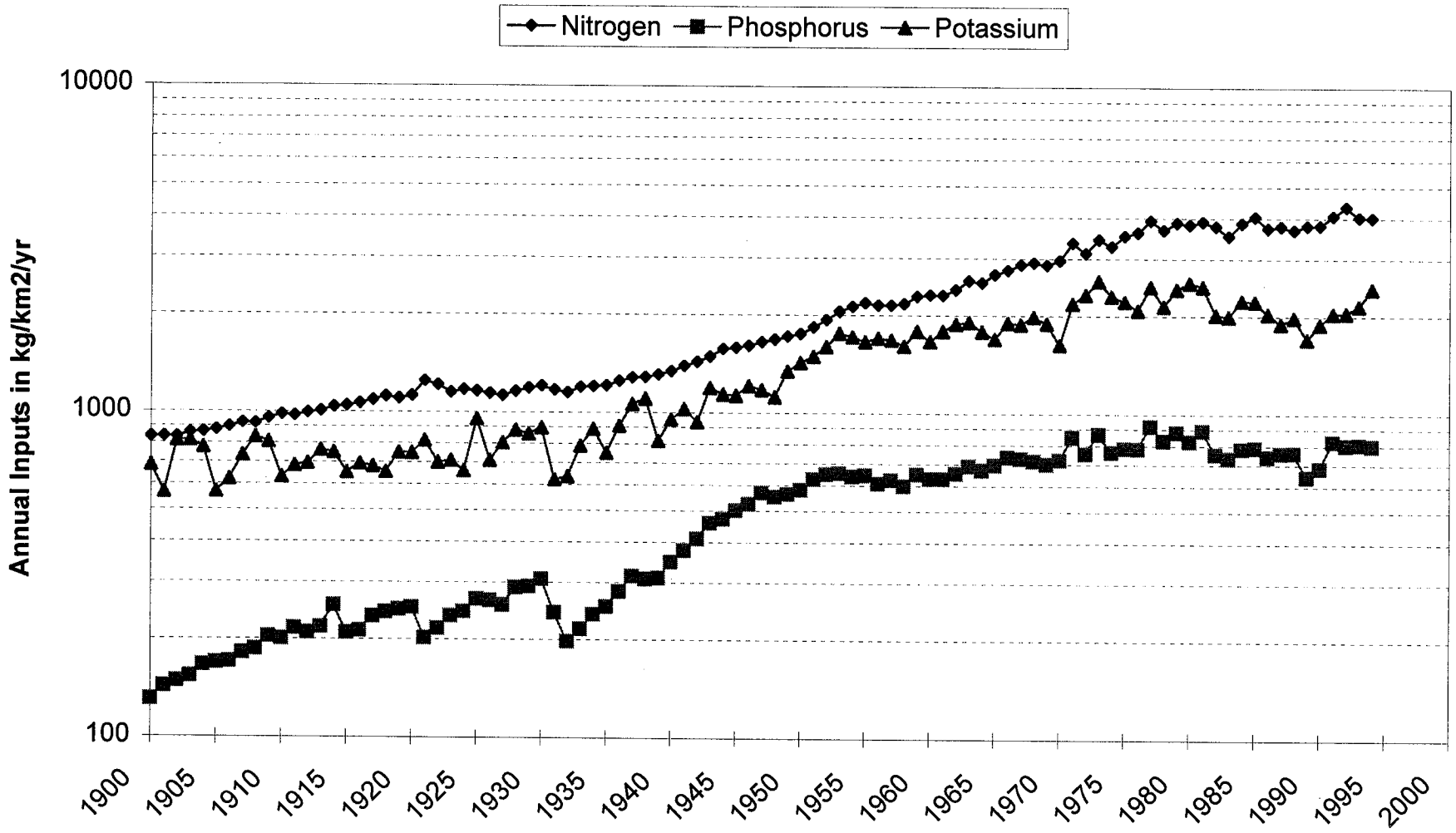

Figure 1. Upper Potomac River Basin Landscape Inputs

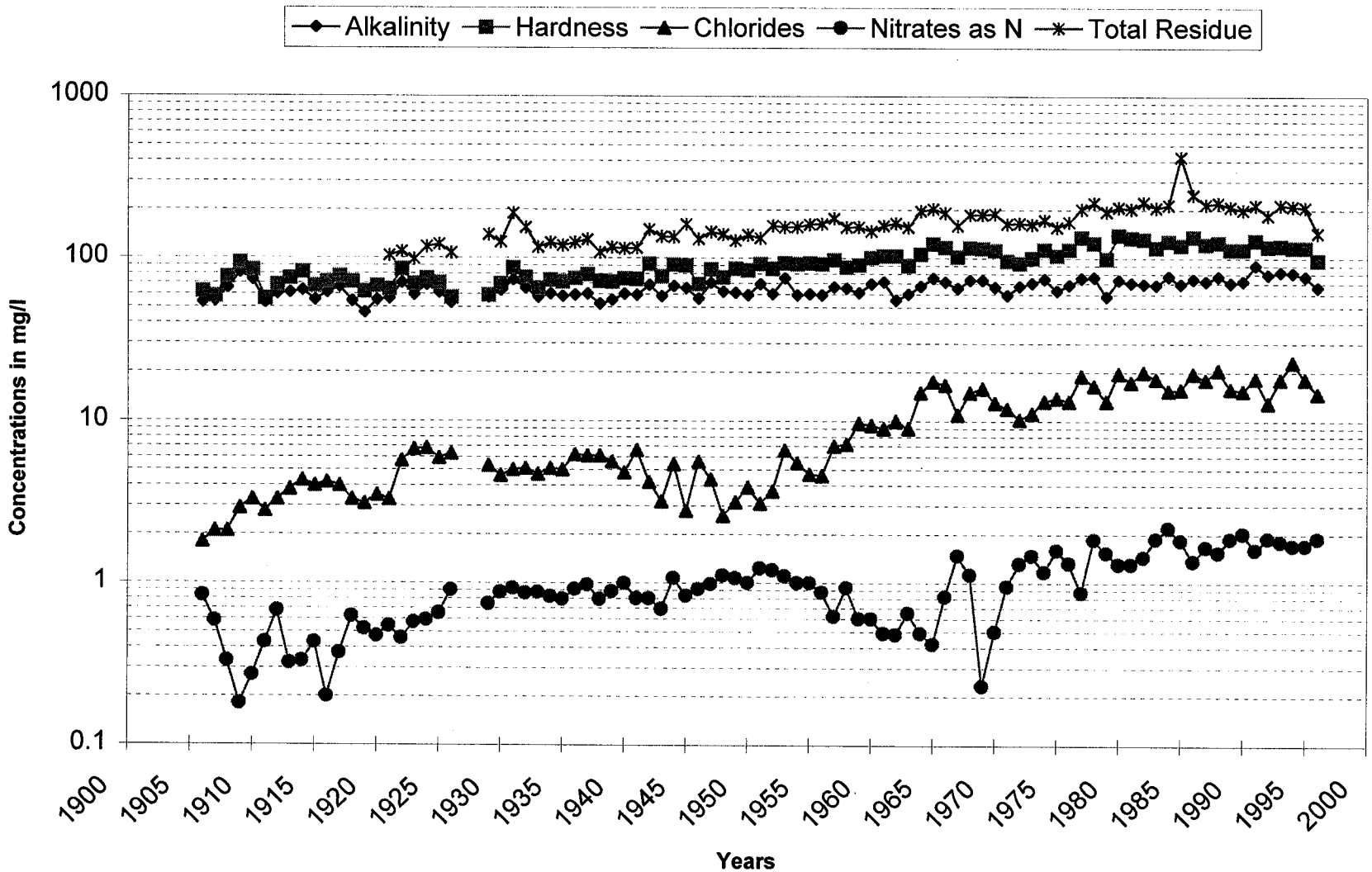

Figure 2. Potomac River Water Quality Trends

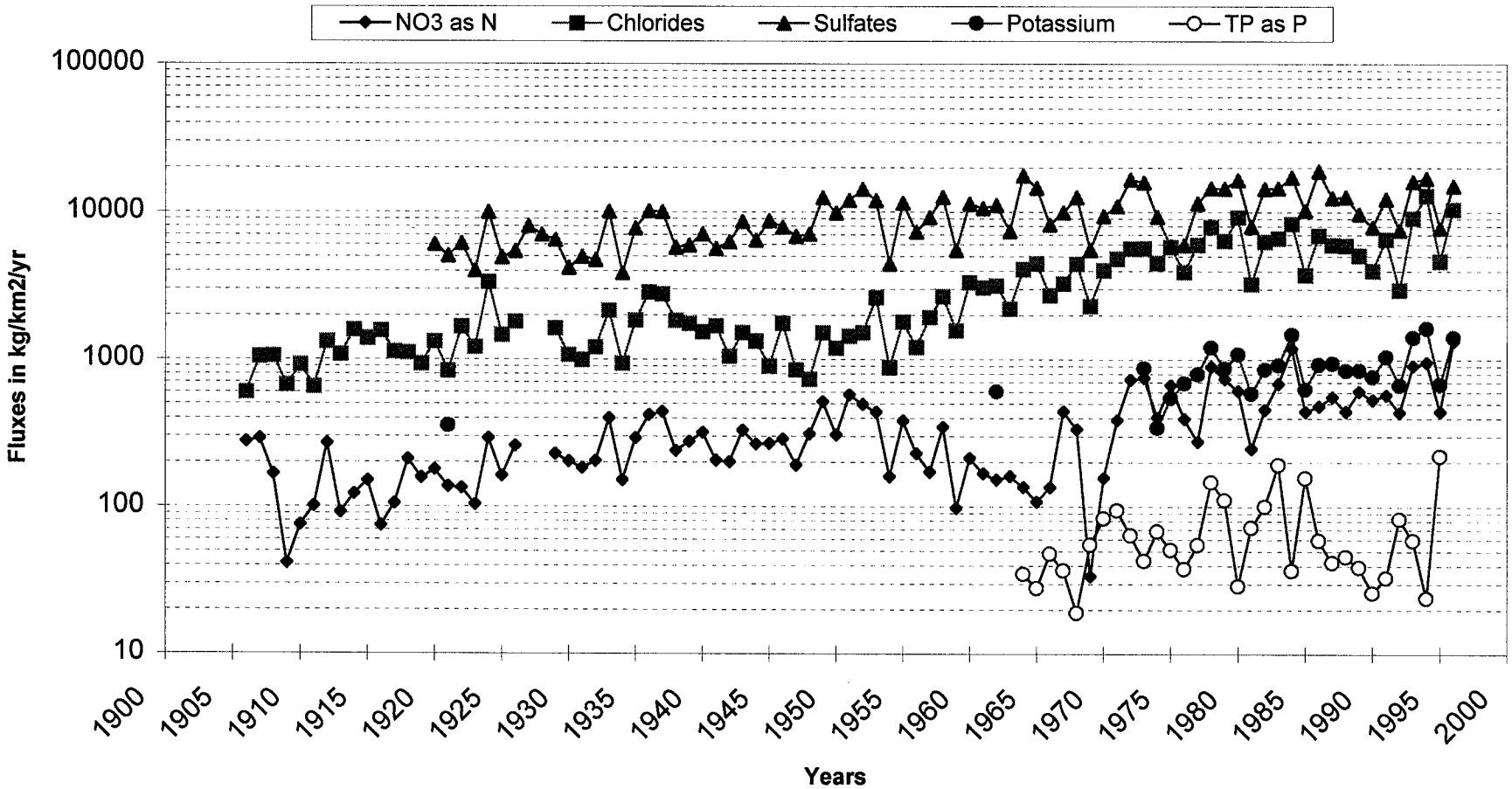

