PHOSPHORUS LOADS TO THE CHESAPEAKE BAY SYSTEM

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1. Introduction and Purpose

The phosphorus loads from the publicly owned treatment works (POTW) or municipal wastewater treatment plants in the Chesapeake Bay basin can be estimated based on existing data and information. However, not all these phosphorus loads will reach the tidal system of the Bay and the Bay proper after they are released from the POTWs. A portion of the municipal phosphorus loads in the upper sub-basins of major tributaries will be lost before it reaches the fall line. That is, one pound of phosphorus which enters the free-flowing river is subject to in-stream processes (e.g., settling, algal uptake, mineralization, dilution, etc.) which result in a reduced load arriving at the fall line than originally entered the river.

The fraction of the municipal phosphorus loads transported from the sub-basins to the Bay is important to the assessment of the eutrophication status of the Bay. Such a fraction is called the delivery ratio. In general, the delivery ratio is higher for the downstream sub-basins than that for the upstream sub-basins. That is, the phosphorus loads in the downstream sub-basins may not be subject to significant attenuation and may reach the tidal system and the Bay proper in their entirety.

The purpose of this study is to quantify the POTW phosphorus loads entering the Bay. Three major river basins (Susquehanna, Potomac, and James) are selected for the study. Figure 1 shows the three major river basins and the sub-basins above the fall line. Nonpoint phosphorus loads above and below the fall line are also determined to compare with the fall line POTW loads.

For the other river basins of the Chesapeake Basin (e.g., York, Patuxent, etc.), little or no portion of these watersheds are located above the fall line. Therefore, it is assumed that all of the nonpoint and point phosphorus loads entering the waterways in these basins are delivered to the Bay (i.e., delivery ratio = 1.0).

