VIRGINIA WATER RESOURCES RESEARCH CENTER

DECEMBER 2006 REPORT OF THE ACADEMIC ADVISORY COMMITTEE TO VIRGINIA DEPARTMENT OF ENVIRONMENTAL QUALITY:

FRESHWATER NUTRIENT CRITERIA FOR RIVERS AND STREAMS

SPECIAL REPORT

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December 2006 Report of the Academic Advisory Committee to Virginia Department of Environmental Quality: Freshwater Nutrient Criteria for Rivers and Streams

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Acronyms and Abbreviations

AAC: Academic Advisory Committee
ALU: aquatic life use
CEDS: Comprehensive Environmental Data System
CFR: Code of Federal Regulations
cfs: cubic feet per second
cfs/sq.mi.: cubic feet per second per square mile
Chl-*a*: chlorophyll-*a*
cm/yr: centimeters per year
coseg: county segment
CPMI: Coastal Plain Macroinvertebrate Index
DEQ: Virginia Department of Environmental Quality
DT: detection limit
EPA: Environmental Protection Agency
FY: fiscal year
GWLF: Generalized Watershed Loading Functions
H_o: null hypothesis
ha: hectare
HBI: Hilsenhoff Biotic Index
HSPF: Hydrological Simulation Program – FORTRAN
HUP: Hydrologic Unit Program
ID: identification code
lbs/yr: pounds per year
µg/L: micrograms per liter
µS/cm: micro-Siemens per centimeter
MGD: million gallons per day
mg/L: milligrams per liter
mi^2: square miles
N: nitrogen
NAWQA: USGS National Water-Quality Assessment
NPS: non-point source
NO_2^- : nitrite
NO_3^-: nitrate
P: phosphorus
PO_4^{3-}: phosphate
PS: point source
R^2: coefficient of determination
SCI: Stream Condition Index
SPARROW: Spatially Referenced Regression on Watersheds
TKN: total Kjeldahl nitrogen
TMDL: total maximum daily load
TN: total nitrogen
TP: total phosphorous
U.S.: United States
USGS: United States Geological Survey

Contents

Summary

This report reviews activities conducted by the Academic Advisory Committee to the Virginia Department of Environmental Quality (DEQ) between July and December 2006. Activities were conducted for the purpose of developing recommendations for DEQ regarding nutrient criteria for freshwater rivers and streams.

In its June 2006 report to DEQ, the AAC recommended that DEQ establish nutrient criteria for rivers and streams by addressing independently the two effects described by the Environmental Protection Agency (EPA): localized and downstream-loading effects. The current report and activities address nutrient criteria development within that framework.

Section I of this report addresses the development of screening values for wadeable streams. Reference (*i.e.*, characteristics of relatively undisturbed or least disturbed streams) and effect-threshold concentrations for in-stream nutrients that have been suggested by other studies are reviewed. Reference values for total nitrogen (TN) and total phosphorus (TP) tend to vary by U.S. EPA's Nutrient Ecoregions and are generally higher in the eastern portions of the state than in the west. Effect-threshold values derived from other studies tend to vary more widely in part due to the variety of effect endpoints that have been employed in developing these threshold-concentration estimates. A review of TMDL studies that have been completed for nutrient-impaired streams revealed few usable reference concentrations because they are generally load-based studies (and do not report the streamflow information that could be used to calculate nutrient concentrations). An analysis of DEQ monitoring data found that Stream Condition Index (SCI, an indicator of benthic macroinvertebrate community status) values tend to vary negatively with nutrient concentrations. When using a statewide data set, these data allow the development of statistically significant regression models of the in-stream nutrient-SCI relationships. Application of these models yields "critical values" (*i.e.*, nutrient values corresponding with the SCI = 60 impairment threshold) for TN (0.8 mg/L), total Kjeldahl nitrogen (TKN) (0.3 mg/L), and TP (0.05 mg/L). However, even after a data-selection process intended to focus analysis on sites where no influence by non-nutrient stressors is evident, the variability of SCI response to nutrients is large; thus, the analysis did not allow direct derivation of appropriate screening values.

The committee is also conducting analyses to address development of localized criteria in wadeable streams; those analyses are not described in this report.

Section II of the report addresses the downstream-loading component of nutrient criteria. A pilot-scale analysis using data from the Rappahannock River Basin illustrates a potential approach to developing numeric nutrient criteria to address downstream-loading effects. The committee recommends that the downstream-loading component be developed as narrative criteria within an effective water-quality management framework. This framework includes localized criteria with numeric components, clearly defined impairment-designation processes, and water-quality management processes that are effective in addressing and mitigating impairments.

The report is presented as a draft, in anticipation of interactions among AAC members, interactions between the AAC and DEQ, and further analyses to be conducted in the coming months. A final report for the current fiscal year is due to DEQ in the summer of 2007.

I.A. Review of Other Studies with Relevance to Development of Nutrient Criteria for Wadeable Streams in Virginia

C. E. Zipper and J. L. Walker

This section reviews studies conducted by others with relevance to the development of nutrient criteria for wadeable streams in Virginia. Numeric values suggested by other studies that pertain to wadeable streams in Virginia, its neighboring states, and the mid-Atlantic region are provided in Table 1. Because the AAC has completed an extensive review of scientific literature on nutrient criteria development (Walker *et al.* 2006), this review will be brief. Several of the studies summarized below have been reviewed with greater detail in Walker *et al.* (2006).

Reference Values Representing "Relatively Undisturbed" or "Least Disturbed" Conditions

U.S. EPA calculated 25th-percentile values for water-borne nutrients in rivers and streams from all available data by aggregate nutrient ecoregions for the conterminous U.S. (for Virginia's waters, see U.S. EPA 2000a-c). EPA designated these 25th percentiles as "reference values," noting that the 25th percentiles of "all water bodies" tend to correspond with the 75th percentiles of reference water bodies (*i.e.*, relatively undisturbed or least disturbed water bodies of a given type). The AAC (2006) calculated comparable values for Virginia using Virginia DEQ ambient (10/99 – 9/05) and probabilistic (2001 – 2004) monitoring data for the ecoregions in Virginia (Because only a few streams in Aggregate Ecoregion 14 were sampled by the probabilistic monitoring program, the 25th percentile was not calculated from this data set). The AAC suggested that subregion 63 of Aggregate Ecoregion 14 was a more appropriate reference for Virginia because of its development status.

Smith *et al.* (2003) used modeling procedures (Spatially Referenced Regression on Watersheds, SPARROW) to estimate by EPA Aggregate Nutrient Ecoregion the natural background nutrient concentrations in rivers and streams. SPARROW is a recognized water-quality monitoring procedure that was developed over an extended time period by the U.S. Geological Survey (USGS). SPARROW utilizes USGS in-stream water-quality databases for calibration. Smith *et al.* (2003) note that the EPA assumption that the 25th percentiles of "all water bodies" tends to correspond with the 75th percentiles of reference water bodies is supported by very few studies, and that such findings may be influenced by the fact that most reference water bodies occur in relatively small streams. They expressed their results as the 75th percentile of predicted natural-background concentrations by ecoregion to allow comparisons to EPA's calculated 25th-percentile "reference" values. These comparisons were made with and without consideration of recent atmospheric nitrogen deposition.

In another study, the researchers followed the U.S. EPA reference approach in proposing nutrient criteria values but developed alternative nutrient regions, called *environmental nutrient zones*. The ecoregion subdivisions were based on differences in many factors (*e.g.*, soils, climate, vegetation, geology, and land use). The nutrient zones were determined from the relations between median TN or median TP and the most statistically significant environmental characteristics (excluding land use). The zones that included data from the New and Big Sandy rivers in Virginia (from the Kanawha-New River Basins NAWQA study) are Environmental Nitrogen Zone-4 (ENZ-4) and Environmental Phosphorus Zone-2 (EPZ-2). Criteria were proposed using the 75th percentile of data from sites within each zone that represent "reference" conditions, *i.e.*, sites in watersheds with less than 25 percent agricultural land use. Proposed criteria values for the zones that included data from the New River and Big Sandy River were 0.67 mg/L for TN and 0.05 mg/L for TP (Robertson *et al.* 2001). Criteria were also suggested based on the 25th percentile of all the data within a given zone. From the 25th percentile of all the data for ENZ-4, a TN criterion of 0.51 mg/L could be expected. The 25th percentile for EPZ-2 would yield a TP criterion of 0.02 mg/L (Robertson *et al.* 2001).

Clark *et al.* (2000) obtained data from 85 sites across the United States and used those data to estimate concentrations and yields of selected nutrients in streams draining relatively undeveloped basins. The median values in Table 1 are from sites in Virginia, its neighboring states, and other states within EPA Region 3. Nitrate-N data were available for 16 sites of this type, whereas other nutrient parameters were only available from 7 sites. The data represent mean annual flow-weighted concentrations for the 1990 – 1995 time periods.

The AAC has recommended to Virginia DEQ that nutrient concentrations in "relatively undisturbed" or least-disturbed streams should not be considered as an appropriate basis for establishing nutrient criteria in the rivers and streams of Virginia. Instead, the numeric criteria should be based on a method that adheres closely to the Code of Federal Regulations (CFR) by protecting the designated uses of the water body. In fact, the CFR defines the term criteria as "elements of State water quality standards, expressed as constituent concentrations, levels, or narrative statements, representing a quality of water that supports a particular use. When criteria are met, water quality will generally protect the designated use" [40 CFR 131.3(b)].

Other Suggested Nutrient Thresholds

A nutrient threshold can be defined as the concentration at which an effect, such as eutrophication or biological impairment, begins to occur. Potential threshold values derived from studies conducted within Virginia and the region are included here. Some of the published nitrogen and phosphorus values discussed in this section, however, were not presented in the literature as "threshold values." For example, Hornberger *et al*. (1977) recommend not using the values from their study as strict thresholds but rather general indications of the trophic condition.

Hornberger *et al.* (1977) used a subjective ranking of the eutrophic state of six river sites, five in Virginia and one in New Hampshire, based on their best professional judgment, knowledge of the land use, and measurements of nitrates, phosphates, and chlorophyll-*a*. They also determined the productivity at each site from continuous measurements of dissolved oxygen, temperature, and solar radiation and then compared their proposed eutrophic state with the results from the productivity study. They determined that productivity measurements can be used to classify the eutrophic state of rivers. Based on the production and respiration measurements, Hornberger *et al.* (1977) classified Baker River in New Hampshire as "clean" (oligotrophic). This river had NO_3+NO_2(N) concentrations of 0.1 – 0.2 mg/L and PO_4(P) concentrations of <0.003 mg/L. From the productivity measurements in the Rappahannock River, the water quality was listed as possibly eutrophic even though the river seemed "unpolluted" from the qualitative impressions of the authors. The range of nutrient concentrations for the Rapphannock River overlapped with those of the high eutrophic rivers (NO_3+NO_2[N] = 0.3 – 0.7 mg/L; PO_4[P] = 0.003 – 0.05 mg/L). The nutrient concentrations for the four rivers rated eutrophic from the productivity measurements (Mechums, South Fork

Rivanna, Rivanna, and South) ranged from 0.1 to 1.0 mg/L for NO_3+NO_2(N) and <0.003 to 0.30 mg/L for PO_4(P) (Hornberger *et al.* 1977).

Ponader *et al.* (2005) conducted a study of periphytic algae and diatom assemblages in Virginia streams. From the observed changes in the diatom assemblages, the authors suggested threshold limits of 0.5 mg/L for NO_3-N and 0.05 mg/L for TP to protect against conditions they termed as nutrient impairment. NO_3-N was used as an indicator of nitrogen status because other nitrogen-concentration variables (TKN, TN) were not measured successfully. The NO_3-N threshold was selected because benthic chlorophyll-*a* levels above 100 mg/m^2 occurred at NO_3-N levels above 0.5 mg/L, although several sites with NO_3-N levels above 0.5 mg/L did not exceed benthic chlorophyll-*a* levels of 100 mg/m^2. The TP threshold identification was based on the finding that several diatom species indices correctly assigned samples to the TP concentration categories 0.01 – 0.05 mg/L and 0.05 – 0.10 mg/L.

Stevenson *et al.* (2006) studied the correspondence of various algal biomass indicators with nutrient concentrations in 102 Michigan and northwestern Kentucky streams. High algal biomasses were rare in both areas if TP was < 0.03 mg/L and TN was <1 mg/L, and they recommended these levels as potential "targets to prevent a high probability of nuisance accrual of Cladophora." They also recommended that, to protect streams with naturally low levels of productivity and algal biomass, "nutrient concentrations should probably be constrained" to 0.4 mg/L TN and 0.01 mg/L TP. The lead author of this study is assisting the state of Kentucky in its development of nutrient criteria.

Laboratory and field studies by Lemly (2000) and Lemly and King (2000) demonstrated a direct linkage between bacterial growth on benthic macroinvertebrates and macroinvertebrate mortality. Lemly and King (2000) studied two third-order, low flowing, cypress-gum wetland streams in the Cape Fear basin in North Carolina. The stream they classified as unenriched had macroinvertebrate orders that were free of bacterial growth, mean TN concentrations between 0.715 – 1.97 mg/L, and mean TP concentrations below 0.200 mg/L (0.054 – 0.198 mg/L). The stream in the study that was classified as enriched, based primarily on land use (hog farms were present in the watershed), had macroinvertebrate orders that were colonized by bacteria, and generally had higher nutrient concentrations (mean TN = 1.93 – 3.89 mg/L; mean TP = 0.169 – 0.620 mg/L) (Lemly and King 2000).

A Technical Advisory Committee recommended to Virginia DEQ in 1987 that the range of 0.1 – 0.2 mg/L for TP in flowing waters should be considered as appropriate for screening purposes (IEN 1987). The committee report provides little background on the reasoning applied by the group in recommending these limits, other than the likelihood that variations in natural background levels of TP in streams made a range of concentrations appropriate instead of designating a single threshold concentration. The group agreed that no standard for nitrogen in flowing waters was necessary.

Table 1. Reference values for nutrient concentrations and other potential threshold values in Virginia and regional waters reported in other studies. All values are expressed as total nitrogen and total phosphorous unless otherwise noted.