Figure 3. Potomac River Fluxes

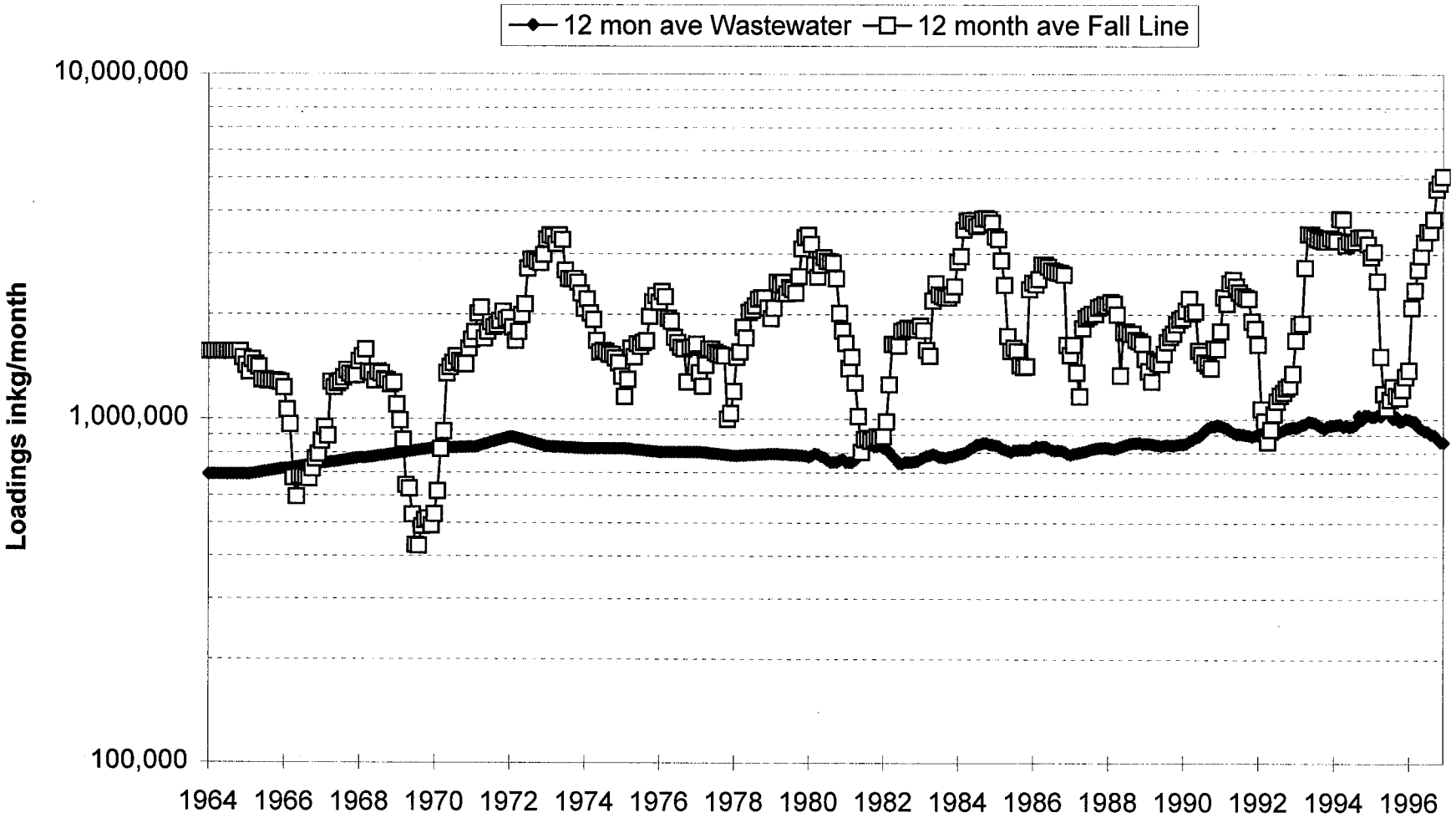

Figure 4. Fall Line & Wastewater TN Monthly Loadings

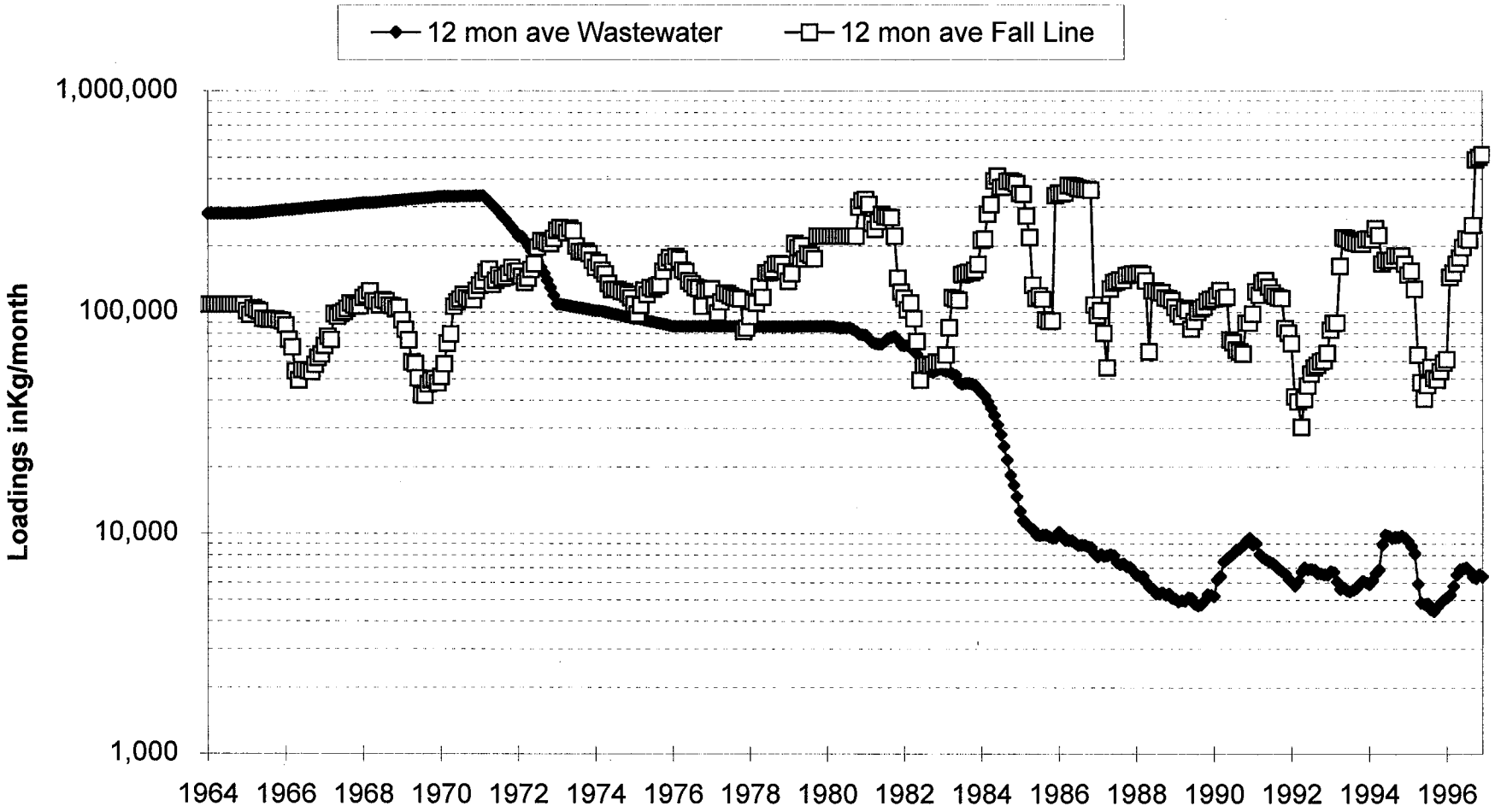

Figure 5. Fall Line & Wastewater TP Monthly Loadings

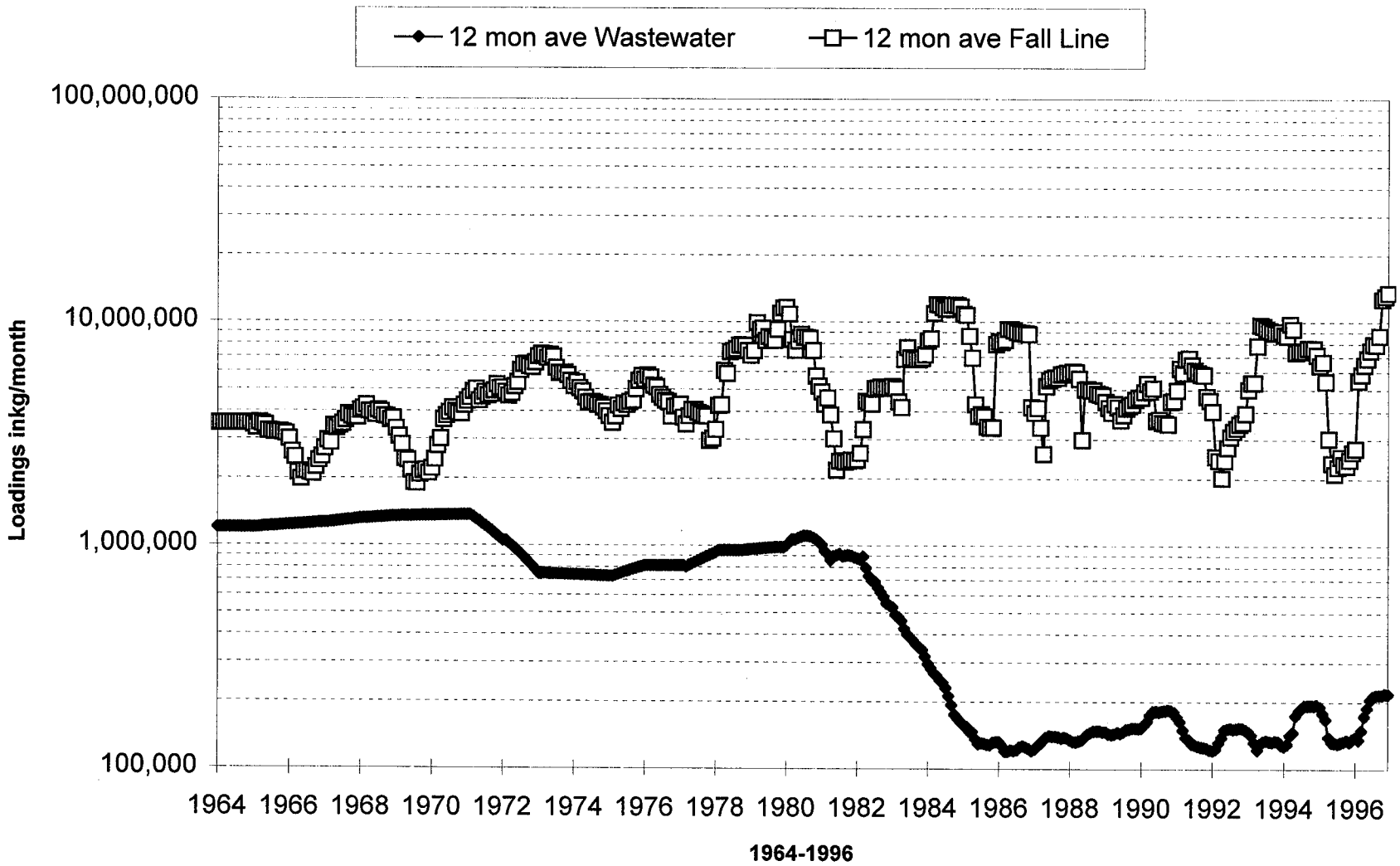