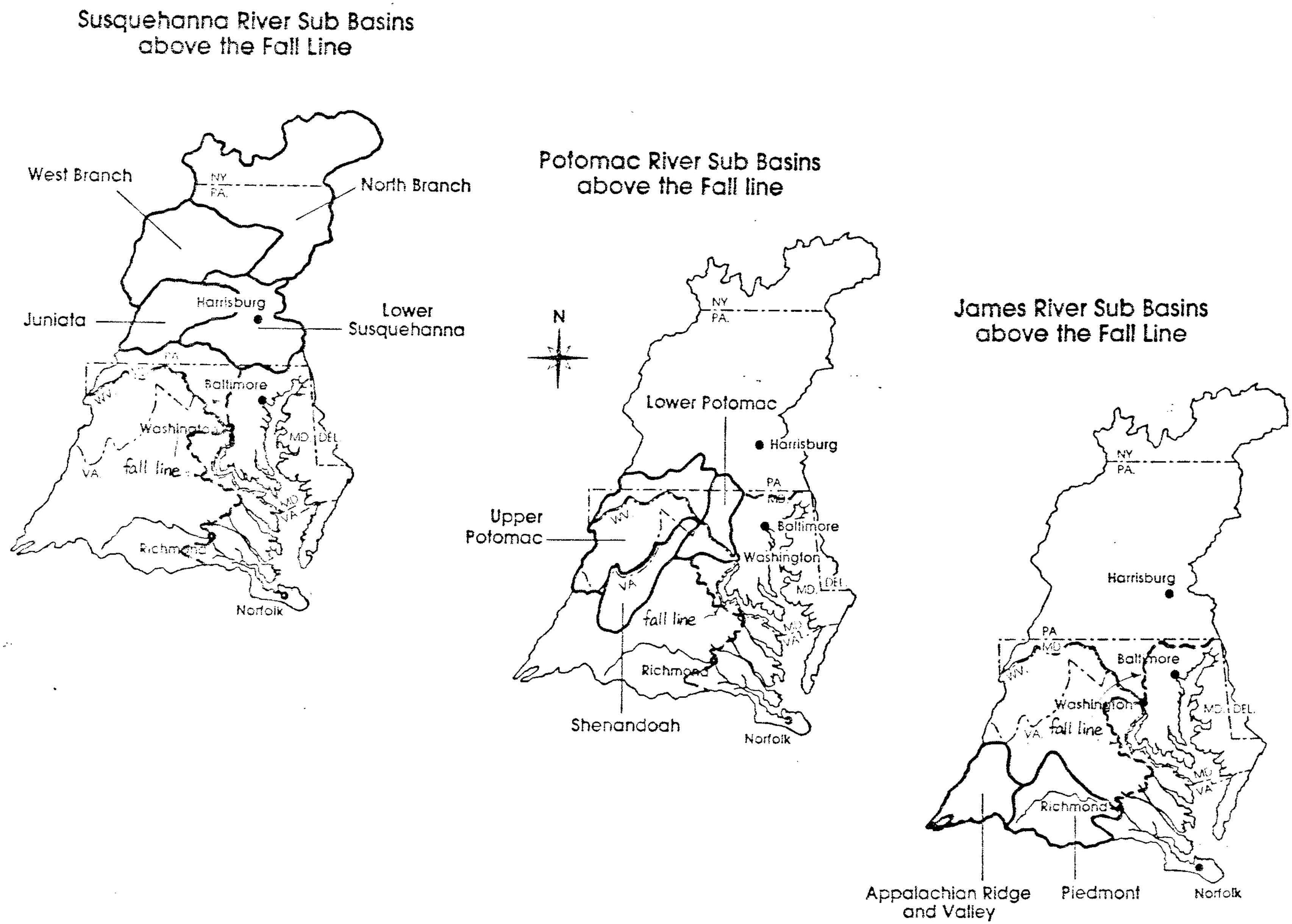

Figure 1. Sub-basins above the Fall Line in Susquehanna, Potomac, and James River Basins of the Chesapeake Bay (from U.S. EPA, 1983b)

When Considering nonpoint source loads, it is essential to take into account their substantial variability due primarily to hydrologic differences from year to year. For example, the fall line phosphorus load at Chain Bridge of the Potomac River attributable to nonpoint sources varies by more than a factor of 4 between "wet" and "dry" years. Thus, it would be useful to determine a range of phosphorus loads associated with possible extremes in hydrologic conditions. The concept of dry, average, and wet years is therefore utilized to define such a range in delivery ratios and loads.

The 1983 POTW loads are then incorporated with the delilvery ratios to form the POTW loads from the sub-basins to the Bay during dry year, average year, and wet year. Subsequently, the percentage contributions from nonpoint and point sources from each river basin of the Bay are derived. Finally, the errors associated with the phosphorus load estimates are also quantified.

2. Study Approach

A Chesapeake Bay Basin Model (the Bay Model) has been developed by the Northern Virginia Planning District Commission (NVPDC) for the EPA Chesapeake Bay Program (NVPDC, 1983). The output of the Bay Model is the nutrient (both phosphorus and nitrogen) loads from the watershed to the Bay system under various hydrologic conditions. In addition, the Basin Model has developed the delivery ratios for a number of selected sub-basins in the Chesapeake Bay watershed. The present study adopts the approach taken in the Basin Model study and utilizes the model results as well as other information developed by the Chesapeake Bay Program as a basis for this report. As a first step of the analysis, it is necessary to review the Basin Model and to evaluate its suitablility to this study.

2.1 Chesapeake Bay Basin Model

The Basin Model is an early version of HSPF (Hydrologic Simulation Program - Fortran) which consists of EPA's nonpoint pollution washoff submodel, known as NPS, operated in series with an in-stream (receiving water) pollutant transport submodel. In general, NPS simulation of nonpoint pollution loadings from impervious areas relies upon a dry weather pollutant accumulation rate and a first-order washoff algorithm while simulation of pollutant washoff from cropland pervious areas relies upon soil loss algorithms and sediment potency factors (i.e., ratio of pollutant mass to sediment mass).

The in-stream pollutant transport submodel simulates flow routing and pollutant transport in free-flowing streams and lakes with an hourly time-step. Each free-flowing reach is assumed to be completely mixed, and outflow is computed using a form of kinematic wave routing. In-stream processes represented by the model include: heat transport; biochemical oxygen demand (BOD) changes due to decay, sinking, sediment releases, and decomposition of dead algae; nitrification-denitrification; phosphorus transformations; and phytoplankton growth, respiration and sinking.

For the major river basins (e.g., Susquehanna, Potomac, and James) tributary to the Bay, the Basin Model simulates streamflow and transport of point source and nonpoint pollution loadings in the free-flowing streams upstream of the fall lines. For coastal watersheds (e.g., Chester, Choptank, and York river basins) which are drained by major estuaries and the Bay, this model simulates the freshwater streamflows and pollutant loadings delivered to tidal waters.