Study	N (mg/L)	P (mg/L)	Source
Relatively Undisturbed / Least Disturbed Reference Values:			
Ecoregion 11			
25th percentile of Virginia ambient monitoring data	0.38	≤0.01	AAC 2006
25th percentile of Virginia probabilistic monitoring data	0.265	≤0.01	AAC 2006
25th percentile of available monitoring data (regional)	0.31	0.01	U.S. EPA 2000a
75th percentile of SPARROW-modeled background	0.29 ±0.09	0.02 ±0.01	Smith *et al.* 2003
Ecoregion 9			
25th percentile of Virginia ambient monitoring data	0.45	0.025	AAC 2006
25th percentile of Virginia probabilistic monitoring data	0.35	0.02	AAC 2006
25th percentile of available monitoring data (regional)	0.69	0.037	U.S. EPA 2000b
75th percentile of SPARROW-modeled background	0.28 ±0.08	0.05 ±0.02	Smith *et al.* 2003
Ecoregion 14			
25th percentile of Virginia ambient monitoring data	0.92	0.054	AAC 2006
25th percentile of available monitoring data (regional)	0.71	0.031	U.S. EPA 2000c
25th percentile of available monitoring data (regional, subregion 63)	0.87	0.0525	U.S. EPA 2000c
75th percentile of SPARROW-modeled background	0.76 ±0.30	0.02 ±0.005	Smith *et al.* 2003
Statewide and Regional			
75th percentile of environmental nutrient zones containing Virginia watersheds with less than 25% agricultural land use	0.67	0.05	Robertson *et al.* 2001
25th percentile of all data in environmental nutrient zones containing Virginia streams	0.51	0.02	Robertson *et al.* 2001

Median values from “undeveloped, relatively undisturbed” stream basins in mid-Atlantic U.S.	0.384	<0.03	Clark *et al.* 2000
Medians, undeveloped (as oxidized N, phosphate P)	0.176	<0.008	Clark *et al.* 2000

Other Suggested Nutrient Thresholds			
Corresponding nutrient conditions for Baker River (NH) rated oligotrophic based on productivity measurements	0.1 – 0.2	<0.003	Hornberger *et al.* 1977
Corresponding nutrient conditions for Rappahannock River (VA) rated possibly eutrophic based on productivity measurements	0.3 – 0.7	0.003 – 0.05	Hornberger *et al.* 1977
Corresponding nutrient conditions for Virginia rivers rated eutrophic based on productivity measurements	0.1 – 1.0	<0.003 – 0.30	Hornberger *et al.* 1977
Virginia: Change in diatom assemblages		0.05	Ponader *et al.* 2005
Virginia: Periphytic algae >100 mg/m^2 (as nitrate N)	0.5		
Kentucky and Michigan: Prevent a high probability of nuisance Cladophora	1.0	0.03	Stevenson *et al.* 2006
Kentucky and Michigan: Protect stream communities where low levels of in-stream productivity are natural conditions	0.4	0.01	
North Carolina: “Unenriched” stream with benthic macroinvertebrates free of bacteria	≤1.97	≤0.198	Lemly and King 2000
North Carolina: “Enriched” stream with benthic macroinvertebrates colonized by bacteria	≥1.93	≥0.169	Lemly and King 2000
Current Virginia “screening values”	n/a	0.1 – 0.2	IEN 1987

I.B. Analysis of Nutrient Concentrations in Approved TMDLs in Virginia

G. Yagow

As of November 21, 2006, twelve TMDLs with a nutrient component had been approved in Virginia. Nine stream segments have approved TMDLs for phosphorus, and three segments have approved TMDLs for nitrates (DEQ 2006a). A summary of these TMDLs is given in Table 2.

Table 2. Nutrient TMDLs approved in Virginia.

Stream	Contractor	HUP	Model	Reference Watershed
South Run	Louis Berger	A19R	GWLF	Popes Head Creek
Cooks Creek	Tetra Tech	B25R, B26R	GWLF	Hays Creek?
Mill Creek	Tetra Tech	B27R	GWLF	Hays Creek
Pleasant Run	Tetra Tech	B29R	GWLF	Hays Creek
Muddy Creek	Tetra Tech	B22R	GWLF	Hays Creek
UT to Chickahominy	GMU, Tetra Tech	G05R	Reckhow	
Spring Branch	NR RC&D, MapTech	K32R	Eutromod	
NF Blackwater	Tetra Tech	L08R		Big Chestnut Creek
Muddy Creek	UVA	B42	HSPF	
Dry River		B41, B43	HSPF	
North River		not modeled		

Stream	TMDL	Annual Flow	Average TP Endpoints	TMDL	In-stream N
	(lbs P/yr)	(cm/yr)	(mg/L)	(lbs N/yr)	(mg/L)
South Run	1,124		0.053 - 0.070		
Cooks Creek	9,367				
Mill Creek	6,001				
Pleasant Run	3,910				
Muddy Creek	6,088				
UT to Chickahominy	432.69				
Spring Branch	427.10		0.0481*		
NF Blackwater	6,960				
Muddy Creek				not given	10
Dry River				not given	10
North River					

* Simulated by the EUTROMOD model in Bryant Pond as corresponding to the eutrophication threshold in Carlson's Trophic State Index.

All of the nitrate TMDLs were developed for exceedences of the nitrate drinking water standard (10 mg/L NO_3-N). These TMDLs used the nitrate standard as the TMDL target, and the TMDL was written in terms of concentrations rather than loads.

All of the phosphorus TMDLs were based on stressor analyses for identified benthic impairments and used the reference watershed approach for setting the TMDL endpoints. All of the phosphorus TMDLs were defined in terms of annual loads. Only two of these TMDLs included information in their online reports related to in-stream concentration equivalents, as shown in Table 2.

Although it would be possible to calculate mean annual concentrations if mean annual flows were available for the various TMDLs, this information was not presented in any of the reports except for South Run, and to some extent in the Spring Branch TMDL. In the South Run TMDL, mean annual flows and mean annual concentrations were presented for various allocation scenarios and compared with mean annual concentrations based on Tributary Strategy cap loads as shown in Table 3.

Table 3. Comparison of South Run TMDL average annual total phosphorus concentrations for various allocation scenarios with Tributary Strategy mean annual target concentrations.

Scenario	**Nonpoint Source[1]**		**Point Source**		**Average Annual Simulated TP**	**Tributary Strategy***					
						Shenandoah River			**Rappahannock River**		
	(mg/L)	(cfs)	(mg/L)	(MGD[2])	(mg/L)	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
1	0.053	9.58	1.59	0.072	**0.070**	**0.054**	**0.126**	**0.219**	**0.055**	**0.122**	**0.27**
2	0.053	9.58	0.3	0.247	**0.062**						
3	0.053	9.58	-	-	**0.053**						

[1] Based on GWLF simulation results for South Run
[2] million gallons per day
* Source: DEQ 2005

The simulated annual average TP concentrations for South Run, the minimum mean annual concentrations for meeting Tributary Strategy cap loads, and the concentration in Spring Branch that corresponded with a Trophic Status Index of 60, all fall within a narrow band from 0.048 to 0.070 mg/L.

I.C. Analysis of DEQ Monitoring Data to Develop Nutrient Screening Values

C. E. Zipper and E. P. Smith

Summary

This section describes an analysis of Virginia DEQ monitoring data conducted for the purpose of developing nutrient screening values. DEQ provided a data set that included both biological monitoring (benthic macroinvertebrates) and water-quality monitoring data for identical locations and similar times. Those data were screened for the purpose of identifying and removing observations for which the data record contains evidence of potential effects on the aquatic community by non-nutrient stressors. The data were then analyzed with the goal of defining relationships between in-stream nutrient concentrations and the Stream Condition Index (SCI), an indicator of the benthic community status. The analysis yielded statistically significant relationships between SCI and log-transformed nutrient variables (TKN, TN, and TP, expressed as mg/L concentrations). These relationships indicate that "critical values" (nutrient concentrations that correspond with the SCI = 60 impairment threshold) for TKN, TN, and TP are 0.3, 0.8, and 0.05 mg/L respectively. These levels are similar to the nutrient thresholds identified by prior studies (Section I.A. of this report) and TP impairment thresholds estimated by the few TMDL studies that cited concentrations (Section I.B.). However, SCI responses to nutrient concentrations are highly variable, as indicated by the wide prediction intervals occurring within the SCI-prediction models. Therefore, we consider this analysis to be inconclusive as a basis for recommending in-stream nutrient concentrations that may be used as screening values.

Introduction

The screening-value approach differs from other methods for defining water-quality criteria because nutrients differ from traditional stressors in a fundamental manner. Whereas traditional stressors generally exert toxic influences that directly degrade the system, low-level inputs of nutrients serve to increase the productivity of the system. At higher levels (over enrichment), nutrients may become a stress to the system. Furthermore, variations among physical characteristics of river-and-stream systems affect the responses of those systems to nutrient enrichment. As a result, biotic responses to nutrient enrichment at specific concentration levels are highly variable among river and stream systems.

The screening value approach recommended to protect localized uses in wadeable streams in Virginia was described more fully in the June 2006 AAC report to DEQ. The process is summarized in Figure 1. The screening value approach is applied with the intention of limiting assessment errors despite the inherent variability of responses to nutrients by aquatic systems. Type I errors occur when water quality assessments list the stream as impaired, but the stream supports its designated uses. Type II errors occur when the water quality assessment fails to list the stream as impaired even though the stream does not support its designated uses (Figure 2).

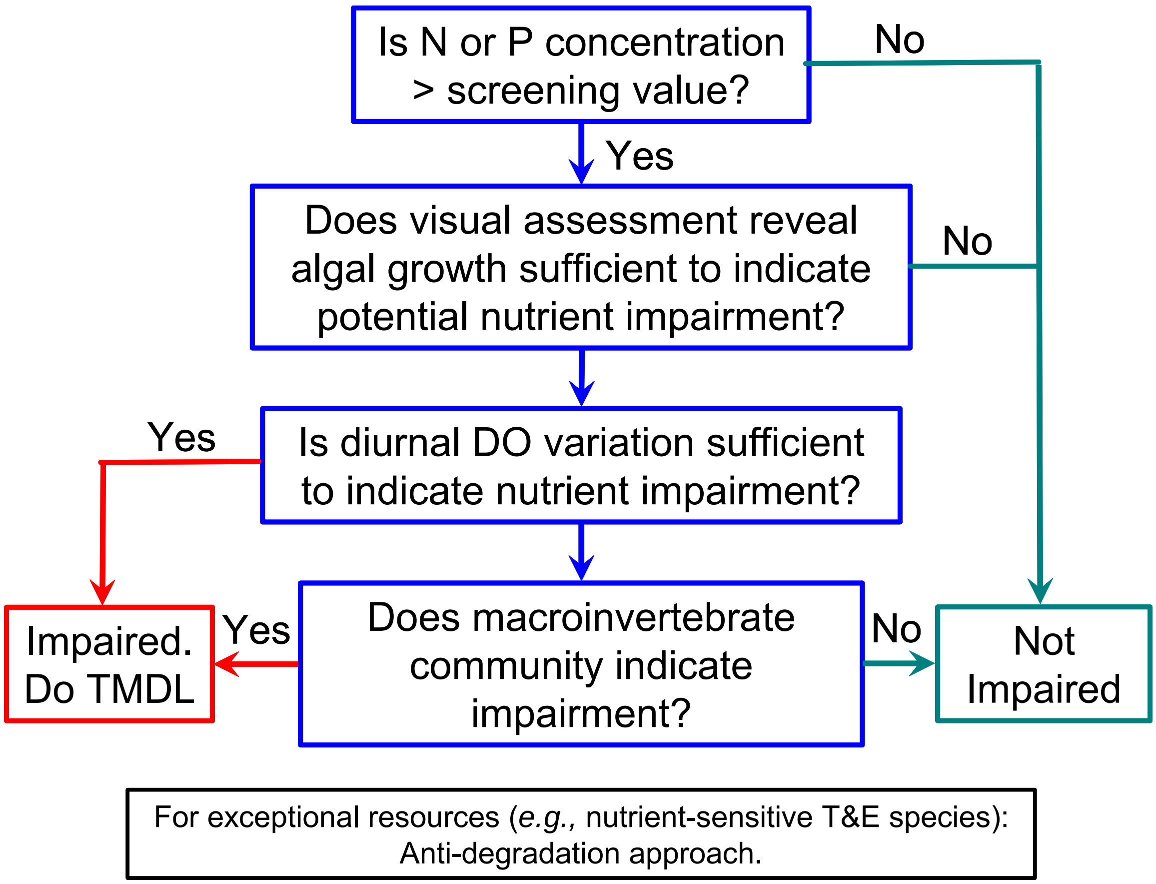


Figure 1. The screening process recommended by the Academic Advisory Committee to the Virginia Department of Environmental Quality for implementation as the localized component of nutrient criteria in wadeable streams (AAC 2006).

		Ho: Stream Supports Designated Use	
		TRUE	FALSE
Water-quality assess-ment lists stream as impaired	YES (Reject Ho)	Type I Error	Correct Decision
	NO (Accept Ho)	Correct Decision	Type II Error

Figure 2. A representation of the Type I and Type II error concepts as they apply to water quality assessments.

A secondary goal of using the screening value approach is to efficiently utilize DEQ's resources while meeting the goals of the Clean Water Act. A screening-value exceedance does not necessarily result in an impairment designation. Instead, the response to a screening-value exceedance is additional stream monitoring. The purpose of the additional monitoring is to provide a more definitive assessment. Therefore the screening value can be established conservatively so as to limit Type II errors despite the nutrient-response variability of stream communities. Type I errors (and the consequent resource expenditures for TMDL studies of streams where the designated use has not been impaired) can also be limited by this approach.

Application of the screening-value approach, however, does require an evaluation of trade-offs: Setting the screening value very conservatively, so as reduce the Type II error, probably increases the number of non-impaired sites caught by the screen. For each of these sites, DEQ must expend resources to make the correct assessment decision (limit Type I errors). Thus, the screening value approach embodies a trade-off between error limitation and water-monitoring resource expenditures. In this analysis, we evaluate potential screening values within the above conceptual framework.

Methods

A data set for use in this analysis was prepared by DEQ and provided to the AAC in late November 2006. As a first step in data preparation, DEQ personnel accessed the Ecological Data Application System (EDAS) database (1989 to present) to identify all records of benthic macroinvertebrate community assessment in Virginia streams that were conducted at a level sufficient to calculate a stream condition index (SCI) value (Burton and Gerritson 2003). All water-quality records associated with the biological monitoring location were accessed and used to create two data files: (1) all records within the three months preceding and one month following each biological monitoring observation, and (2) all water-quality monitoring records for locations where biological monitoring observations had been recorded since 1989. DEQ probabilistic, routine ambient, and special study biological monitoring observations were included. The biological monitoring records contained a calculated SCI value and various benthic macroinvertebrate and habitat metrics. The water-quality monitoring records contained site-measured parameters such as conductivity, pH, and dissolved oxygen. Laboratory measured nutrient parameters and other associated water-quality constituents such as non-filterable residue (total suspended solids) were also included.

Nutrient Variables

Various analytical procedures have been used to estimate in-stream nutrients. The nutrient parameters in the data set, therefore, were analyzed and in some cases adjusted to produce a consistent water-quality data set suitable for subsequent analysis.

When total nitrogen (TN) was not measured directly but constituent components were measured, TN was calculated as the sum of the constituents. Where nitrite-N was reported as ≤0.05 mg/L, a proxy value for nitrite-N was estimated based on the corresponding nitrate-N value (the majority of nitrite-N values ≤0.05 mg/L were assigned as ≤0.01 mg/L). Where total Kjeldahl N (TKN) or oxidized N was not measured directly but could be calculated from measured values of TN and the corresponding TN component, those values were calculated and used in the analysis. The majority of TKN values were reported at 0.1 mg/L precision; those few values reported at 0.01 precision and >0.07 mg/L were rounded to 0.1 mg/L. When TKN was reported as ≤0.1 mg/L, that value was rounded to 0.05 mg/L for use in the analyses.

Because TP was analyzed only to the 0.1 mg/L level of precision prior to July 1999, all data prior to July 1999 were deleted. Additionally, TP observations made after June 1999 that were reported as ≤0.1 mg/L (14 of 1286 TP observations) were deleted. The correspondence of measured ortho-P with measured TP values was evaluated to determine the feasibility of using measured ortho-P to estimate missing TP values; that possibility was rejected. The ortho-P variable was determined as unsuitable for use in subsequent analyses because of a high number of observations reported as ≤0.05 mg/L during the 2003 – 2004 period.

Data Record Screening and Selection

Data were screened to identify and eliminate biological monitoring observations potentially influenced by non-nutrient stressors. Any monitoring location described or coded as being below a point-source discharge was removed from the database. DEQ "reference filters" (*i.e.,* criteria used by DEQ biologists in locating biological monitoring references) were applied (Table 4, DEQ 2006b). Any location demonstrating a consistent pattern of failing to satisfy the reference filtering screens for reasons other than TN, TP, and dissolved oxygen (DO) were eliminated from subsequent analyses. The "% Urban" composition of watershed areas was determined for pre-2005 probabilistic monitoring locations using land-use data compiled by the DEQ probabilistic monitoring group. Additionally, land-use data assembled by the Virginia Institute of Marine Sciences GIS lab in late 2005 was applied to DEQ monitoring stations to identify urban land-use percentages. For those monitoring locations represented in both DEQ and VIMS databases, the urban land-use percentages were in close agreement.