Figure 6. Fall Line & Wastewater TOC Monthly Loadings

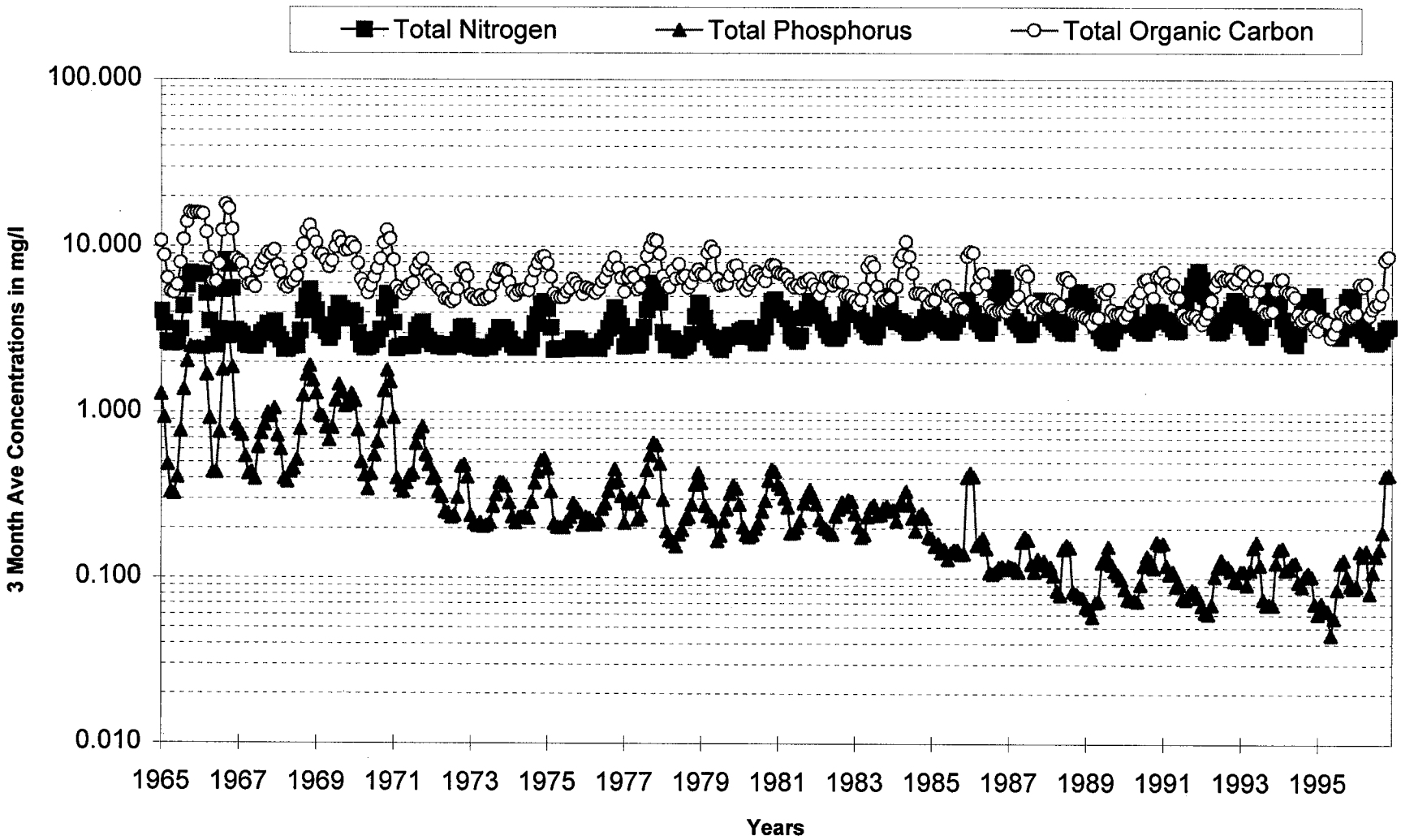

Figure 7. Calculated Point-of-Entry for the Upper Estuarine Nutrient Concentrations from Combined Wastewater and Riverine Inputs