The model calibration and verification results were compared with the data collected by the U.S. Geological Survey (USGS) fall line monitoring study on a daily, monthly, and annual basis. Daily loading comparisons provided an excessively rigorous test of the nonpoint pollution loading factors derived from the test watershed modeling studies, while the monthly and annual loading comparisons were used to guide adjustments to receiving water submodel parameters and baseflow/interflow calibrations.

In summary, the model calculated fall line loads match the USGS fall line loads reasonably well. Most of the correlation coefficients between the calculated and measured loads are over 0.85 and many are 0.90 or higher (NVPDC, 1983). In general, inorganic phosphorus tends to exhibit the least satisfactory match in all three river basins (Susquehanna, Potomac, and James). However, total phosphorus loads are accurately simulated by the model. Further, goodness-of-fit is relatively better for total nutrients (total phosphorus and total nitrogen) than for nutrient components (e.g., inorganic phosphorus and nitrate nitrogen). As expected, monthly comparisons typically exhibit better goodness-of-fit than daily comparisons, due to the greater variability in daily loadings. In view of the need of the present study (development of annual phosphorus loads), applying the Basin Model results to the analysis is appropriate because the model yields reasonably accurate annual phosphorus loads.

2.2 Sources of Data and Information

The primary source of data and information used in this study is the result from the Chesapeake Bay Basin Model (NVPDC, 1983). Additional information such as delivery ratios was obtained from Mr. Joseph Macknis of U.S. EPA Chesapeake Bay Program (CBP). A number of study reports prepared by the CBP (EPA, 1982,1983a,b) were also consulted for additional information.

3. Results of Analysis

3.1 Delivery Ratio

The delivery ratios for the point and nonpoint phosphorus loads from the sub-basins above the fall line of the three major river basins are first analyzed for different hydrologic conditions. The year 1974 was selected as the typical (average) year because its flow-frequency curve most closely resembled that for the 1966-1978 period. NVPDC selected dry and wet years based upon consideration of flow-frequency curves for the period 1966-1978 for all the basins in the Chesapeake Bay and generally selected the year which was driest or wettest in the majority of basins. The year 1966 was considered the dry year while the year 1975 as the wet year. As such, model operations for an extended low streamflow period can be expected to provide the greatest insights into the baywide impacts of point source (municipal and industrial) discharges, while model operations for a "wet year" characterized by relatively high streamflows provide the greatest insights into "worse case" impacts of nonpoint sources of pollution. It should be pointed out that in the Basin Model, the delivery ratios and the phosphorus loads are calculated using the following assumptions:

- 1980 land use;
- 1980 POTW and industrial loads; and
- 1966 hydrology (dry year), 1974 hydrology (average year), and 1975 hydrology (wet year).

Table 1 shows the delivery ratios of nonpoint and point source loads for the three major river basins. As expected, the wet year hydrology

Table 1. Delivery Ratios of Phosphorus Loads for Sources above Fall Line*

Major Basin	Dry Year NPS[1]	Dry Year PTS[2]	Avg Year NPS[1]	Avg Year PTS[2]	Wet Year NPS[1]	Wet Year PTS[2]
Susquehanna:						
West Branch	36	17	50	11	57	12
North Branch	19	16	27	11	44	12
Juniata	19	20	27	16	38	17
Lower Susquehanna	59	51	82	59	90	64
Sub-basin Combined	33	26	46	22	60	24
Potomac:						
Upper Potomac	47	18	65	14	73	18
Shenandoah	47	18	65	8	76	10
Monacacy	57	38	79	32	92	41
Lower Potomac	61	57	85	68	99	89
Sub-basin Combined	50	24	69	17	83	23
James:						
Appalachian Ridge & Valley	55	32	57	30	57	34
Piedmont	46	74	76	69	94	80
Sub-basin Combined	49	65	66	61	78	70

* from J. Macknis of EPA Chesapeake Bay Program
1 Nonpoint Sources
2 Point Sources

yields much higher delivery ratios for nonpoint loads than the dry year or average year. On the other hand, the delivery ratios for point source loads vary slightly with the hydrologic conditions.

In general, the delivery ratio increases from an upstream sub-basin to a downstream sub-basin within any particular major basin. In addition, the delivery ratios of point source loads are always smaller than those associated with nonpoint source loads, properly reflecting the different nature between these two types of loads. There may be other factors, however, such as watershed slope and existence of reservoirs which further complicate the effect on a case-by-case basis.