Each biological monitoring observation was paired with a single water-quality observation. For most probabilistic samples, only one water-quality monitoring observation was available during the 3 months prior to or 1 month following the biological monitoring event. For locations where more than one water-quality measurement was available, criteria used to select the water-quality monitoring observation included (a) availability and completeness of water-quality nutrient measurements, (b) temporal proximity, and (c) measured total suspended solids concentrations that indicated a non-stormflow sampling event.

Table 4. DEQ reference-filter standards for use in Mountain and Piedmont ecoregions.

% Urban	<5%
Total Nitrogen*	< 1.5 mg/L
Total Phosphorus*	< 0.05 mg/L
Specific Conductance	< 250 uS/cm
Dissolved O_2*	> 6 mg/L
pH	< 6 or > 9
Habitat Scores:	
Total	>140**
Channel Alteration	>11
Epifaunal Substrate/Cover	>11
Riparian Vegetative Zone	>11
Embeddedness***	>11

* Not applied in current study
** Interpreted as >10 per habitat element quantified. At most sites, fewer than 14 habitat variables had been evaluated.
*** Mountains only

Observations within the Coastal Plain physiographic region (EPA Level III ecoregions 63 and 65 – see Figure 3) were scrutinized, recognizing that the SCI has been validated only for Virginia's mountain and piedmont regions. Fifteen "Coastal Plain" observations were found to occur within the post-screening data. These observations were included because (a) recorded SCI values were highly correlated ($R^2 = 0.76$) with the Coastal Plain Macroinvertebrate Index (CPMI) values used by DEQ for Coastal Plain assessments; (b) assessment decisions for 14 of the 15 sites would be identical using either the SCI or the CPMI value, and the 15th Coastal Plain site was located very close to the Piedmont boundary; and (c) inclusion of the Coastal Plain sites improved the statistical relationships between water-quality nutrients and SCI.

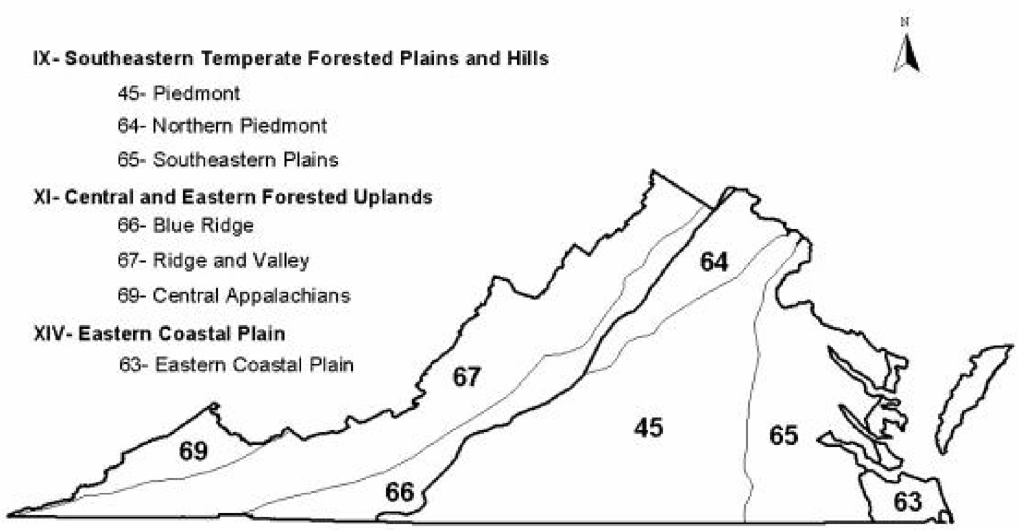


Figure 3. EPA Nutrient Ecoregions (9, 11, and 14) and Level III Ecoregions in Virginia.

Correspondence of SCI Values to Water-Quality Nutrient Levels

Data analysis was initiated by evaluating the probability of detecting biological impairments at various water-quality nutrient levels using the scale in Table 5 (DEQ 2006b). Stressed and severely-stressed categories were considered to be impaired.

Table 5: Virginia Stream Condition Index (SCI) scores and associated aquatic life use (ALU) tiers and assessment listings.

SCI Score ALU	ALU Tiers	Assessment
<42	Severe Stress	Impaired
>42 – <60	Stress	Impaired
>60 – <73	Good	Not Impaired
>73	Excellent	Not Impaired

A series of statistical models were constructed and analyzed in an effort to predict SCI scores based on in-stream nutrient and chlorophyll-*a* measurements.

Results

A total of 262 biological monitoring observations at 181 locations were selected as suitable for use in the subsequent analysis (Table 6). Distributions of nutrient and chlorophyll-*a* water-quality values were non-normally distributed (skewed) (Figure 4), as is commonly observed in water-quality studies. Therefore, log-transformed values were used in the development of the predictive models.

Nutrient concentrations in the analyzed data set were highest in Ecoregion 14 and lowest in Ecoregion 11 (Table 7), as expected based on prior analyses (AAC 2006). TKN, TN, TP, and chlorophyll-*a* levels varied among the tiers of aquatic life use in Ecoregion 9, where the greatest number of SCI observations were located. In general, higher nutrient and chlorophyll-*a* values tended to occur in association with lower aquatic life use tiers in Ecoregion 9 (Table 7). This pattern was not present in Ecoregion 11. Instead, nutrient levels in Ecoregion 11 tended to decline with increasing benthic macroinvertebrate community stress (as indicated by declining SCI scores). Few benthic-impaired sites, however, were located in Ecoregion 11. Only 4 SCI observations, all indicating severely stressed communities, were located in Ecoregion 14.

Histograms representing the percentages of benthic macroinvertebrate observations within various aquatic life use tiers for various nutrient-concentration ranges, statewide, are displayed in Figure 5. Stressed and severely stressed communities are assessed by DEQ as impaired. These histograms show generally increasing levels of stress with increasing nutrient and chlorophyll-*a* values, although with varying consistency. This pattern is least evident for oxidized N (N as NO_2^-+NO_3^-) and is highly evident for TKN and TP.

Table 6. Characteristics of biological and associated water-quality monitoring observations selected for analysis. Mean and median units: NO_2+NO_3, total Kjeldahl nitrogen (TKN), total nitrogen, and total phosphorus = mg/L; chlorophyll-*a* = µg/L.

	- - - Ecoregion - - -			State
	11	9	14	
Observations	80	178	4	262
Locations	55	122	4	181
Count				
SCI	80	178	4	262
$NO_2 + NO_3$	77	156	4	237
TKN	70	147	4	221
Total Nitrogen	73	162	4	239
Total Phosphorus	79	171	4	254
Chlorophyll-*a*	44	103	3	150
Mean				
SCI	71.60	61.50	34.78	64.18
$NO_2 + NO_3$	0.23	0.31	1.53	0.31
TKN	0.12	0.36	0.68	0.29
Total Nitrogen	0.34	0.65	2.11	0.58
Total Phosphorus	0.017	0.047	0.110	0.04
Chlorophyll-*a*	0.95	1.94	2.11	1.65
Median				
SCI	74.30	64.18	33.43	67.78
$NO_2 + NO_3$	0.12	0.17	1.44	0.16
TKN	0.10	0.30	0.65	0.20
Total Nitrogen	0.27	0.46	2.14	0.42
Total Phosphorus	0.01	0.04	0.08	0.03
Chlorophyll-*a*	0.50	1.14	1.99	0.89

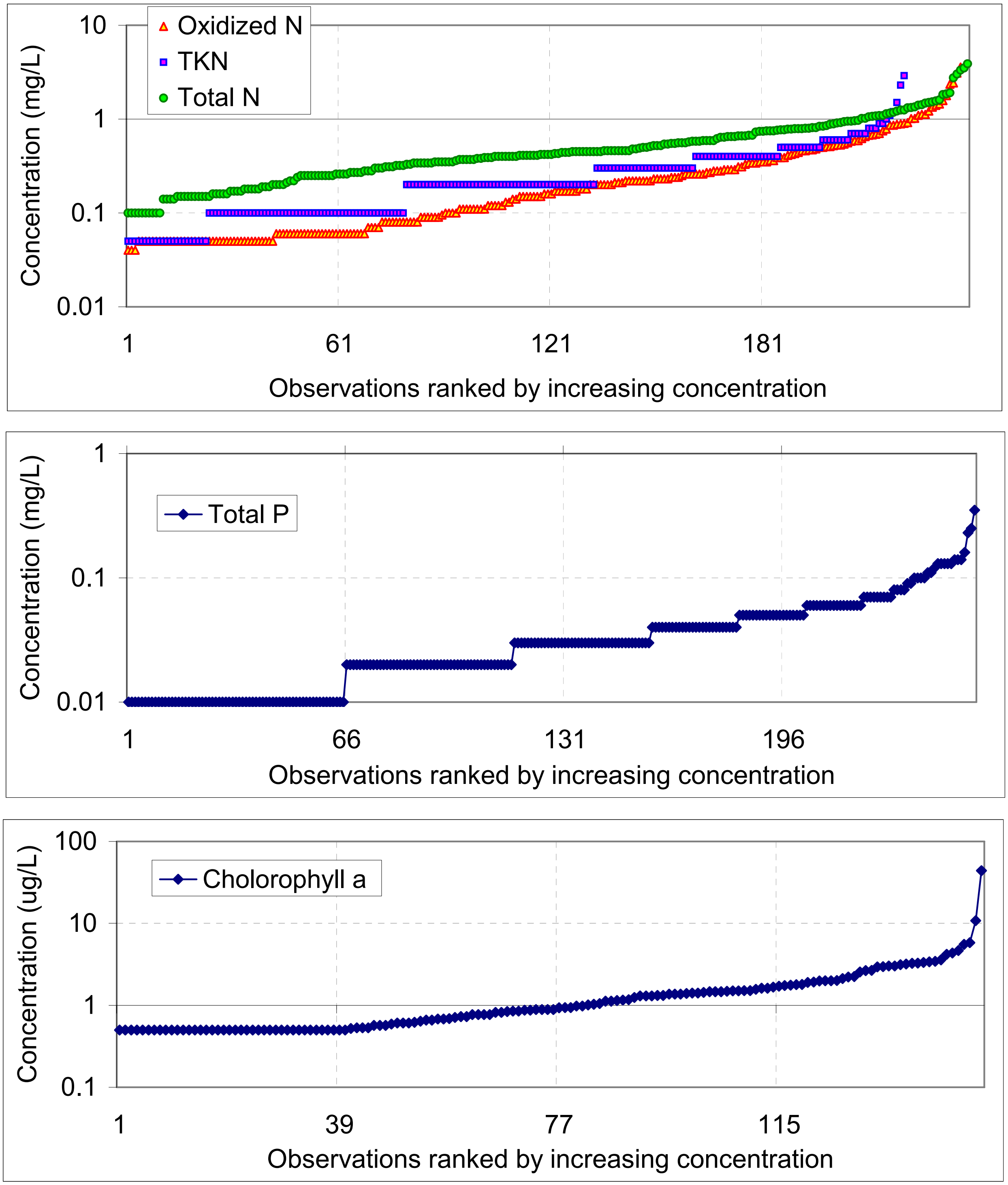


Figure 4. Distributions of selected variables within the data set used for analysis; because distributions are skewed, variables are plotted on log scales.

Table 7. Mean nutrient and chlorophyll-*a* values (mg/L), stream condition index (SCI) values, and SCI observation counts by ecoregion and aquatic life use tier.

	- - - - - - - - Aquatic Life Use Tier - - - - - - - - -				
	Excellent	**Good**	**Stress**	**Severe Stress**	**All**
NO_2+NO_3					
Eco 11	0.17	0.33	0.16	0.05	0.23
Eco 9	0.31	0.30	0.32	0.36	0.31
Eco 14				1.53	1.53
All	**0.23**	**0.31**	**0.30**	**0.56**	**0.31**
TKN					
Eco 11	0.13	0.12	0.10	0.05	0.12
Eco 9	0.22	0.28	0.38	0.80	0.36
Eco 14				0.68	0.68
All	**0.16**	**0.23**	**0.36**	**0.74**	**0.29**
TN					
Eco 11	0.30	0.44	0.20	0.10	0.34
Eco 9	0.55	0.60	0.62	1.06	0.65
Eco 14				2.11	2.11
All	**0.40**	**0.56**	**0.58**	**1.22**	**0.58**
TP					
Eco 11	0.017	0.017	0.018	0.010	0.017
Eco 9	0.036	0.039	0.055	0.084	0.047
Eco 14				0.110	0.110
All	**0.024**	**0.033**	**0.051**	**0.085**	**0.039**
Chl-*a*					
Eco 11	1.01	0.92	0.88	0.50	0.95
Eco 9	1.08	1.26	3.06	2.59	1.94
Eco 14				2.11	2.11
All	**1.04**	**1.16**	**2.75**	**2.39**	**1.65**
SCI					
Eco 11	77.77	67.43	54.96	41.12	71.60
Eco 9	76.49	67.24	52.57	35.37	61.50
Eco 14				34.78	34.78
All	**77.25**	**67.30**	**52.82**	**35.52**	**64.18**
Count					
Eco 11	42	31	6	1	80
Eco 9	29	81	51	17	178
Eco 14				4	4
All	**71**	**112**	**57**	**22**	**262**