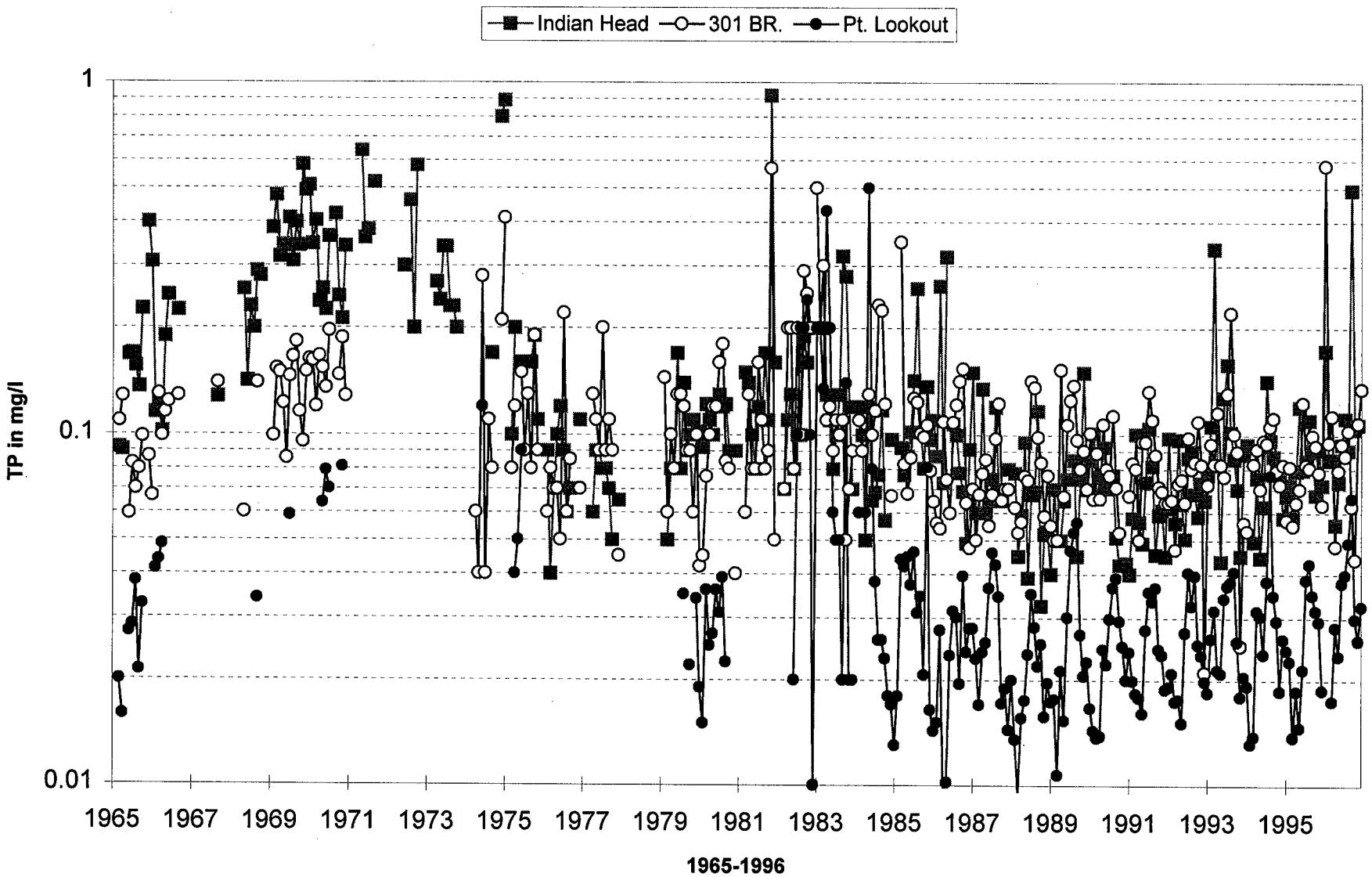

Figure 8. Potomac Estuary TP Surface Concentrations

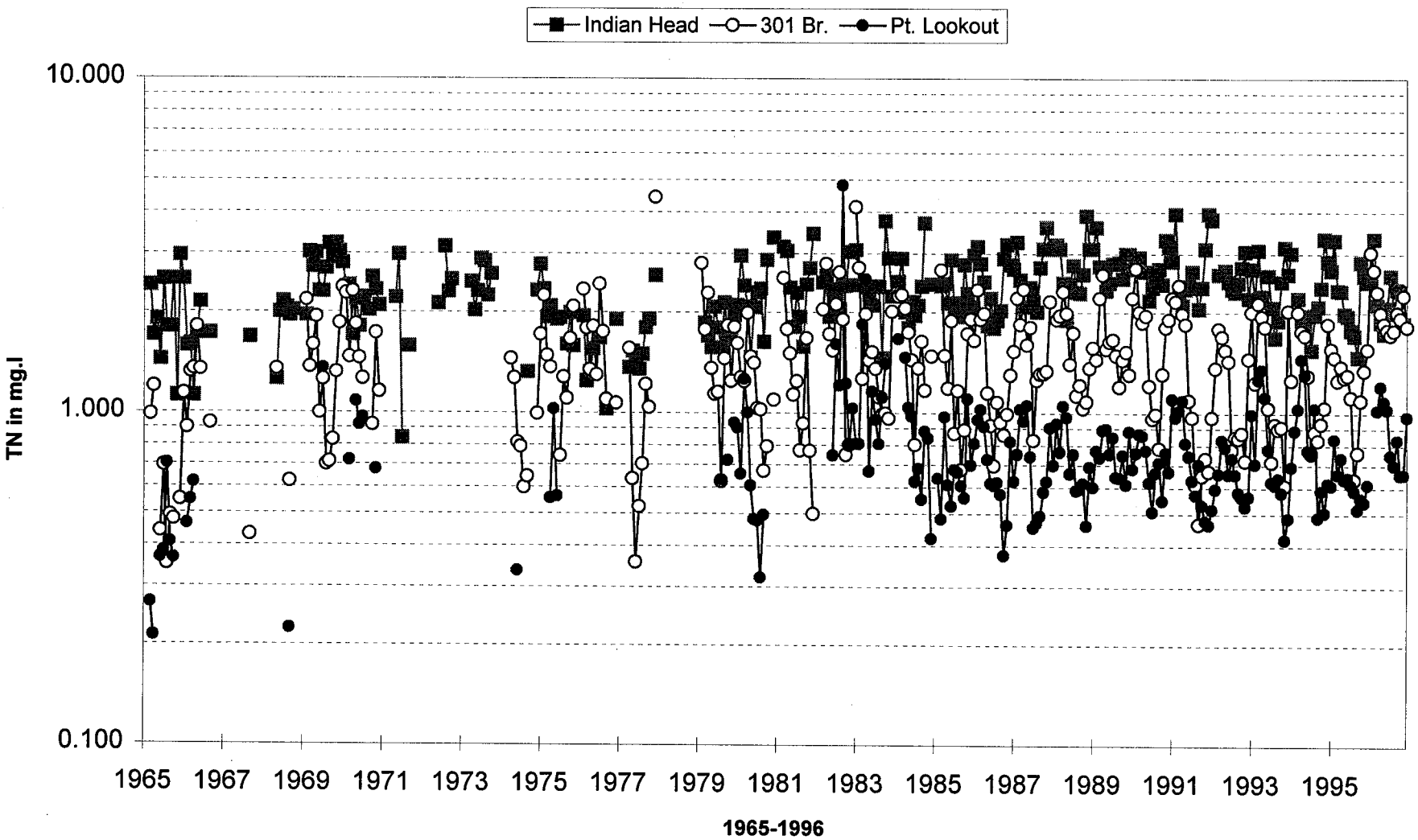

Figure 9. Potomac Estuary TN Surface Concentrations

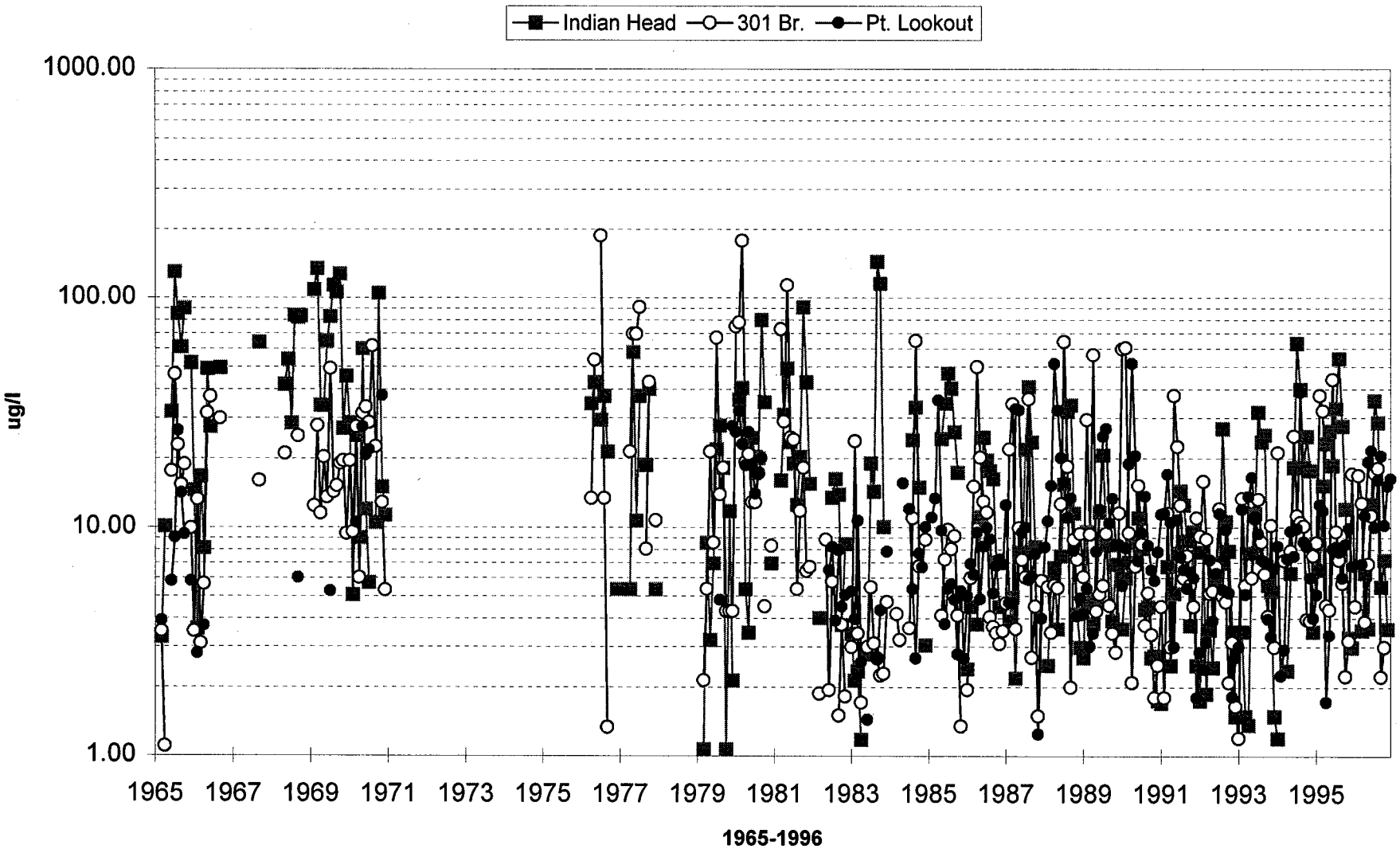