3.2 Total Phosphorus Loads

Based upon the derived delivery ratios, the total phosphorus loads (both nonpoint and point source loads at the fall line) from each sub-basin can be quantified. Tables 2, 3, and 4 present the loads to the Bay for dry year, average year, and wet year, respectively. The point source loads are summarized as industrial and POTW loads. Both the 1980 and 1983 POTW loads which are derived from Lung (1984) are presented in these tables. Finally, the loads from the sources below the fall line are shown in Tables 2,3, and 4.

Since the spring, summer, and fall seasons are most critical from a eutrophication management standpoint, the assessments of long-term water quality impacts as well as the estimates of nutrient loadings are focused on the seven-month period extending from April 1st through October 31st (NVPDC, 1983). For each production run to generate the nutrient loads, the Basin Model produces flow/loadings for the April-October period (plus a one-month antecedent period). Thus, the total phosphorus loads shown in Tables 2 to 4 are on a loading rate (lbs/day) basis calculated for the period from March to October under the dry year, average year, and wet year hydrologic conditions, respectively.

Table 2. Phosphorus Loads (lbs/day) to Chesapeake Bay from Major River Basins, Dry Year

River Basin	Sources above fall line NPS	Ind*	POTW 1980+	POTW 1983+	Sources below fall line NPS	Ind*	POTW 1980+	POTW 1983+
Susquehanna:								
West Branch	1800		120	100				
North Branch	1730		750	620				
Juniata	260		90	80				
Lower Susquehanna	2630		780	650				
Total	6420	100	1740	1450	-	-	-	-
Potomac:								
Upper Potomac	960		130	150				
Shenandoah	530		150	160				
Monacacy	260		160	180				
Lower Potomac	380		30	30				
Total	2130	30	470	520	1420	930	3250	1650
James:								
Appalachian Ridge & Valley	660		35	40				
Piedmont	810		315	370				
Total	1470	-	350	410	475	1910	9940	9040

* 1980 loads
+ derived from Lung (1984)

Table 3. Phosphorus Loads (lbs/day) to Chesapeake Bay from Major River Basins, Average Year

River Basin	Sources above fall line		POTW		Sources below fall line		POTW	
	NPS	Ind*	1980+	1983+	NPS	Ind*	1980+	1983+
Susquehanna:								
West Branch	2520		70	60				
North Branch	2430		490	410				
Juniata	360		70	60				
Lower Susquehanna	3690		840	700				
Total	9000	90	1470	1230	-	-	-	-
Potomac:								
Upper Potomac	1330		110	120				
Shenandoah	740		65	70				
Monacacy	360		130	150				
Lower Potomac	530		35	40				
Total	2960	20	340	380	1730	930	3250	1650
James:								
Appalachian Ridge & Valley	680		35	40				
Piedmont	1320		320	370				
Total	2000	-	360	410	860	1910	9940	9040

* 1980 loads
+ derived from Lung (1984)

Table 4. Phosphorus Loads (lbs/day) to Chesapeake Bay from Major River Basins, Wet Year

River Basin	Sources above fall line NPS	Ind*	POTW 1980+	POTW 1983+	Sources below fall line NPS	Ind*	POTW 1980+	POTW 1983+
Susquehanna:								
West Branch	4070		80	70				
North Branch	7240		530	440				
Juniata	910		80	70				
Lower Susquehanna	10410		920	760				
Total	22630	100	1610	1340	-	-	-	-
Potomac:								
Upper Potomac	3690		140	160				
Shenandoah	1530		90	100				
Monacacy	1890		180	200				
Lower Potomac	1890		50	50				
Total	9000	30	460	510	4880	930	3250	1650
James:								
Appalachian Ridge & Valley	1570		40	50				
Piedmont	3330		370	420				
Total	4900	-	410	470	2680	1910	9940	9040

* 1980 loads

\+ derived from Lung (1984)

Tables 2, 3, and 4 show that nonpoint loads are significant above the fall line in each of these three major river basins. On the other hand, point source loads are much more significant in the Potomac and James basins below the fall line. While industrial loads are usually smaller than the POTW loads, their contribution above the fall line is even smaller. Also note the decrease of POTW loads from 1980 to 1983 (see Lung, 1984).

Tables 5, 6, and 7 show the relative contributions between nonpoint and point source loads in each major river basin under the dry year, average year, and wet year conditions. Also shown in Tables 5,6, and 7 are the percentage contributions from other river basins (Western Chesapeake and Upper Bay, Eastern Shore, Patuxent, Rappahannock, and York). The relative contributions from point sources decrease from dry year to wet year (from 61.9% to 28.8%). While the Susquehanna basin provides the most nonpoint loads, the James basin (particularly below the fall line) contributes the most point source loads among all river basins.