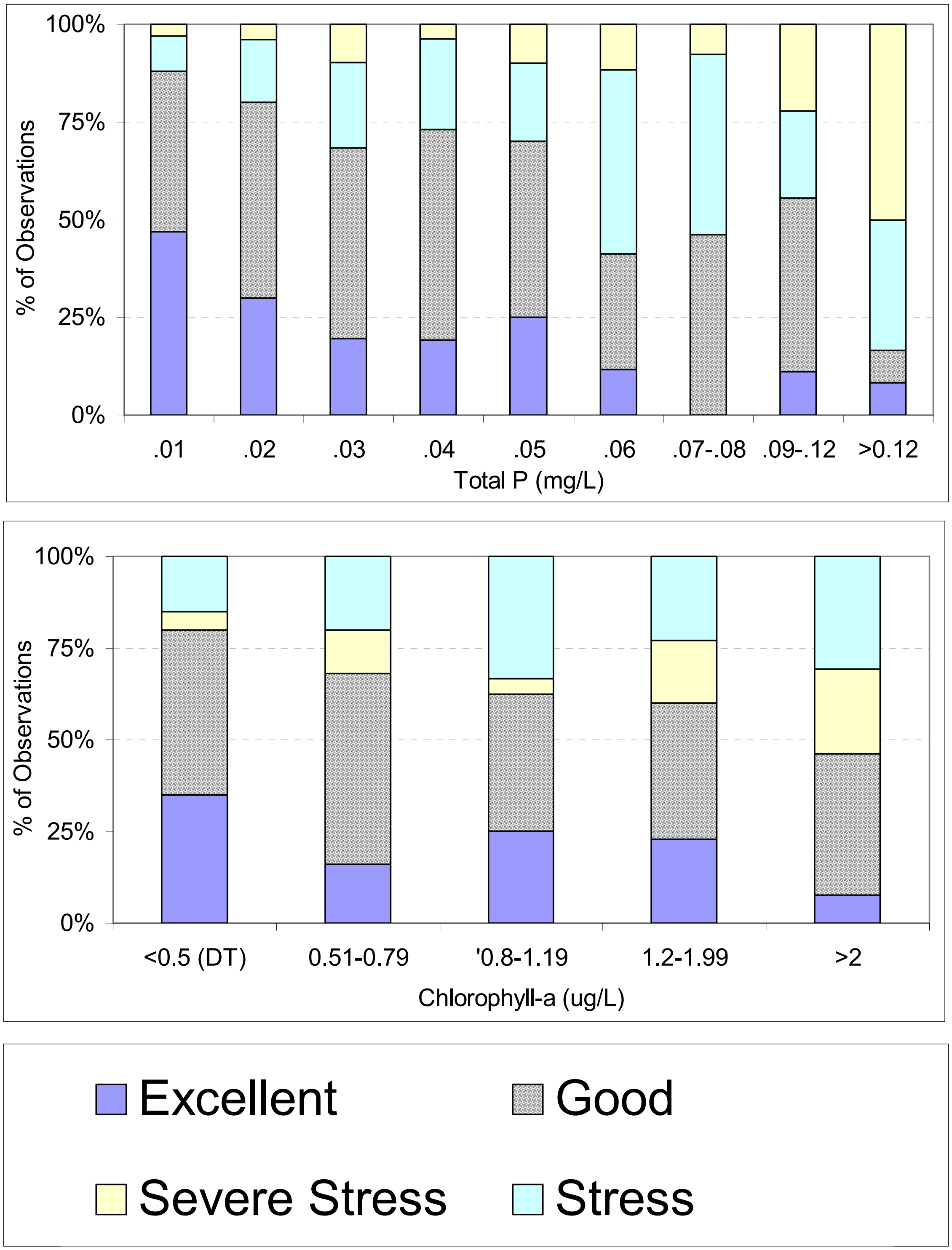
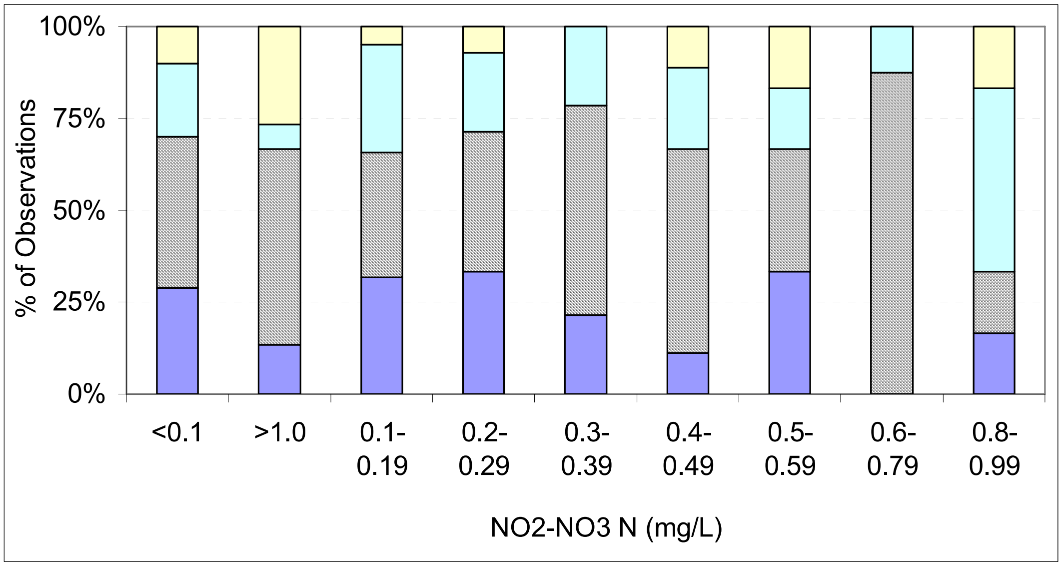
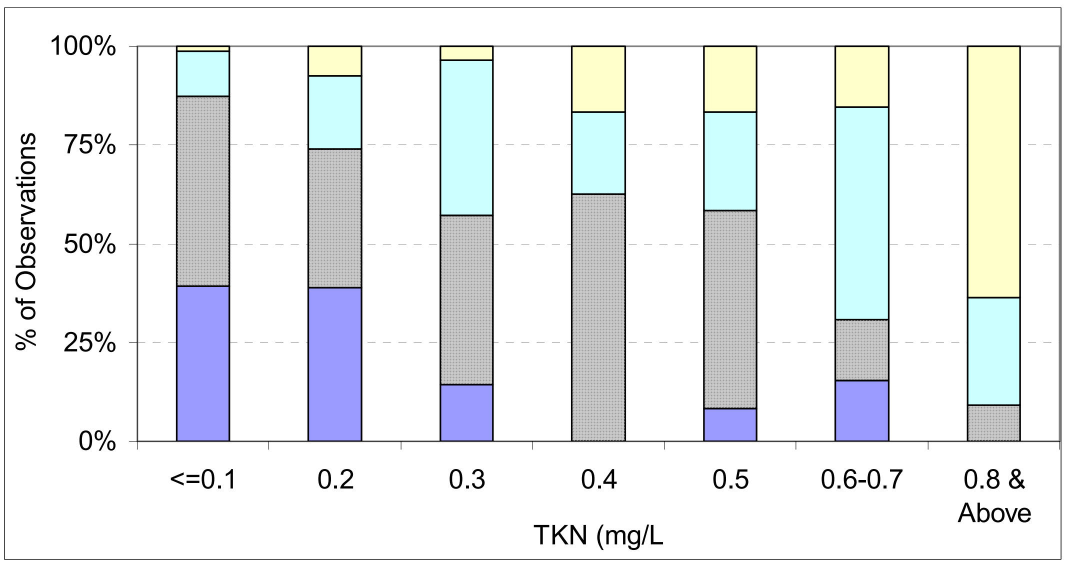


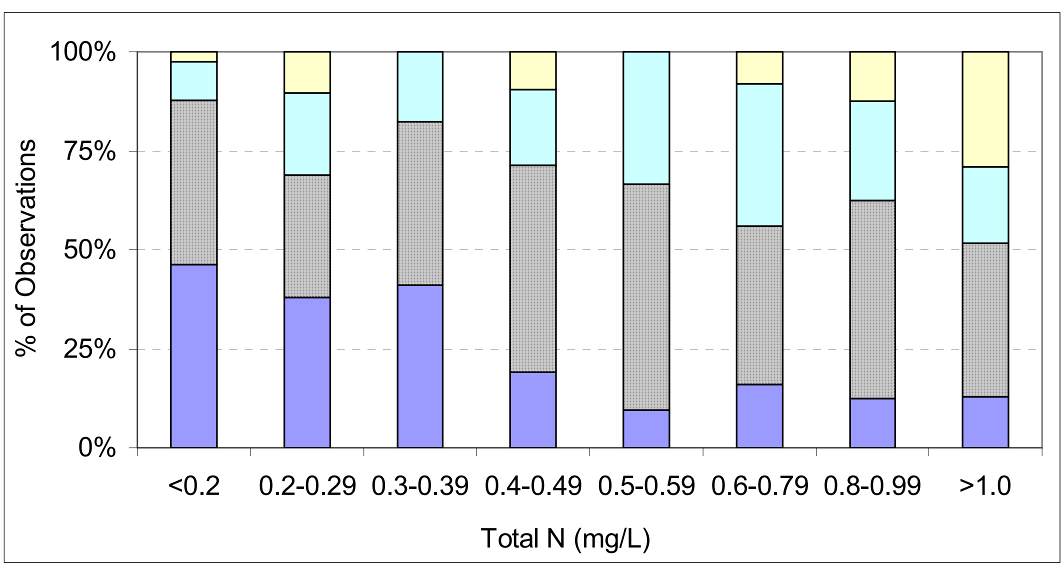
Figure 5. Histograms representing percentages of benthic macroinvertebrate observations within various aquatic life use tiers occurring within different nutrient categories. Stressed and severely stressed communities are defined as impaired. Histograms for nitrogen water-quality variables are displayed on the following page.



100%
75%
50%
25%
0%
% of Observations
<0.1
>1.0
0.1-0.19
0.2-0.29
0.3-0.39
0.4-0.49
0.5-0.59
0.6-0.79
0.8-0.99
NO2-NO3 N (mg/L)



100%
75%
50%
25%
0%
% of Observations
<=0.1
0.2
0.3
0.4
0.5
0.6-0.7
0.8 & Above
TKN (mg/L



100%
75%
50%
25%
0%
% of Observations
<0.2
0.2-0.29
0.3-0.39
0.4-0.49
0.5-0.59
0.6-0.79
0.8-0.99
>1.0
Total N (mg/L)

Several models were developed to test the dependence of SCI on in-stream nutrients using log-transformed nutrient concentrations as independent variables (Table 8). Of the nutrient variables determined as suitable for model development, TKN showed the strongest relationship with SCI (highest R^2) whereas oxidized N showed the weakest relationship. TP demonstrated a stronger monovariate relationship with SCI than did TN. A multivariate model combining TKN with TP demonstrated a slightly higher R^2 (0.24) than did a monovariate model using only TKN ($R^2 = 0.23$). Because the oxidized nitrogen showed such a weak relationship with SCI ($R^2 \leq 0.01$), it was not considered further.

Table 8. Stream Condition Index (SCI) prediction models evaluated.

Independent Variable	Functional Form	Adjusted R^2	Critical Value*
Oxidized N	SCI = 61.4 - 1.38 * Ln(NO2+NO3)	0.008	
TKN	SCI = 51.4 - 7.70 * Ln(TKN)	0.233	0.3
TN	SCI = 58.9 - 6.21 * Ln(TN)	0.127	0.8
TP	SCI = 39.6 - 6.85* Ln(TP)	0.177	0.05
Chlorophyll-*a*	SCI = 62.4 - 7.34 * Ln(Chl-*a*)	0.134	
TKN and TP	SCI = 45.0 - 6.00 * Ln(TKN) -2.53 * Ln(TP)	0.241	n/a

* mg/L value where SCI = 60

Using the monovariate models, “critical values” for TKN, TN, and TP were determined as the concentrations corresponding with SCI = 60. This SCI value was selected for defining critical nutrient values because it is used in stream assessments to differentiate impaired from non-impaired stream systems. The resulting critical values identified for TN and TP (Table 8) were at levels higher than common reference values for ecoregions 9 and 11 (Table 1, Section I.A.), which comprise most of the state’s land area. The 60% confidence interval (which represents a 20% risk of generating a Type II error, or a 20% probability that the screening value would fail to capture an impaired site) failed to encompass SCI = 60 for TKN and TP concentrations above common reference values (Table 1, Section I.A.; Figure 6).

The bivariate prediction model (utilizing TKN and TP) was also unable to define higher-than-reference-value TKN and TP combinations that would be capable of predicting SCI > 60 with acceptable precision (Figure 7).

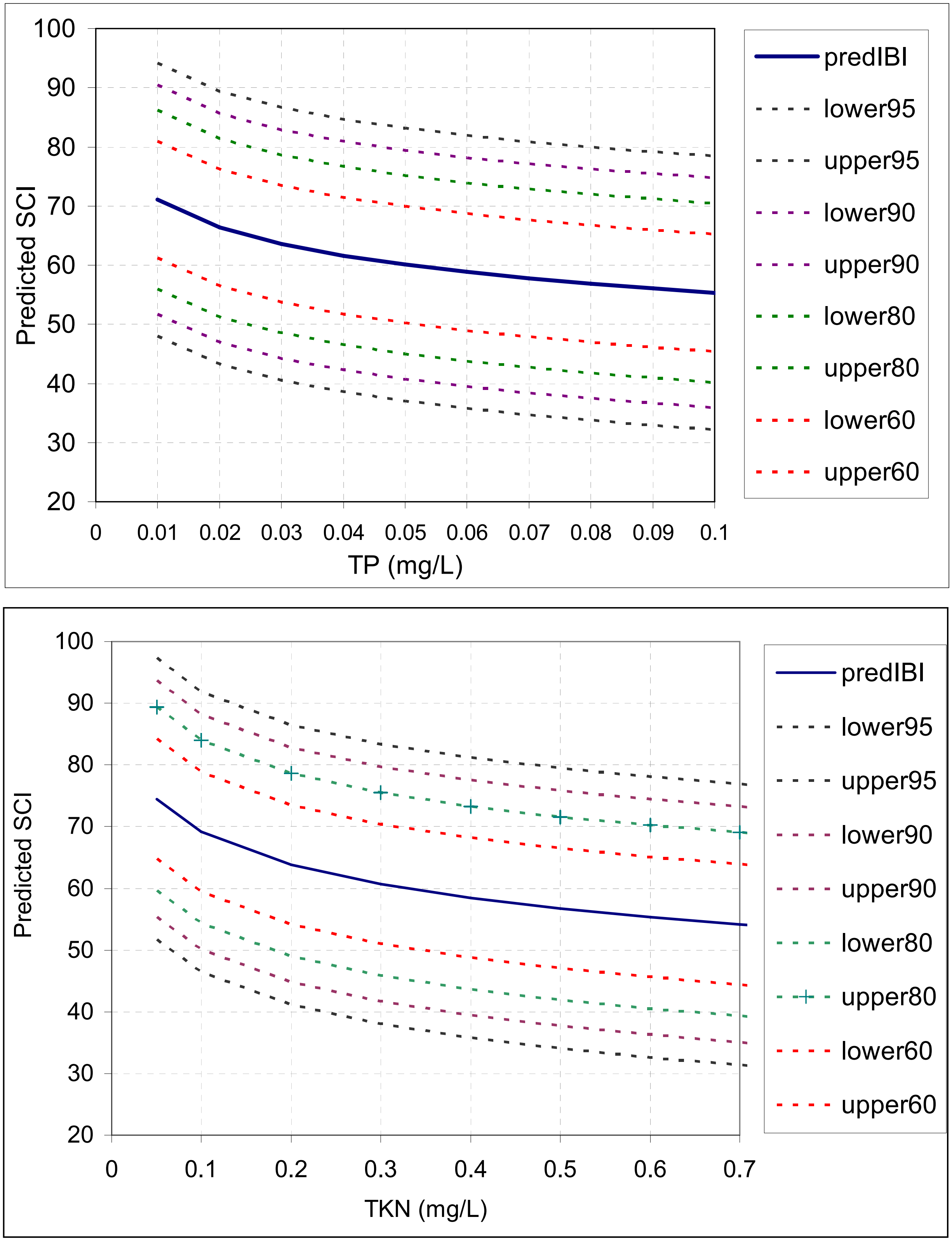


Figure 6. Stream Condition Index (SCI) dependence on TP and TKN represented by monovariate prediction models (solid line), with 95%, 90%, 80%, and 60% prediction intervals (dashed lines).