Figure 10. Potomac Estuary Chlorophyll Surface Concentrations

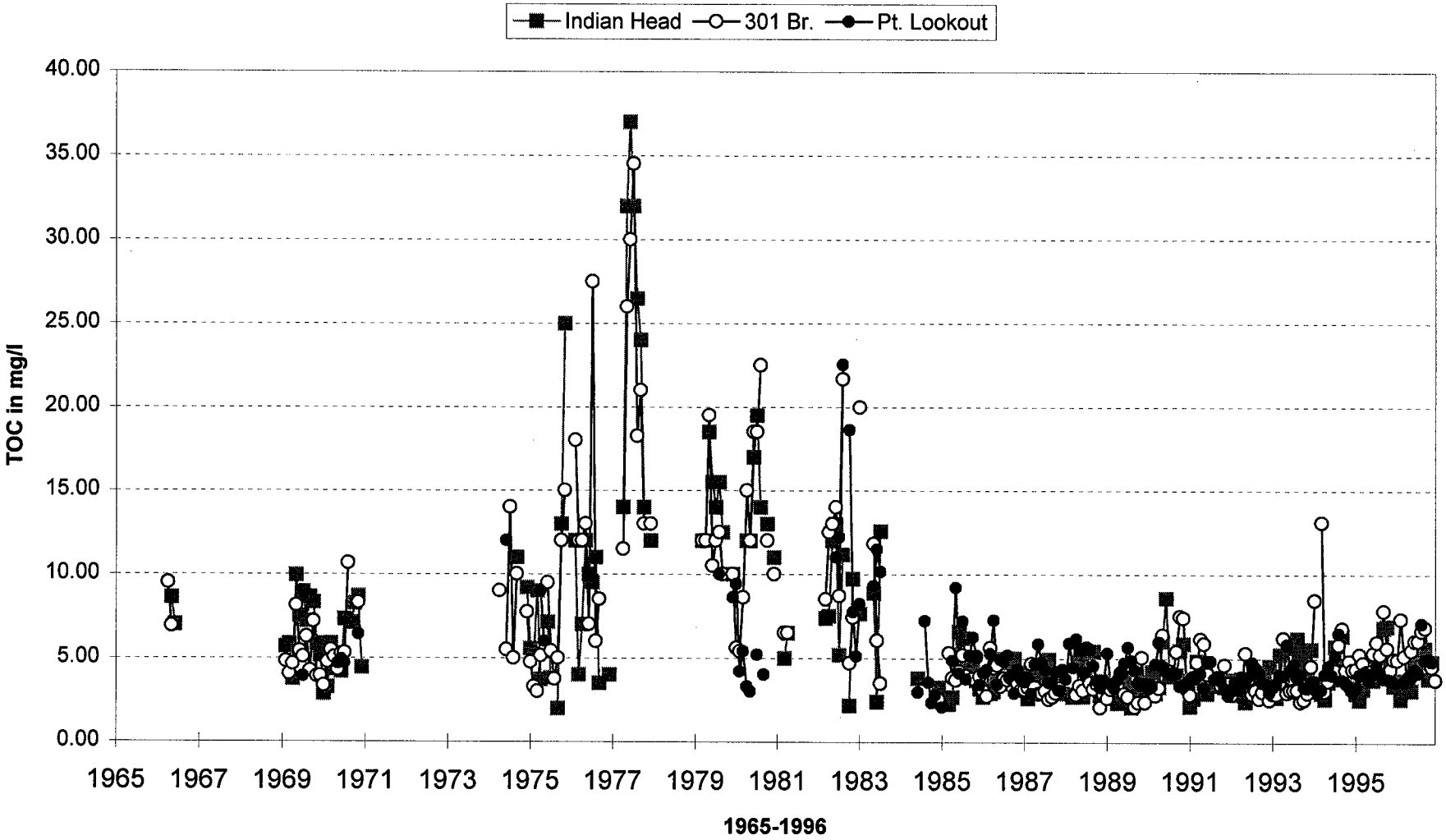

Figure 11. Potomac Estuary TOC Surface Concentrations

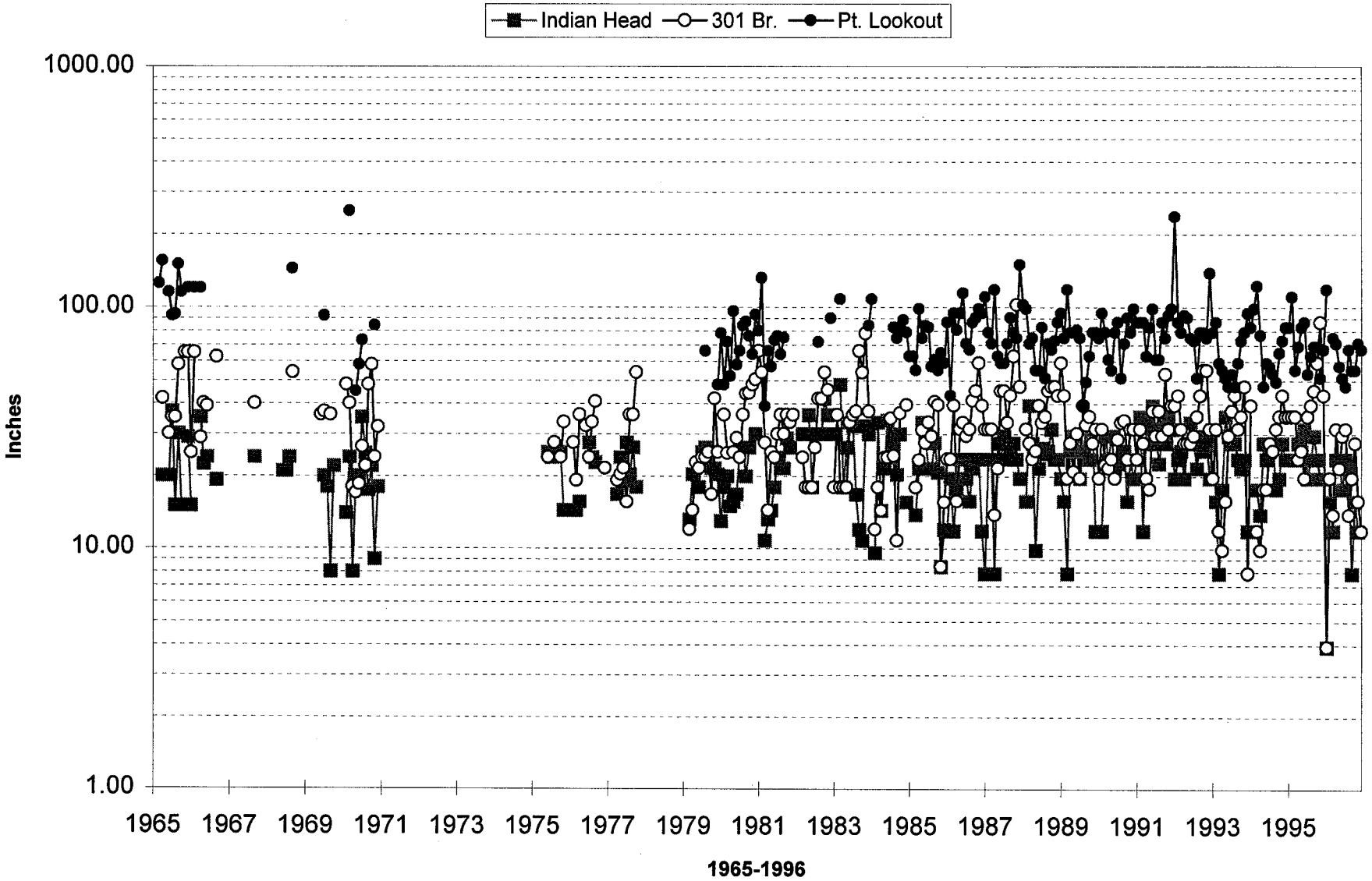

Figure 12. Potomac Estuary Secchi Disk Depths