Finally, the total phosphorus loads from all major river basins under the dry year, average year, and wet year conditions are summarized in Table 8. Also shown are the total loads associated with different (1980 and 1983) POTW loads for comparison purpose. Under the same hydrologic condition, the difference between the 1980 and 1983 loads shown in Table 8 reflects the reduction in POTW loads from 1980 to 1983.

3.3 Error Estimates

The Basin Model provides reasonably good fit with the observed data, particularly in terms of the phosphorus loads at the fall line for the three major river basins. However, there are some differences between the model calculations and data which warrant some discussions. As a first step in error analysis, it is necessary to examine the sources of errors.

Table 5. Percent of Phosphorus Loads to Chesapeake Bay from Major River Basins, Dry Year

River Basin	Nonpoint	Ind*	POTW+
Susquehanna			
above fall line	15.7	0.2	3.6
below fall line	-	-	-
Potomac			
above fall line	5.2	0.1	1.3
below fall line	3.5	2.3	4.0
James			
above fall line	3.6	-	1.0
below fall line	1.2	5.0	24.0
Western Chesapeake and Upper Bay	1.5	0.4	16.3
Eastern Shore	4.3	0.3	1.1
Patuxent	0.6	0.1	1.9
Rappahannock	1.2	0.1	0.2
York	1.4	0.1	0.1
Total	38.1	8.5	53.4

* 1980 industrial loads (U.S. EPA, 1983b)
+ 1983 POTW loads (Lung, 1984)

Table 6. Percent of Phosphorus Loads to Chesapeake Bay from Major River Basins, Average Year

River Basin	Nonpoint	Ind*	POTW+
Susquehanna			
above fall line	19.2	0.2	2.6
below fall line	-	-	-
Potomac			
above fall line	6.3	-	0.8
below fall line	3.7	2.0	3.5
James			
above fall line	4.2	-	0.9
below fall line	1.8	4.4	20.9
Western Chesapeake and Upper Bay	3.1	0.3	14.3
Eastern Shore	4.4	0.2	0.9
Patuxent	0.7	0.1	1.6
Rappahannock	1.5	0.1	0.2
York	1.8	0.1	0.1
Total	46.8	7.4	45.8

* 1980 industrial loads (U.S. EPA, 1983b)
+ 1983 POTW loads (Lung, 1984)

Table 7. Percent of Phosphorus Loads to Chesapeake Bay from Major River Basins, Wet Year

River Basin	Nonpoint	Ind*	POTW+
Susquehanna			
above fall line	25.8	0.1	1.5
below fall line	-	-	-
Potomac			
above fall line	10.3	-	0.6
below fall line	5.6	1.0	1.9
James			
above fall line	5.6	-	0.5
below fall line	3.1	2.3	11.2
Western Chesapeake and Upper Bay	4.7	0.2	7.6
Eastern Shore	8.3	0.1	0.5
Patuxent	1.3	-	0.9
Rappahannock	3.1	0.1	0.1
York	3.5	-	0.1
Total	71.2	3.8	25.0

* 1980 industrial loads (U.S. EPA, 1983b)
+ 1983 POTW loads (Lung, 1984)

Table 8. Phosphorus Loads (lbs/day) to Chesapeake Bay

River Basin	Dry Year 1980[1]	Dry Year 1983[2]	Average Year 1980[1]	Average Year 1983[2]	Wet Year 1980[1]	Wet Year 1983[2]
Susquehanna	8450	7970	11840	10320	25710	24070
Potomac	10840	6680	11700	7670	21020	17000
James	14580	13305	15470	14220	20290	19000
Western Chesapeake	8870	4660	9760	5550	12430	8220
Eastern Shore	3100	2960	3400	3260	8640	8500
Patuxent	1930	490	1950	510	2730	1290
Rappahannock	920	730	1130	885	3150	2960
York	620	620[3]	900	900[3]	3100	3100[3]
Total	49310	37415	56150	43315	97070	84140

1. The point source loads are based on the 1980 POTW loads from U.S. EPA (1983b) and 1980 industrial loads

2. The point source loads are based on the 1983 POTW loads (Lung, 1984) and 1980 industrial loads

3. Assuming no change in loads from the York River basin between 1980 and 1983 because nonpoint loads dominate the total loads in this basin.