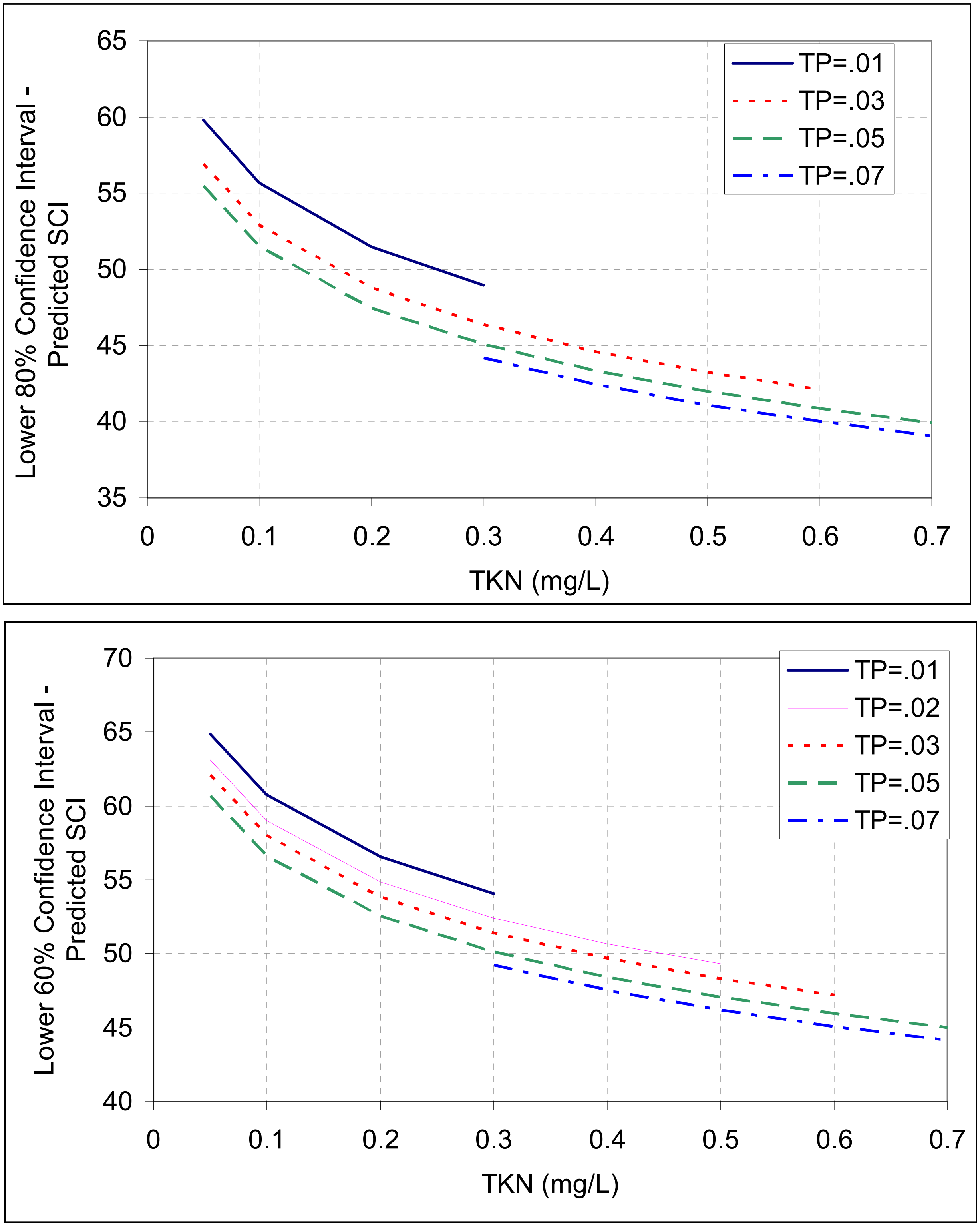


Figure 7. Lower boundaries of the 80% (above) and 60% (below) Stream Condition Index (SCI)-prediction intervals for various (TKN, TP) combinations contained within the data set, as per the bivariate (TKN, TP) SCI prediction model.

Discussion

The indication that TKN is a better predictor of SCI than TN is consistent with the observation that TKN measurements from unfiltered samples (such as those which are utilized by DEQ monitoring) include planktonic algae biomass N. It appears reasonable to expect that planktonic algae levels would be higher in nutrient-impaired streams than in other streams.

The nitrogen critical values of 0.8 mg/L for TN and 0.3 mg/L for TKN are consistent with the threshold value identified by Ponader *et al.* (2005) for periphytic algae > 100 mg/m^2 (0.5 mg/L nitrate N). These critical values are comparable to nutrient thresholds identified in other studies (Section I.A.). The critical value for TP (0.05 mg/L) is identical to the TP value identified by Ponader *et al.* (2005) as a threshold for change in algal species composition in Virginia waters. The TP critical value is also comparable to in-stream P concentrations for the two nutrient TMDL studies that included TMDL restoration target concentrations (Section I.B.).

The nutrient-SCI relationships embodied by the SCI prediction models are consistent with expectations and with the assumption that underlie the analysis: In all statewide relationships analyzed, high water-quality nutrient concentrations are related negatively to measured SCI values. These relationships, however, are highly variable, as evidenced by their low R^2 values and wide prediction intervals. Results indicate that the use of the critical values in Table 8 as screening values would be likely result in numerous Type II errors (waters with a SCI < 60 but not identified as possibly nutrient impaired by the TKN, TN, and TP screening values). Thus, if the screening values are to be defined with the goal of limiting Type II errors, defining screening values as nutrient concentrations lower than the critical values would be warranted. However, the data variance embodied by the models creates prediction intervals that are sufficiently wide to render them unusable as a basis for recommending statistically valid screening values.

It is possible that the nutrient concentration-SCI variance may, in reality, be less than that indicated by the data set. Part of the variance could have occurred due to influences by non-nutrient stressors that were not successfully identified by the data screening procedure. Some low SCI scores (including SCI values < 60 that indicate impairment) were found to be present at very low nutrient levels. In fact, for both TN and TP, approximately 10% of the monitoring locations within the lowest concentration category (Figure 5) were associated with SCI < 60. We checked the presumption that such impairments may be non-nutrient related by searching the data set for all observations where low SCI values were associated with low TN and TP concentrations. Of the six observations found to be in the lowest quartile for TN, TP, and SCI, five also exhibited high Hilsenhoff Biotic Index (HBI) scores (highest quartile), indicating a community with a high level of tolerance to organic and nutrient pollution. Unfortunately, most of these observations were taken from probabilistic monitoring samples so we have no way to check whether the low nutrient values recorded by the single water-quality monitoring observation represented are characteristic of the nutrient concentrations that are generally experienced at these locations.

What Are Appropriate Screening Values?

It is possible that the data set used for the analysis reflects both nutrient and non-nutrient stressor effects. Although an effort was made to discard all SCI observations affected by non-nutrient stressors prior to data analysis, there is no guarantee that this goal was achieved. The possibility that the data set includes both nutrient and non-nutrient stressor effects must be considered given that analysis results include apparent benthic impairments (SCI values < 60) at locations with nutrient concentrations that are quite low relative to effect-based thresholds cited in Section I.A.

Considering only the analysis that was described above, one interpretation could be that screening values could be defined as equivalent to reference values characteristic of “relatively undisturbed” or “least disturbed” waters because there appears to be some opportunity for Type II error regardless of the screening value selected. However, we would not argue for this interpretation, given the possibility that some of the low-nutrient concentration impairments (SCI values < 60) considered in the above analysis may have occurred in response to non-nutrient stressors.

Therefore, we consider this analysis to be inconclusive as a basis for recommending in-stream nutrient concentrations that may be used as screening values.

I.D. Ambient Monitoring Nutrient Distributions

C. E. Zipper

One task described by the AAC's FY07 work program is to estimate the implications of a recommended screening hierarchy on additional monitoring that might be required as a result of implementing that screening hierarchy. Although we are not recommending a specific screening mechanism at this time, we believe it is useful to consider the potential DEQ monitoring-resource requirements as if screening values were to be implemented. As a general example, the resources required to conduct a visual assessment would be far less than those required to conduct a benthic macroinvertebrate assessment.

The data included in Figure 8 are intended to serve as a first step in a consideration of the monitoring-resource requirements. These data are only a first step because the DEQ resources required by a screening-value exceedance will be influenced by how the screening process proceeds (See Figure 1, Section I.C.). These data were generated from analysis of the database assembled and analyzed in the course of completing the AAC FY06 work program. The database underlying this analysis was comprised of all DEQ ambient chemical monitoring observations collected over the October 1999 – September 2005 time periods, as provided by DEQ to the AAC. When total nitrogen (TN) values were not measured directly, they were calculated from measured values as described previously (Section I.C.). The few TP concentrations for samples collected after June 1999 that were recorded as less than or equal to 0.10 mg/L were removed from the database prior to analysis. All values recorded as being less than or equal to a detection limit have been analyzed as if they were equal to the detection limit value. An annual median was calculated for a monitoring site and included in Figure 8 only if 5 or more observations were recorded at that site during that year.

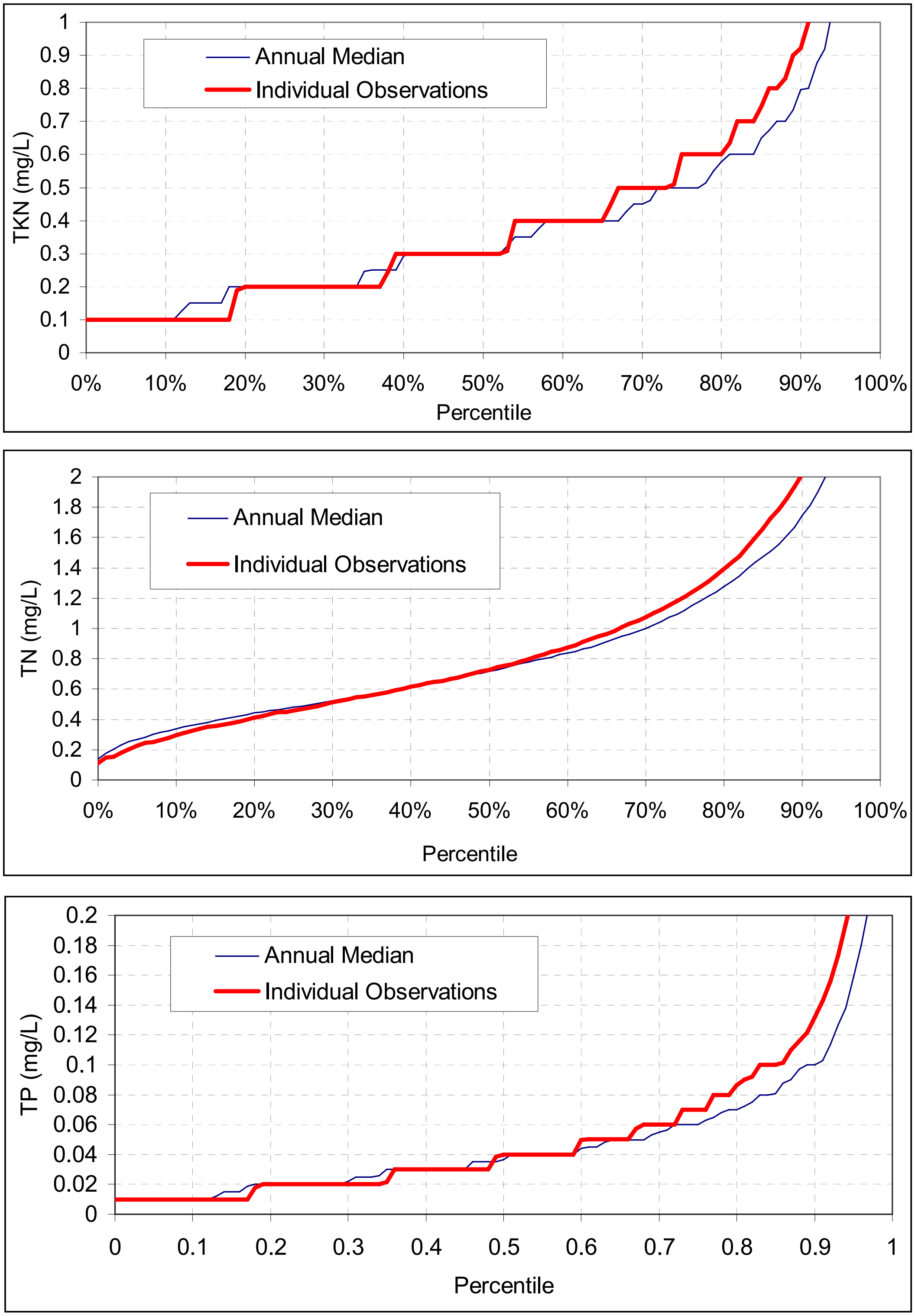


Figure 8. Percentile distributions of Virginia DEQ monitoring data: Individual observations (10/99 – 9/05), and annual medians (all monitoring stations with 5 or more monitoring observations per year), 2000 – 2004.

II.A. Pilot Application of Load-Duration Approach to Rappahannock River Basin

G. Yagow

Task

Develop a pilot application of the load-duration approach at four or five locations within a smaller basin, possibly the Rappahannock, to identify more specifically the issues that might be involved with flow estimation at DEQ sites without flow measurements and their translation into load thresholds for related 2010 cap-load allocations.

Summary

This section reports on an exploratory study to develop procedures for, create examples of, and identify other issues related to the use of load-duration curves as the basis for a possible flow-variable nutrient criteria. Along the way, a simpler approach, referred to as the cap-load method, evolved as a component of, and an alternative to, the more complex load-duration approach. Both approaches could be developed to set numeric nutrient criteria by major river basin and could be used in protecting the uses of downstream receiving waters.

The cap-load approach is based on the point source (PS) and non-point source (NPS) cap loads assigned to county segments upstream of each monitoring station (determined from the Chesapeake Bay Tributary Strategy cap loads for the Rappahannock example). This approach is based on annual averages with numeric criteria developed from the annual cap loads and average daily flows estimated at the monitoring sites.

The load-duration approach is similar to the cap-load approach but requires more in-depth analysis. This approach recognizes that PS contributions are not dependent on surface runoff and NPS load contributions may not increase linearly with increases in runoff and streamflow. This approach uses target cap loads and flow frequency curves (which represent the relationship between the daily streamflow and the percent days the given flow is exceeded) to produce load-duration curves. Loads estimated for each water sample (based on the nutrient concentration and daily flow) could be compared to the load-duration curve for the particular flow to determine if the criterion is exceeded.

Introduction

There are three types of data that must be measured or estimated as the basis for setting, and assessing compliance with a load-based nutrient criterion: (1) an allowable nutrient load to quantify the target load; (2) flow associated with the monitoring data, and (3) monitored nutrient concentrations. Each of these three parameters must be evaluated at the desired assessment points and aggregated over some time period. For this study, the following data sources were used for these three data types: Tributary Strategy cap loads, daily USGS flow data, and DEQ nutrient monitoring data. The boundary of the study area was the Chesapeake Bay model segment 5230, which is essentially hydrologic unit 02080103 and a small portion downstream, as shown in Figure 9.

Figure 9. Chesapeake Bay Phase 4.3 Model Segment 5230 and related county segments.

<u>Cap-Load Data</u>

Virginia Tributary Strategy cap-load data for 2010 were obtained as annual amounts from an Excel spreadsheet provided by the Virginia Department of Conservation and Recreation. Cap loads represent the maximum allowable average annual load needed to achieve water quality goals in the Chesapeake Bay (downstream loading criteria) and are a function of the upstream watershed area. Because the entire Chesapeake Bay portion of Virginia has been assigned N and P cap loads, estimates of maximum annual load were relatively easy to estimate at any point within this area. Cap loads have both nonpoint source (NPS) and point source (PS) components. Model segment 5230 contains part of 10 counties or cities, each part of which is known as a county segment or "coseg" under the Chesapeake Bay Tributary Strategies program in Virginia (see Figure 9). Within each coseg, separate allocations were made for nitrogen (N) and phosphorus (P) by NPS and by PS, as shown in Table 9.

Table 9. Model 5230 coseg cap-load allocations for total nitrogen and total phosphorus.

County	Coseg ID	TN Cap Load (lbs/yr)		TP Cap Load (lbs/yr)	
		PS	NPS	PS	NPS
Albemarle	230051003	0	5,009	0	710
Culpeper	230051047	68,162	570,781	34,405	84,260
Fauquier	230051061	40,177	444,563	14,203	68,279
Fredericksburg	230051630	0	757	0	120
Greene	230051079	0	81,024	0	13,465
Madison	230051113	0	492,795	0	84,769
Orange	230051137	35,526	264,254	13,839	38,982
Rappahannock	230051157	0	326,545	0	54,454
Spotsylvania	230051177	0	52,903	0	5,591
Stafford	230051179	0	45,354	0	4,940

Daily Flow Data

Daily flow data were obtained from selected USGS flow stations with at least 30-years of record, as shown in Table 10. A 30-year span was chosen as a reasonable basis for calculating long-term average daily flow since many statistics are based on 30-year weather normals. Daily streamflow data were downloaded for USGS stations from http://nwis.waterdata.usgs.gov/va/nwis/.

Table 10. Selected USGS daily flow stations in Model Segment 5230.