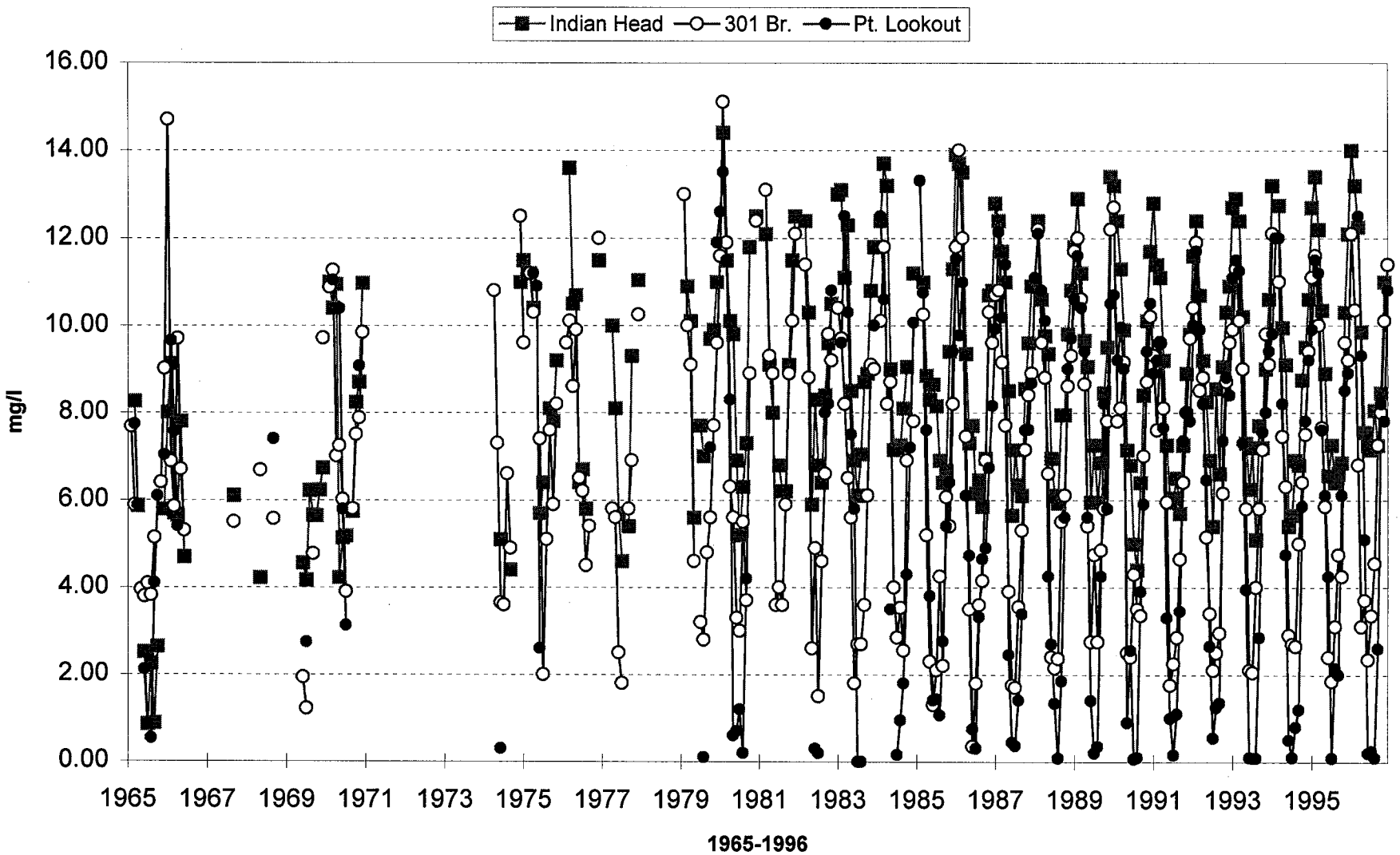

Figure 13. Potomac Estuary Bottom Dissolved Oxygen

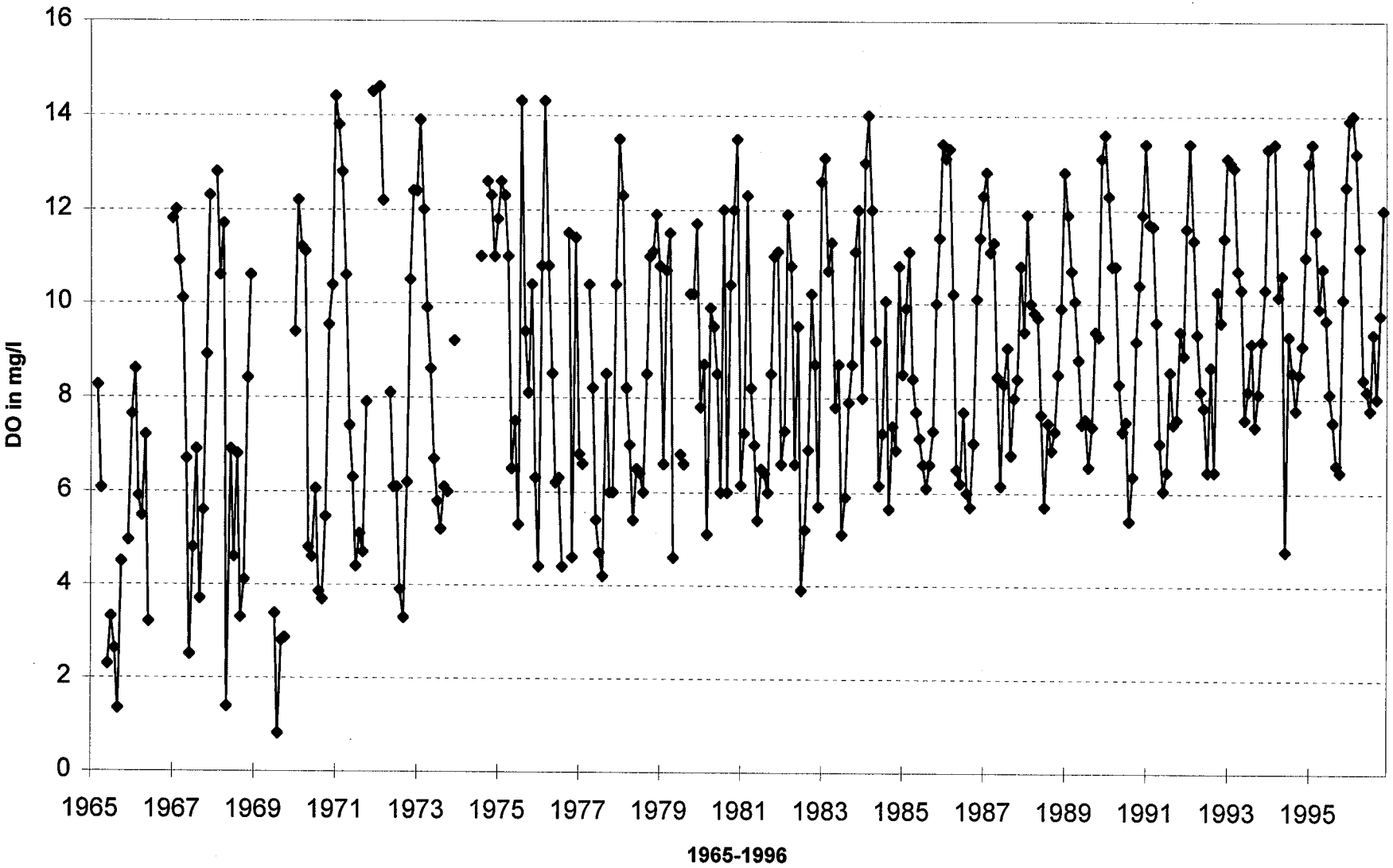

Figure 14. Dissolved Oxyen Concentrations of Potomac Estuary At Piscataway

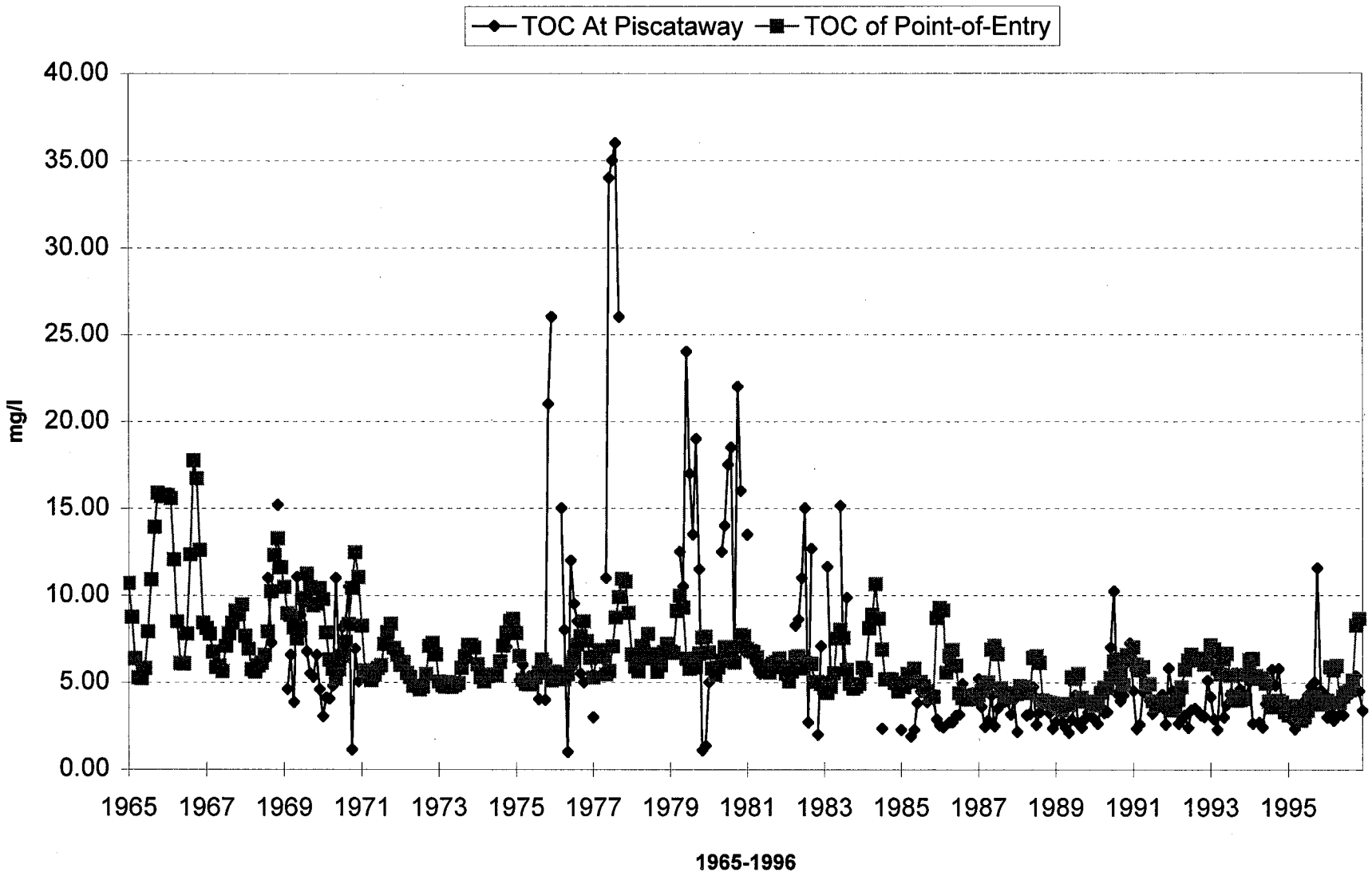