First, based upon the Basin Model results, some of the errors in calculating the phosphorus loads at the fall line can probably be attributed to the fact that the USGS flow-loading relationship do not explicitly account for seasonal differences (e.g., differences in cropland loadings that reflect changes in ground cover) in nonpoint source loadings whereas the Basin Model does (NVPDC, 1983). Second, wastewater treatment plant upgrading during the model calibration/verification period is not reflected in the constant wastewater discharge values used in the Basin Model. In the James River basin, wastewater discharges are the most significant contributors to simulated concentrations for the majority of the calibration/verification period, and therefore errors in discharge records can have a profound impact on the loading estimates at the fall line (NVPDC, 1983). Third, the approximations required to model transport (i.e., the transport submodel) through the large river basins may also contribute to the differences between the model calculations and the observed data.

In addition to the sources of error, it is also important to examine other factors which affect the accuracy of phosphorus loading estimates. First, the loading estimates depend highly upon the time scales associated with the concerned water quality constituent, phosphorus. In the Chesapeake Bay, the time scale to be considered for eutrophication control is a season or a year because daily variations in loads are not expected to affect the Bay. Thus, seasonal or annual phosphorus loads, instead of daily loads, are most appropriate to address the existing problem. The Basin Model (NVPDC, 1983) projects annual loads more accurately than monthly or daily loads. In this regard, the results (from the Basin Model) used in the present analysis minimize the errors in loading estimates because the loads are evaluated on an annual basis.

The accuracy of the treatment plant discharge records is another factor which significantly affects the accuracy of the estimates of loads reaching the Bay. However, such factor becomes more important for the POTWs in the lower sub-basins than the upper sub-basins because of the difference in the delivery ratios. For example, the north and west branches of the upper Susquehanna have a lower delivery ratio (11%) than the lower Susquehanna (59%) under the average year condition (see Table 1). As a result, more accurate estimates of the phosphorus loads released from the POTWs in the lower Susquehanna are required than in the upper Susquehanna. Further, the nonpoint phosphorus loads delivered from most of the upper sub-basins are generally more significant than the point source loads above the fall line. This factor further reduces the need for highly accurate POTW load estimates in the upper sub-basins.

For the same reason, however, the accuracy of the delivery ratios for the nonpoint source loads above the fall line is crucial to the quantification of the fall line nonpoint source loads. Table 4 indicates that the magnitude of the fall line nonpoint loads matches or exceeds the point source (primarily POTW) loads below the fall line under the wet year condition.

It can be concluded that the delivery ratios for nonpoint source loads are the key factor in determining the fall line total phosphorus loads. Effort is therefore, directed toward the determination of errors of fall line loads for the three major river basins. Table 9 presents the ratios of the Basin Model (annual) loads to observed loads at the fall line for the three major river basins from 1974 to 1978 (NVPDC, 1983). The average ratios are 1.17, 1.05, and 0.98 for the Susquehanna, Potomac, and James, respectively. Among the three basins, the error is smallest for the James (2%) and the largest for the Susquehanna (17%) with all factors considered.

Table 9. Ratio of Basin Model Loads to Observed Loads at the Fall Line*

Year	Susquehanna	Potomac	James
1974	1.21	1.19	1.03
1975	1.20	0.96	0.88
1976	1.15	1.02	1.02
1977	1.18	1.20	1.09
1978	1.13	0.90	0.98
Avg	1.17	1.05	0.98

*NVPDC (1983)

4. Summary and Conclusions

The report summarizes the phosphorus loads to the Chesapeake Bay from nonpoint and point sources in three major river basins (Susquehanna, Potomac, and James) under the dry year, average year, and wet year hydrologic conditions. Delivery ratios from the sub-basins of these three river basins are also derived from the results of the Chesapeake Bay Basin Model. Finally, the errors associated with the loading estimates are assessed.

The findings of this study are:

- Delivery ratios vary significantly with hydrologic conditions. As a result, total phosphorus loads to the Bay could vary substantially from year to year, depending on the hydrologic conditions.
- While the nonpoint sources contribute a major portion of the loads at the fall lines of the three major river basins, the point source loads account for a substantial portion of the loads below the fall lines of the Potomac and James River basins.
- On a baywide basis, about 62% of the phosphorus loads entering the Bay would come from point sources during dry year. This loading contribution would decrease to 29% during wet year.
- With the point source loads readily and accurately derived from available monitoring records, the major errors of the loading estimates rest on the derivation of nonpoint source loads, particularly for the sub-basins above the fall lines.

5. References

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