Station ID	Stream Name	Drainage Area (mi^2)	1975-2004 Unit-Area Flow (cfs/mi^2)	Period of Record
01662000	Rappahannock River nr. Warrenton	194.98	0.99	1942 - 1986
01663500	Hazel River at Rixeyville	285.68	1.30	1942 - 2004*
01664000	Rappahannock River nr. Warrenton	619.58	1.20	1942 - 2004
01665500	Rapidan River nr. Ruckersville	114.65	1.40	1942 - 2004**
01666500	Robinson River nr. Locust Dale	179.00	1.35	1943 - 2004
01667500	Rapidan River nr. Culpeper	466.62	1.29	1930 - 2004
01668000	Rappahannock River nr. Fredericksburg	1,341.23	1.35	1907 - 2004

* Data missing between 10/92 and 10/02, and after 09/04.
** Data missing between 07/95 and 07/98.

To facilitate the calculation of average daily flow at the DEQ sites in this river basin, ArcGIS was used to generate watersheds that corresponded with the ambient monitoring sites within model segment 5230, as shown in Figure 10. Because flow is a function of drainage area, flow estimates for the DEQ sites were calculated by multiplying the unit-area flow (cfs/sq.mi.) at the nearest upstream or downstream USGS flow station (Table 10) with the drainage area of the watershed at the DEQ assessment point (Table 11). When two or more USGS flow stations were upstream on separate tributaries from the DEQ assessment point, an area-weighting was performed to calculate the estimated flow at the monitoring station. Calculations were not performed on the two DEQ sites without associated flow, as they were on smaller tributaries without clearly representative USGS flow stations.

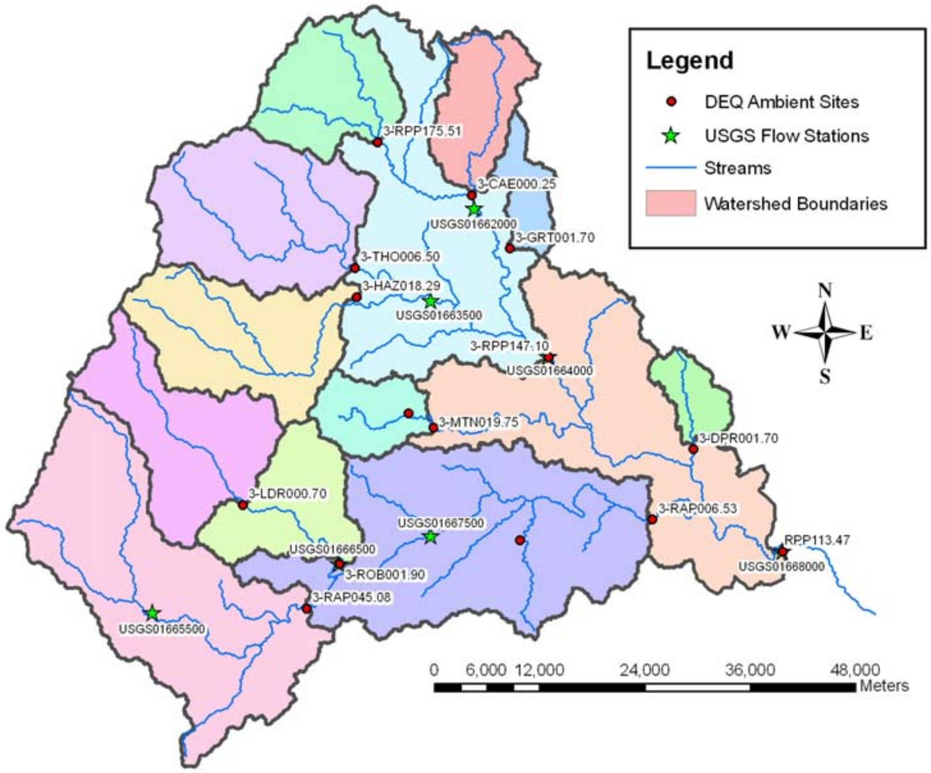


Figure 10. Watershed boundaries for Virginia Department of Environmental Quality (DEQ) ambient monitoring sites for Model Segment 5230.
Also shows nearby U.S. Geological Survey flow stations.

Table 11. DEQ ambient monitoring sites and associated USGS flow stations.

DEQ Site ID	Stream Name	Drainage Area (mi^2)	Period of Record	No. of Samples	USGS Station	Calculated Average Daily Flow (cfs)
DEQ Sites with Associated Flow and Load-Duration Curves						
HAZ018.29	Hazel River	114.87	1987 - 2005	113	01663500	149.8
LDR000.70	Little Dark Run	109.58	1975 - 2004	214	01666500	148.4
RAP006.53	Rapidan River	674.28	1985 - 2005	193	01667500	868.2
RAP045.08	Rapidan River	237.89	1987 - 2005	173	01665500	334.0
ROB001.90	Robinson River	179.00	1975 - 2005	300	01666500	242.4
RPP113.47	Rappahannock River	1,341.23	1985 - 2004	574	01668000	1,811.1
RPP147.10	Rappahannock River	619.58	1975 - 2005	305	01664000	742.7
THO006.50	Thornton River	138.44	1985 - 2005	135	01663500	180.6
DEQ Sites with Associated Flow Only						
CAE000.25	Carter Run	54.95	2002 - 2005	26	01662000	54.5
GRT001.70	Great Run	25.02	1985 - 2005	114	01662000	24.8
RPP175.51	Rappahannock River	74.03	1987 - 2005	150	01662000	73.5
MTN000.59	Mountain Run		1990 - 2005		01665000	
MTN022.45	Mountain Run		1973 - 2005		01665000	
DEQ Sites with no Associated Flow						
DPR001.70	Deep Run		1974 - 2005			
MIR004.05	Mine Run		1974 - 2005			

DEQ Nutrient Data

Monitored nutrient data were obtained for selected DEQ ambient monitoring sites from the following DEQ web site: http://gisweb.deq.virginia.gov/monapp/mon_query_form.cfm. Available nutrient data were downloaded for each site. Because nutrient analysis procedures and recorded parameters have changed over time, the following equations were made for the calculation of TN and TP. The numbers represent DEQ's Comprehensive Environmental Data System (CEDS) parameter codes, as explained below:

TN = ((((613 OR 615) AND (618 OR 620)) OR 630) AND 625) OR 600

TP = 665 OR 70507

where the numbers represent the following CEDS parameter codes:

613 = NO_2-N Dissolved
615 = NO_2-N Total
618 = NO_3-N Dissolved
620 = NO_3-N Total
630 = NO_3-N + NO_2-N Total
625 = Total Kjeldahl Nitrogen
600 = Total Nitrogen
665 = Total Phosphorus
70507 = Total Ortho-Phosphorus (only used when no value was recorded for 665).

Cap-Load-Based Nutrient Criteria

At the March 2006 AAC meeting, the Chesapeake Bay Tributary Strategy cap loads were discussed as a possible basis for setting variable nutrient criteria by major basin. This section illustrates the use of such a procedure at select DEQ sites in the Upper Rappahannock River Basin.

PS cap loads were assigned to individual facilities and were manually assigned to appropriate watersheds based on facility location. NPS cap loads were distributed to each of the watersheds draining to DEQ ambient monitoring sites on an area-weighted basis as a fraction of each coseg (and their associated NPS cap-load allocation) contained within each watershed. A summary of PS and NPS loads summed for the watershed draining to each DEQ ambient site are shown in Table 12.

Table 12. Cap-load allocations for point sources (PS) and non-point sources (NPS) calculated at DEQ ambient sites.

Assessment Point	Upstream Area (ha)	TN Cap Load (lbs/yr)		TP Cap Load (lbs/yr)	
		PS	NPS	PS	NPS
CAE000.25	14,206.39	40,177	85,863	14,203	13,187
DPR001.70	6,111.52	0	33,916	0	4,757
GRT001.70	6,465.11	0	39,075	0	6,001
HAZ018.29	29,746.81	0	158,334	0	25,827
LDR000.70	28,369.91	0	167,652	0	28,807
MTN019.75	9,858.88	68,162	56,692	34,405	8,369
RAP006.53	174,515.94	35,526	979,170	13,839	156,348
RAP045.08	61,542.93	35,526	337,754	13,839	55,486
ROB001.90	46,350.26	0	273,212	0	46,337
RPP113.47	412,735.99	143,865	2,283,228	62,447	355,451
RPP147.10	160,350.99	40,177	861,247	14,203	135,752
RPP175.51	19,143.26	0	100,682	0	16,176
THO006.50	35,823.36	0	169,471	0	28,261

The potential nutrient criteria derived from the cap-load approach were calculated for individual DEQ ambient monitoring sites from the annual cap loads in Table 12 and the average daily flows from Table 11. These potential concentration criteria (cap-load standards) are shown in Table 13. The nutrient data at each DEQ site were evaluated against these values for the most recent 5-years of data (2000 – 2004), representing a pseudo-assessment period. The number of samples used to calculate TN and TP at each site for this period, together with a calculated percent exceedences of the cap-load criteria are also shown in Table 13. Note that sites with PS components generally have larger allowable nutrient concentrations than sites without PS components.

Table 13. Summary of average cap-load standard concentrations for total nitrogen (TN) and total phosphorus (TP) and percent exceedences for 2000 – 2004 data.

DEQ Site	Cap Load Standard		2000-2004			
	TN (mg/L)	TP (mg/L)	No. of TN Samples	% TN Exceedences	No. of TP Samples	% TP Exceedences
CAE000.25*	0.33	0.07	26	100.0%	26	100.0%
GRT001.70	0.10	0.02	114	22.8%	114	22.8%
HAZ018.29	0.54	0.09	5	0.0%	5	0.0%
LDR000.70	0.35	0.06	21	95.2%	21	47.6%
RAP006.53*	0.87	0.14	189	9.0%	189	1.6%
RAP045.08*	1.19	0.21	130	0.8%	130	0.8%
ROB001.90	0.57	0.10	29	37.9%	29	13.8%
RPP113.47*	0.68	0.12	113	68.1%	0	0.0%
RPP147.10*	0.62	0.10	27	29.6%	27	0.0%
RPP175.51	0.26	0.04	122	26.4%	149	26.4%
THO006.50	0.48	0.08	6	100.0%	6	16.7%

* Sites with PS Cap Load components.

Load-Duration-Based Nutrient Criteria

The load-duration approach is essentially an extension of the cap-load approach but requires more in-depth analysis. The constant cap-load criteria, given in terms of concentrations, assume that nutrient loads increase linearly with increases in daily flow. However, we know that PS contributions are fairly constant over time and are independent of surface runoff, whereas NPS nutrient loads are more dependent on runoff and thus streamflow. Modeling data for one stream segment presented in last year's AAC report showed increasing TP concentrations but decreasing TN concentrations with increasing flow. The load-duration approach permits variable allowable nutrient loads at different flows based on the combination of expected PS and NPS contributions in a watershed. Use of these variable target loads at different flows leads to criteria that are flow-variable concentrations. In watersheds with no PS contributions, or where a long-term average concentration criterion is preferred, there is no advantage to the load-duration approach.

To illustrate the steps in the load-duration approach, the following example was created for the entire 5230 model segment. Daily streamflow was downloaded for USGS Station 01668000, loaded into a spreadsheet, and sorted by flow in descending order. A rank was then assigned to each daily flow, and the percentage of the total period was calculated for which the flow was exceeded (%DaysFlowExceeded). The flow frequency curve was then plotted as daily flow versus %DaysFlowExceeded, as shown in Figure 11.

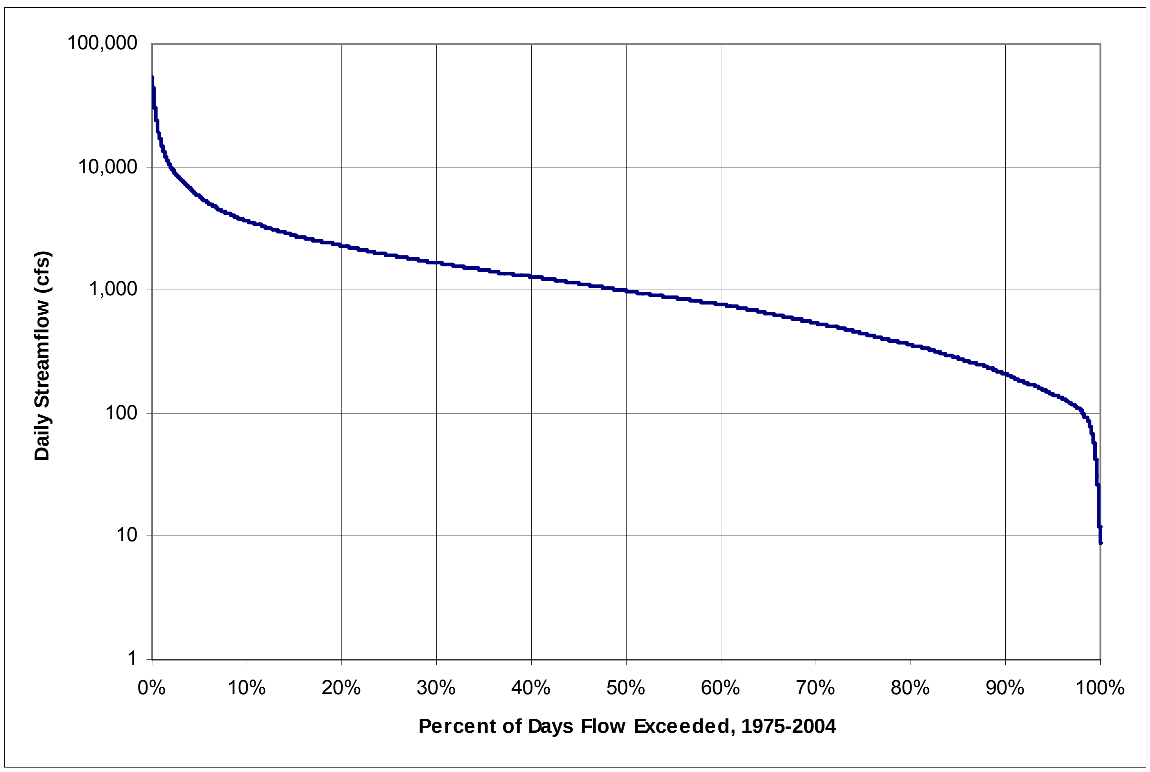


Figure 11. Flow Frequency Curve, USGS 01668000, 1975-2004.

The average annual nutrient concentrations (cap-load criteria) were calculated by adding together the point source (PS) and nonpoint source (NPS) average annual load allocations for the entire model segment and dividing by the average annual daily flow (USGS station 01668000 was roughly coincident with RPP113.47). The concentration criteria for this site were 0.68 mg/L for TN and 0.12 mg/L for TP (Table 13). Daily streamflow was multiplied by the TN concentration criterion to generate the TN load duration curve in Figure 12.