Figure 15. Total Organic Carbon Concentration Trends

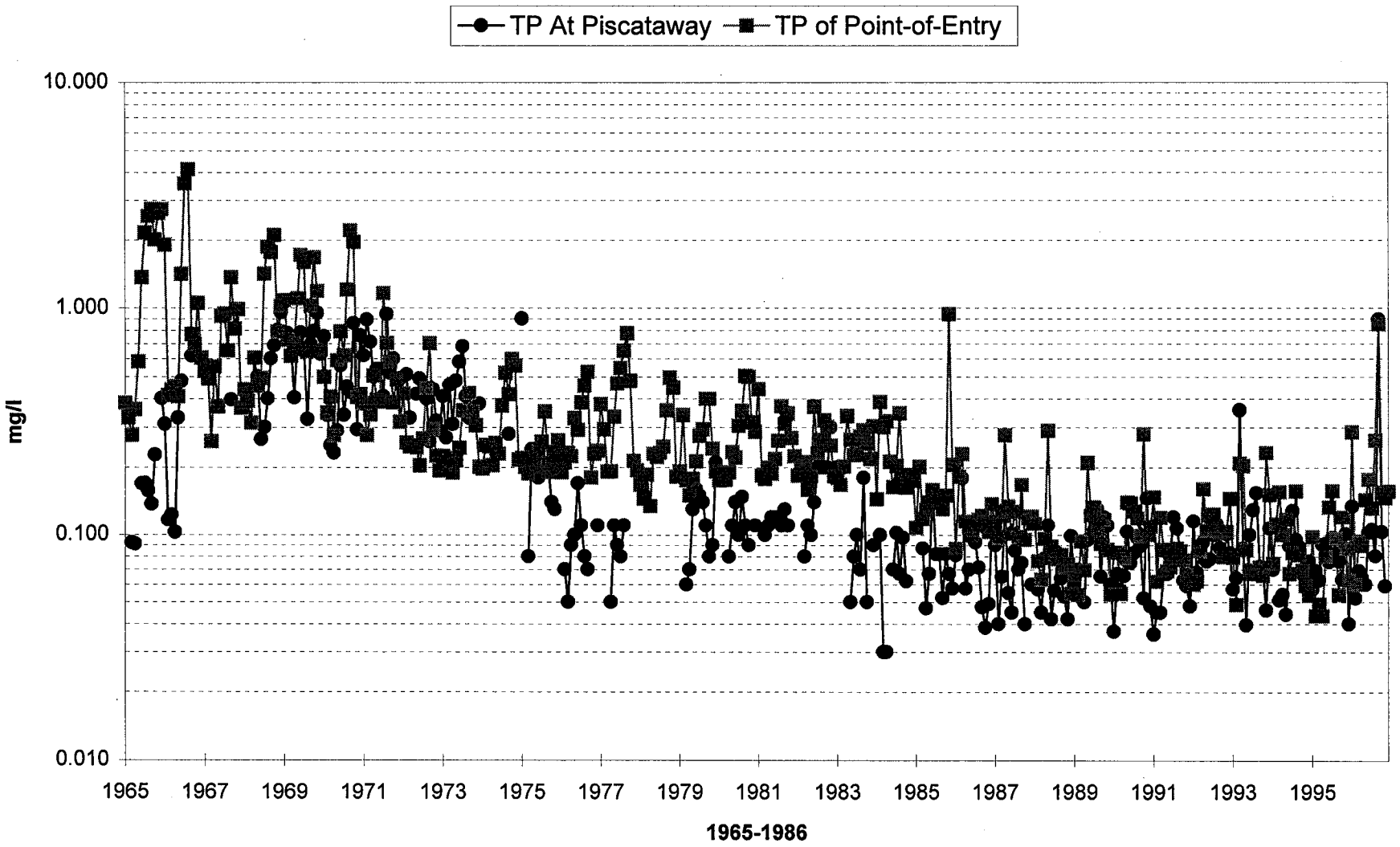

Figure 16. Total Phosphorus Concentration Trends

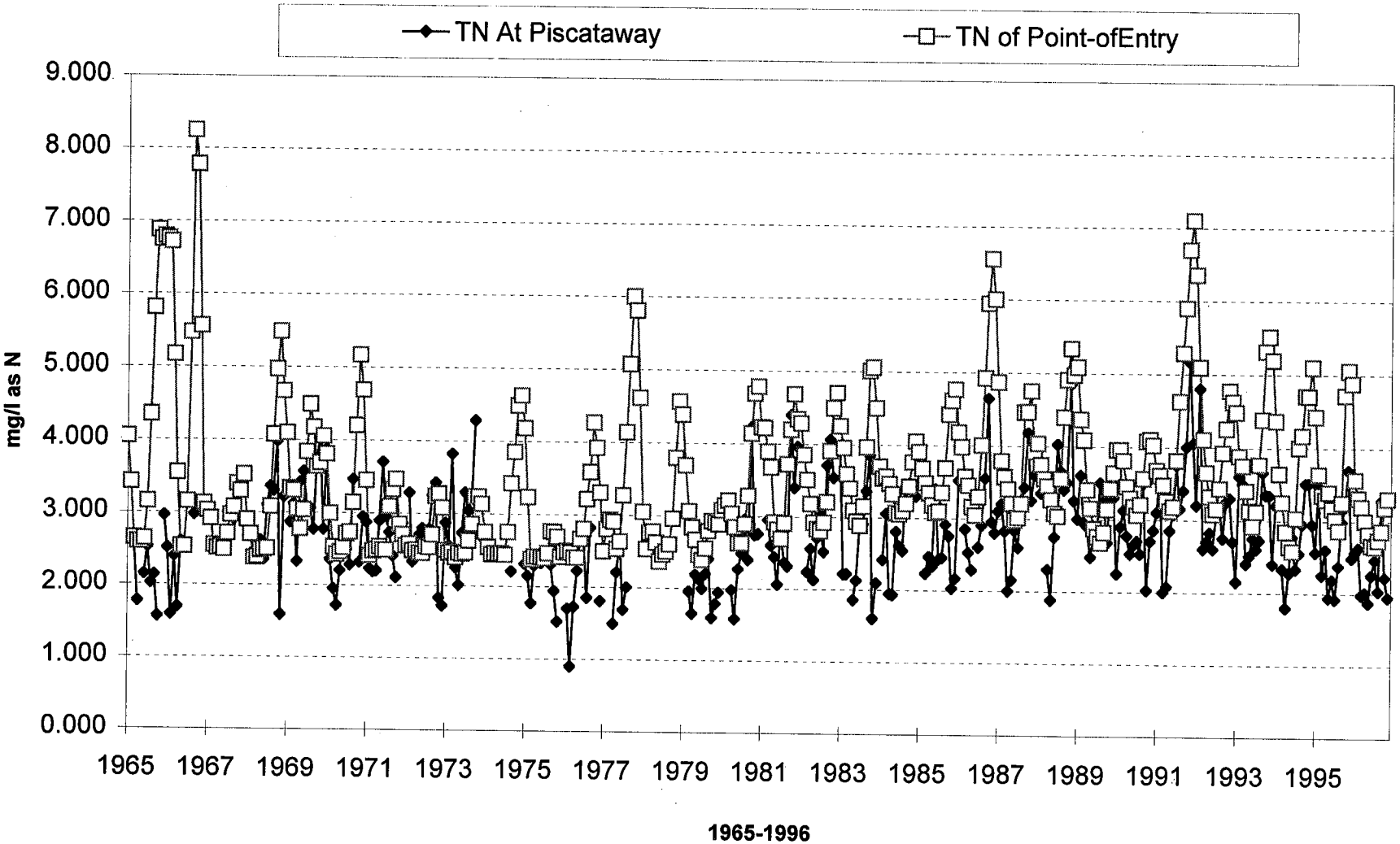

Figure 17. Total Nitrogen Concentration Trends