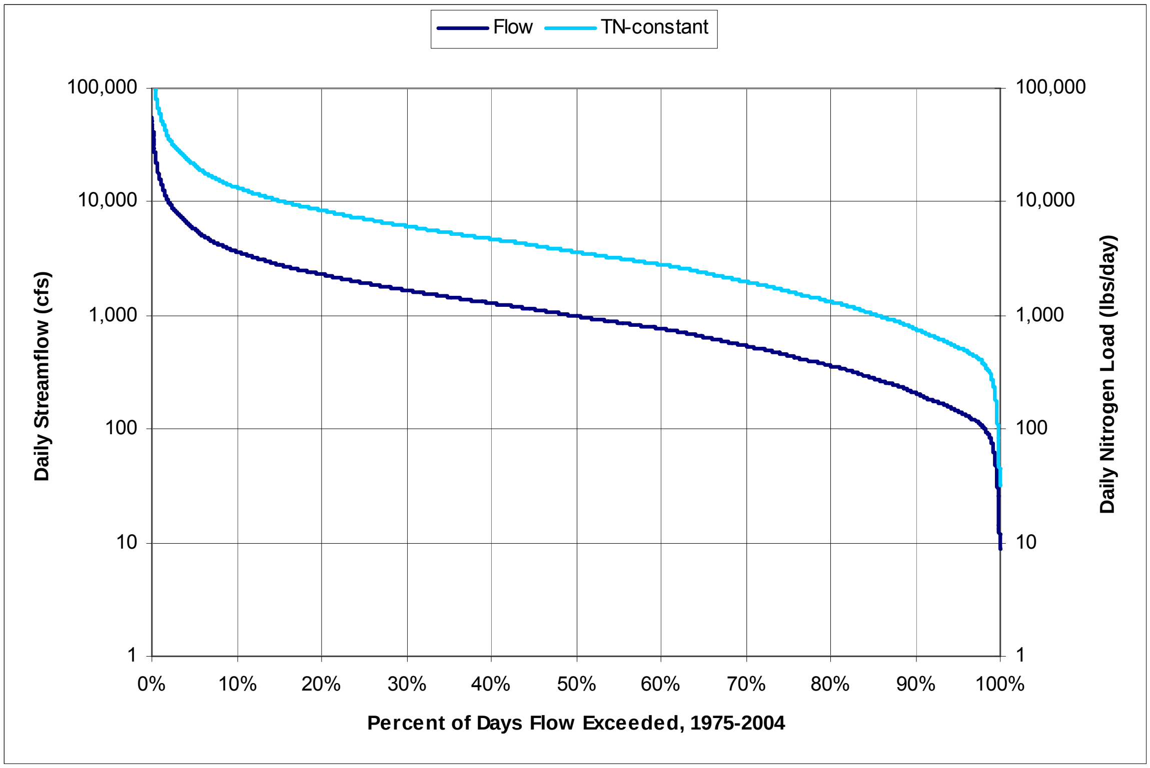


Figure 12. TN Load-Duration Curve, Model Segment 5230.

Average daily flow on the collection date of each DEQ ambient sample was obtained from the USGS flow data and adjusted to the area of the watershed draining to the DEQ site. To calculate the sample-day loads, the average daily flow for the collection date was multiplied by the sample concentration. Sample-day loads were then plotted against the load-duration curve (Figure 13). Sample-day loads that lie above the TN load-duration curve are then assessed as exceeding the criteria. Percent exceedence was calculated both for the entire period of monitored nutrient data at this site and for the most recent 5-year (pseudo-assessment) period, 2000-2004, shown in parentheses in Figure 13.

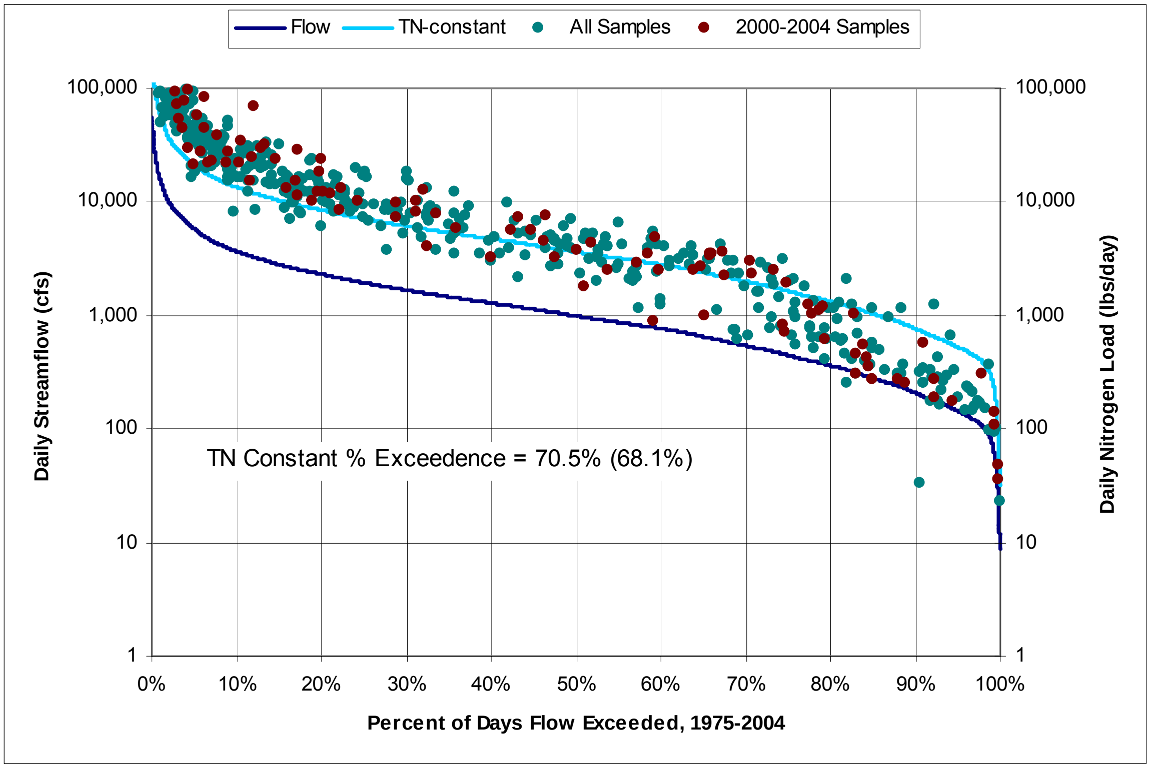


Figure 13. TN Monitoring Data Compared with TN Load-Duration Curve.

In the example above, the load curve is based on a constant concentration criterion derived from the average annual cap load and average annual daily flow. Two additional alternative methods were investigated to develop variable numeric nutrient criteria. Point sources typically have a permitted daily average load, which means that under varying flow conditions, there is a variable pollutant concentration that will achieve the permitted daily load. Theoretically, in order to achieve an average annual target pollutant load, as flow increases from some average baseline, the allowable pollutant concentration must decrease in order not to exceed a constant target load. Therefore, an option was considered to look at declining concentration criteria with increasing flow.

NPS pollutant loads are primarily driven by runoff. Their pollutant contribution is typically minimal during baseflow and higher during larger flows. It should be anticipated, therefore, that pollutant concentrations from NPS loads, where they dominate, will be higher during runoff events. In order to meet a constant target pollutant load under these circumstances, lower allowable concentrations would be needed during baseflow. Therefore a second alternative option was considered to look at increasing concentration criteria with increasing flow.

The following two sets of flow-variable curves were developed for nitrogen (TN) assuming constant PS inputs, and either an increasing (Variable) or decreasing (Declining) contribution from NPS as flow increased. Because phosphorus (TP) loads from NPS typically increase with increases in flow, only the increasing curve was developed for TP.

- Variable: Increasing NPS load with increasing flow
    - Allowable Daily Load = PS + (NPS * (1- %Days Flow Exceeded))^2
- Declining: Decreasing NPS load with increasing flow

Allowable Daily Load = PS + (NPS * 2 * %Days Flow Exceeded)

The resulting variable daily loads were then divided by a daily flow that corresponded with a certain expected long-term return frequency to form two potential variable-flow nutrient concentration criteria. The Variable and Declining standard curves are shown along with the Constant standard curve for TN in Figure 14. Only the Variable and Constant criteria are shown for TP in Figure 15, as explained earlier. Sample-day loads were then compared against each potential criterion. The percent exceedence calculated for the period of record (Figure 14 and Figure 15) and the most recent 5-years of data (Figure 14, in parentheses) are included.

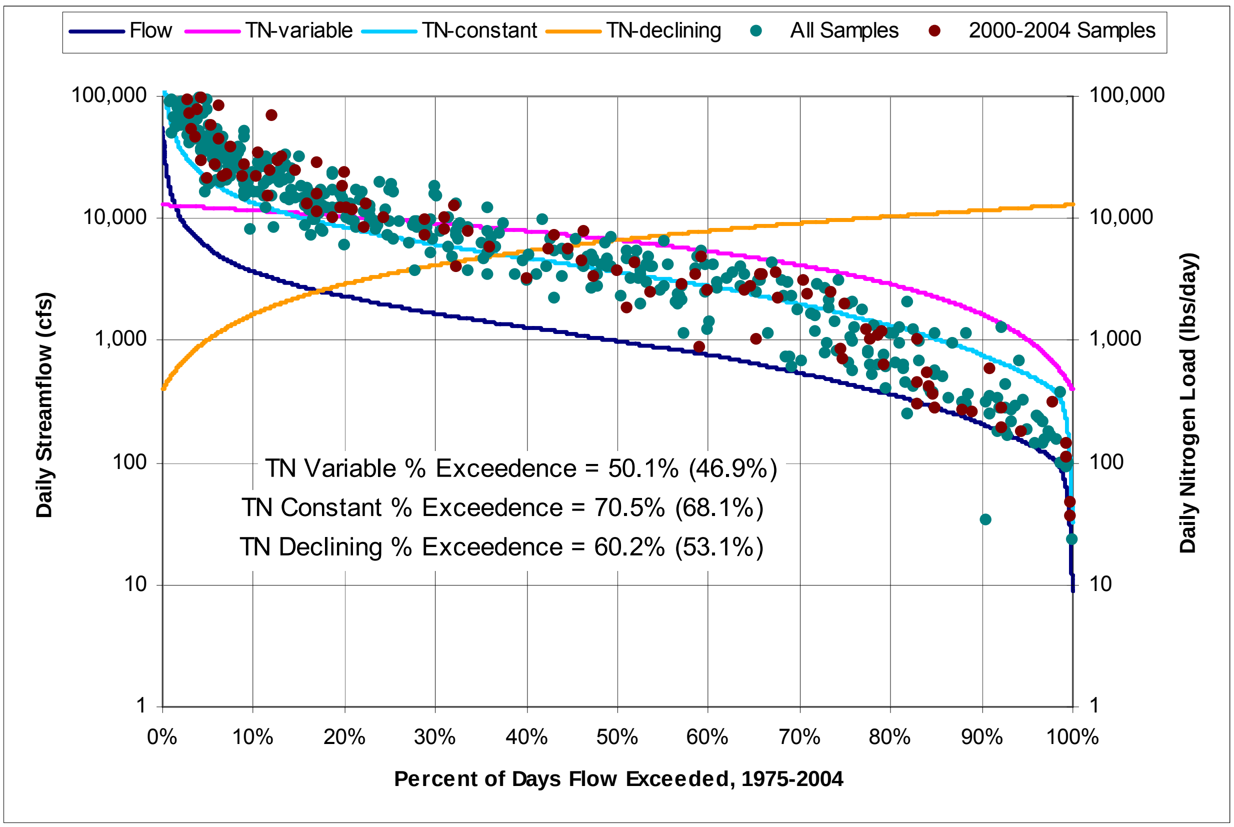


Figure 14. Three alternative TN Load-Duration Curves, RPP113.47.

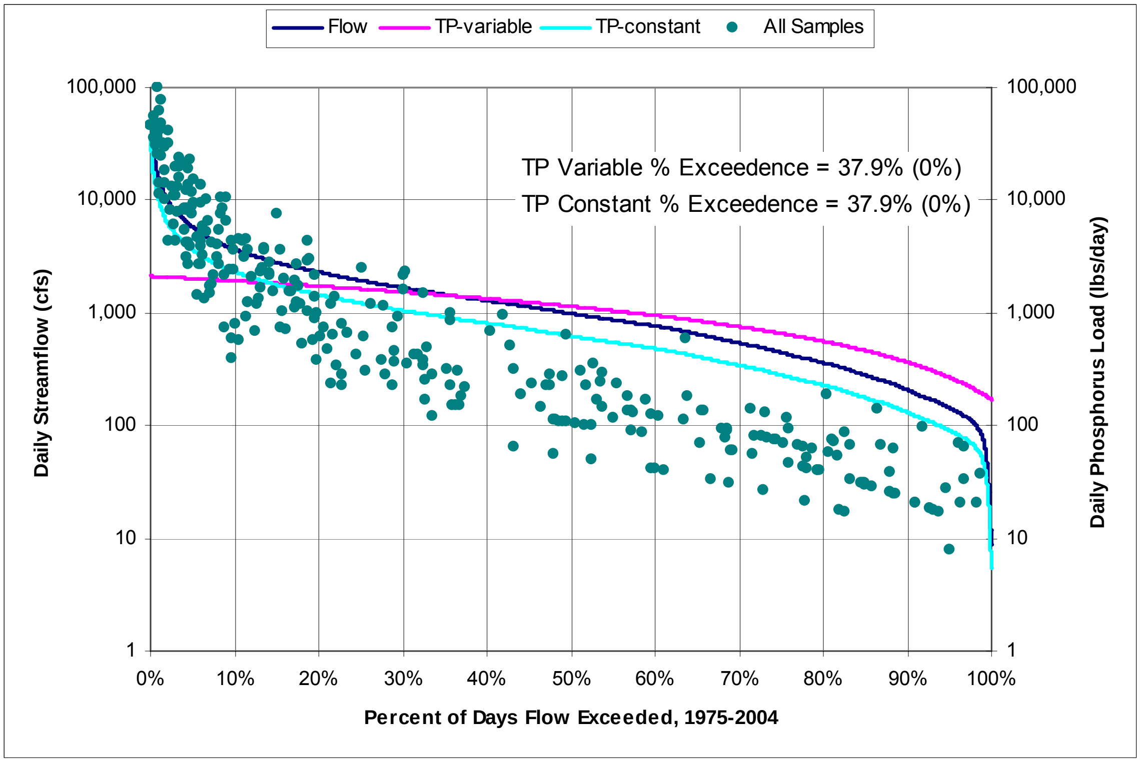


Figure 15. Two alternative TP Load-Duration Curves, RPP113.47.

The previous example illustrates the simplest case, where flow, cap load, and ambient nutrient monitoring data are all available at the same assessment point. Where flow and cap loads were evaluated at points not corresponding with the DEQ site, the assignment of values were similar to the approaches (*e.g.*, area-weighting) used in developing the cap-load criteria. Following the procedures used in the previous example for DEQ site RPP113.47, load-duration curves for TN and TP were constructed for an additional seven DEQ ambient monitoring sites in this basin that contained sufficient data (Figures 16-29).

Also located in the pilot study area were three DEQ sites associated with USGS Station 01662000 and two DEQ sites that could have been associated with USGS Station 01665000 (an oversight in the indirect evolution of this analysis). Both of these USGS stations had the requisite 30 years of data for constructing a flow frequency curve. However, since the gauges were discontinued in 1986 and 1999, respectively, there was no concurrent flow data for calculating sample-day loads from recent samples. Although these stations could not be evaluated with load-duration criteria, they did have sufficient data for evaluating cap-load criteria.

Conclusions

Both the cap-load and load-duration approaches could produce upstream nutrient concentration criteria where annual allowable loads are exceeded. Allowable cap loads within the Chesapeake Bay drainage can be redistributed fairly rationally to watersheds corresponding to any sub-area, such as watersheds corresponding to DEQ ambient monitoring sites.

Unit-area flow can be calculated from long-term data at most USGS stations and applied to upstream areas of nearby DEQ sites. One situation where this strategy is not appropriate is where there are intervening tributaries of a certain order (to be determined) between the flow station and monitoring site. Similarly, monitored nutrient concentrations can be assumed to be representative of, and relatively constant along, a given stream reach on any given day unless there are intervening tributaries or major nutrient sources (such as PS discharges; faulty septic systems; livestock access; golf courses or other large, manicured green spaces; and non-buffered cropland) that would be expected to influence concentrations between the monitoring and assessment points.

Distributed annual cap loads and long-term average daily flow can be used to calculate an average nutrient concentration that could be used as a basis for site-specific nutrient criteria. These criterion concentrations would vary from site-to-site, depending on the mixture of allowable PS and NPS loads within the upstream drainage. Criteria based on this methodology would also be much simpler than the load-duration approach because flow-frequency analyses and load-duration curves would not need to be constructed. Additionally, more USGS flow stations could be used for calculating long-term annual average unit-area flow because this method does not need current data for calculating sample-day loads.