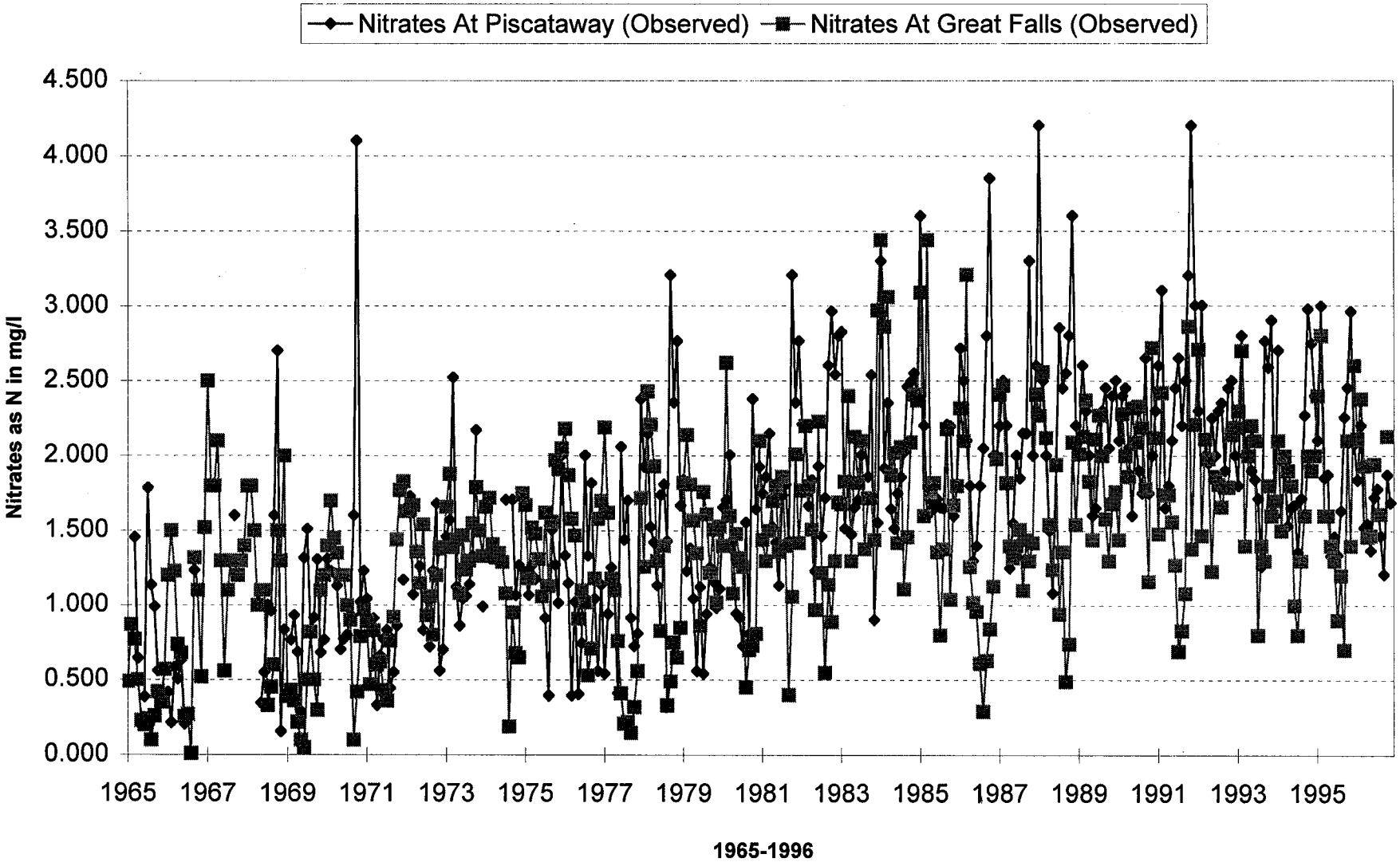

Figure 18. Nitrate Concentration Trends

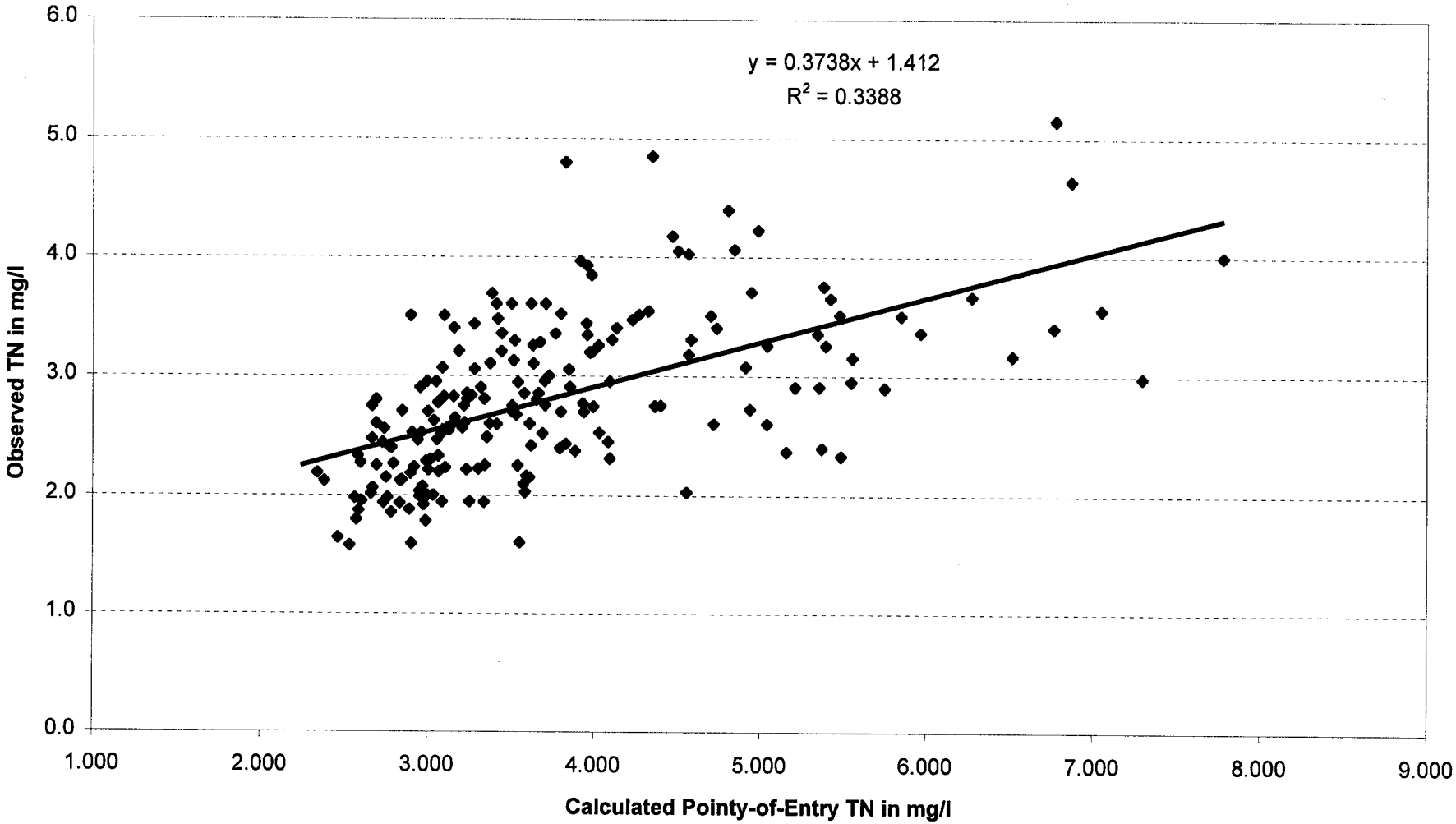

Figure 19. Calculated Point-of Entry TN Versus Observed Concentrations for Potomac Estuary at Piscataway Station 1980--1996