This pilot study, in hindsight, was not properly designed to analyze the potential for using load-duration curves to evaluate flow-variable nutrient criteria. Although six of the 13 DEQ sites in this study had PS components, only two sites had sizeable PS components (equal to 45% or more of the NPS cap load). Unfortunately, neither of the USGS stations associated with these two sites – CAE000.25 and MTN019.75 – had current flow data available. Thus, it was not possible to calculate sample-day loads for comparison with the load-duration curves, or for comparing the percent exceedences between data sets with dominant PS loads and those with dominant NPS loads. The original thinking was that at sites where PS loads dominated, an excessive number of low-flow exceedences may occur, even though total annual load cap loads would still be met.

From the summary in Table 13, cap-load nutrient criteria tended to be larger or more permissive at sites with PS allocations than at the other sites. Because many of the cap-load TP criteria were at or below DEQ's previous analytical minimum detection limit and samples below the detection limit were represented in this analysis as having the detection limit value (0.10 mg/L prior to mid-1999), the number of TP exceedences was artificially inflated.

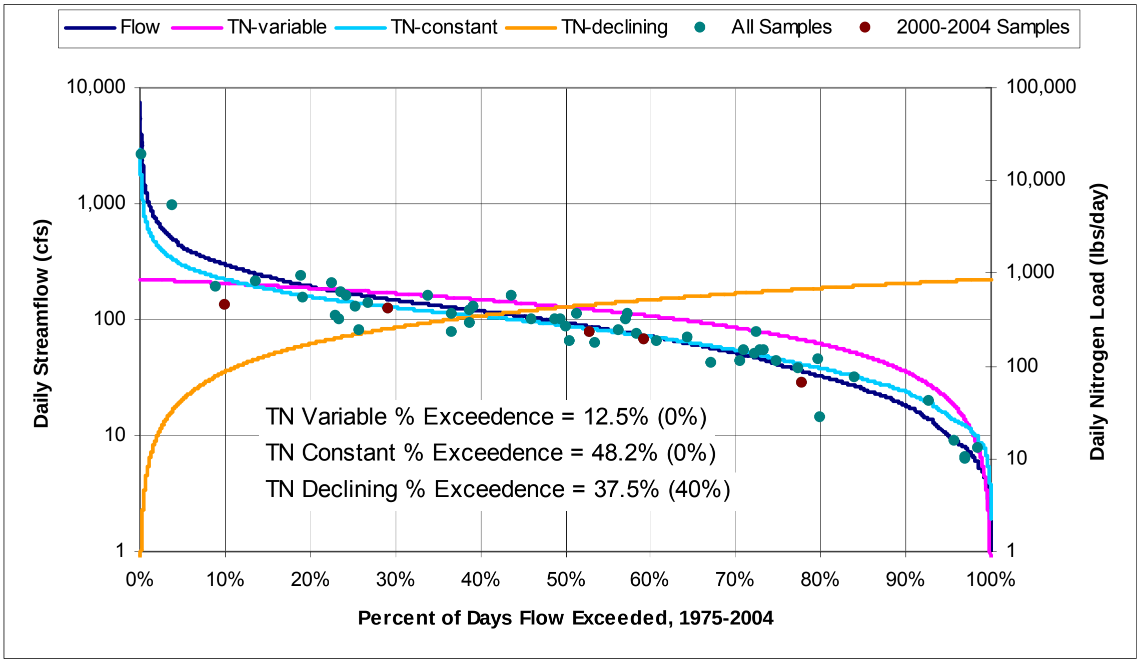


Figure 16. TN Load-Duration Curve for HAZ018.29.

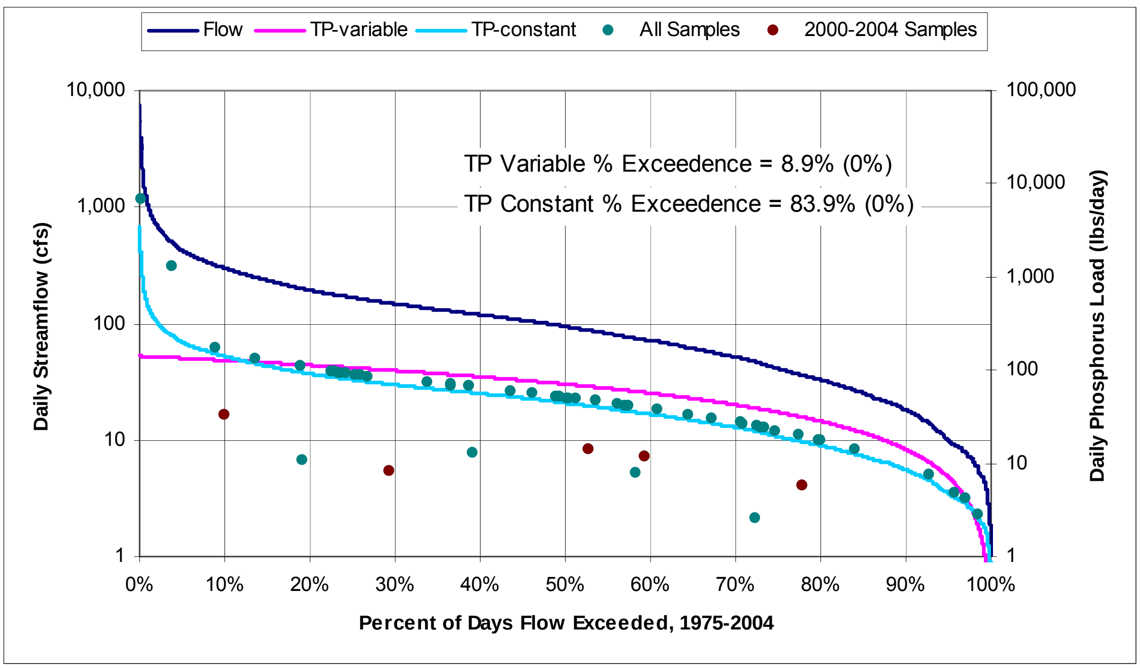


Figure 17. TP Load-Duration Curve for HAZ018.29.

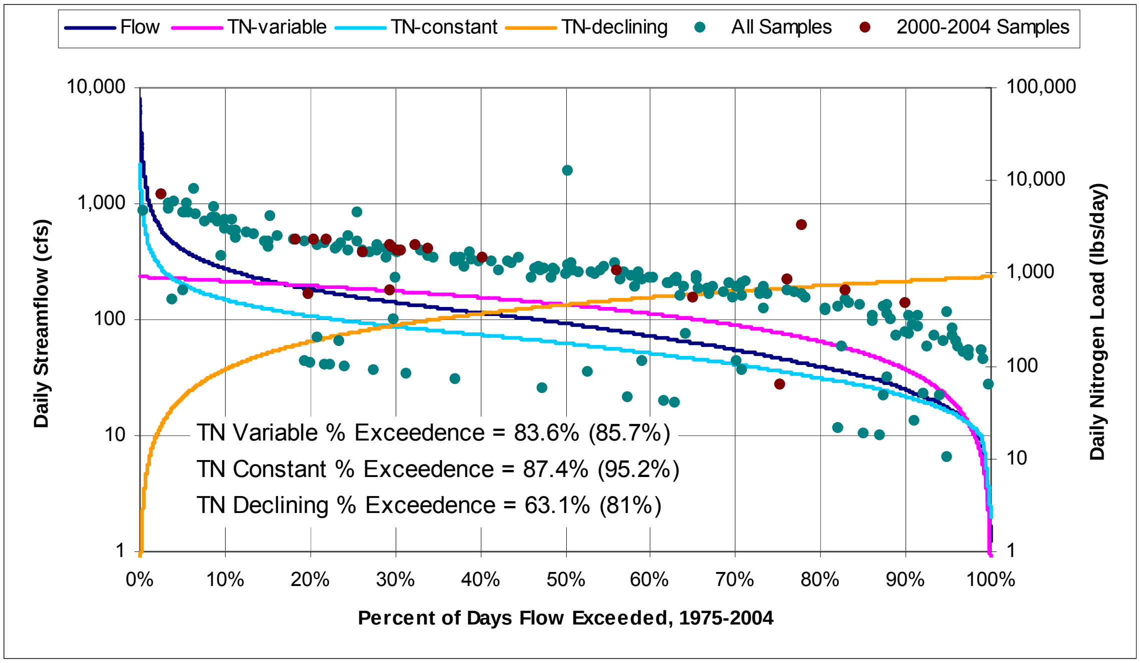


Figure 18. TN Load-Duration Curve for LDR000.70.

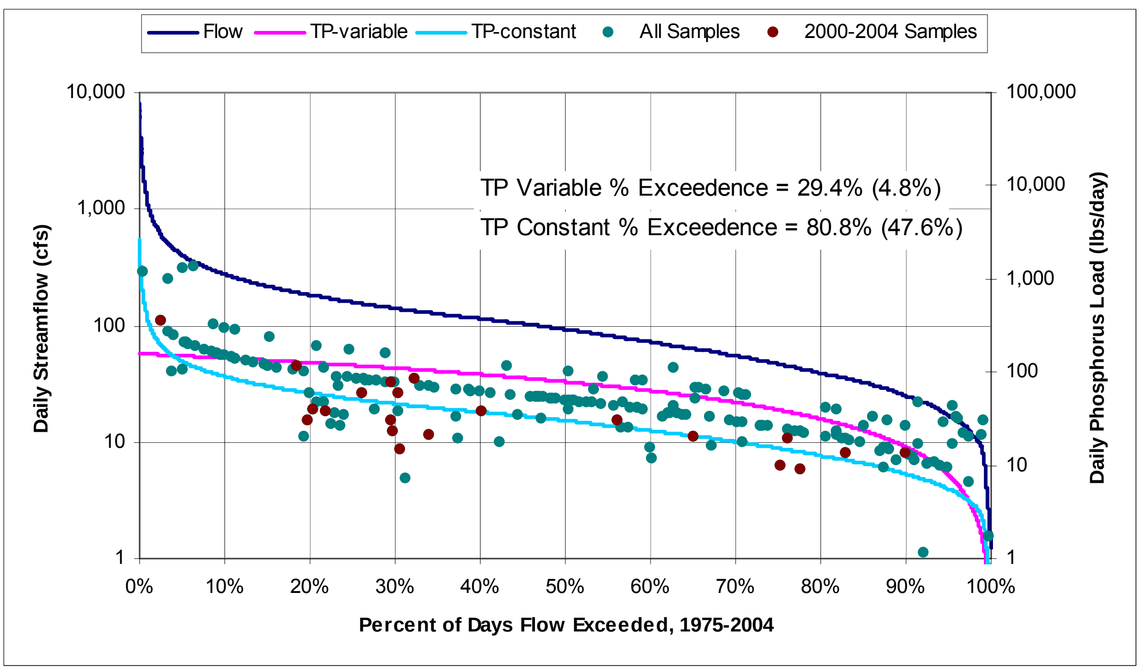


Figure 19. TP Load-Duration Curve for LDR000.70.

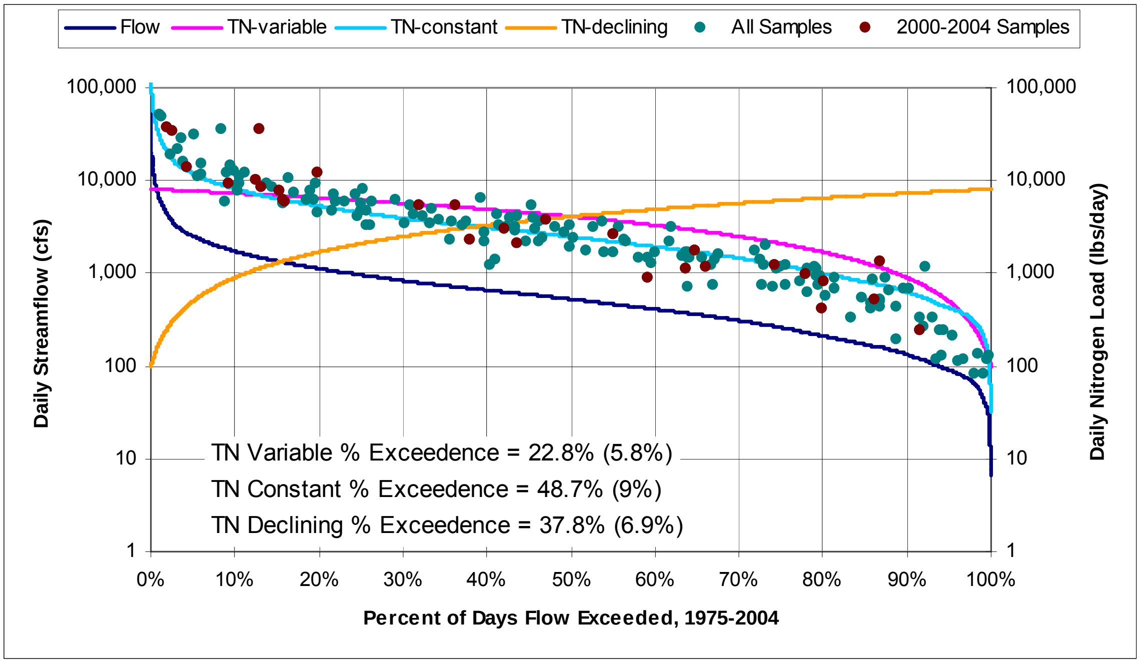


Figure 20. TN Load-Duration Curve for RAP006.53.

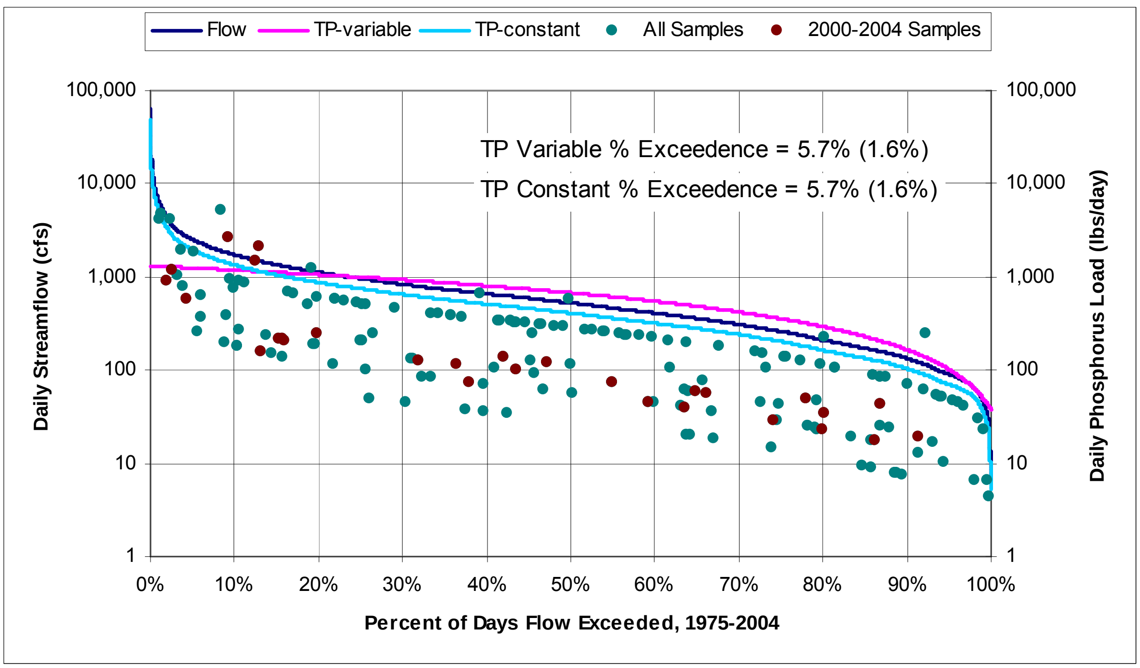


Figure 21. TP Load-Duration Curve for RAP006.53.

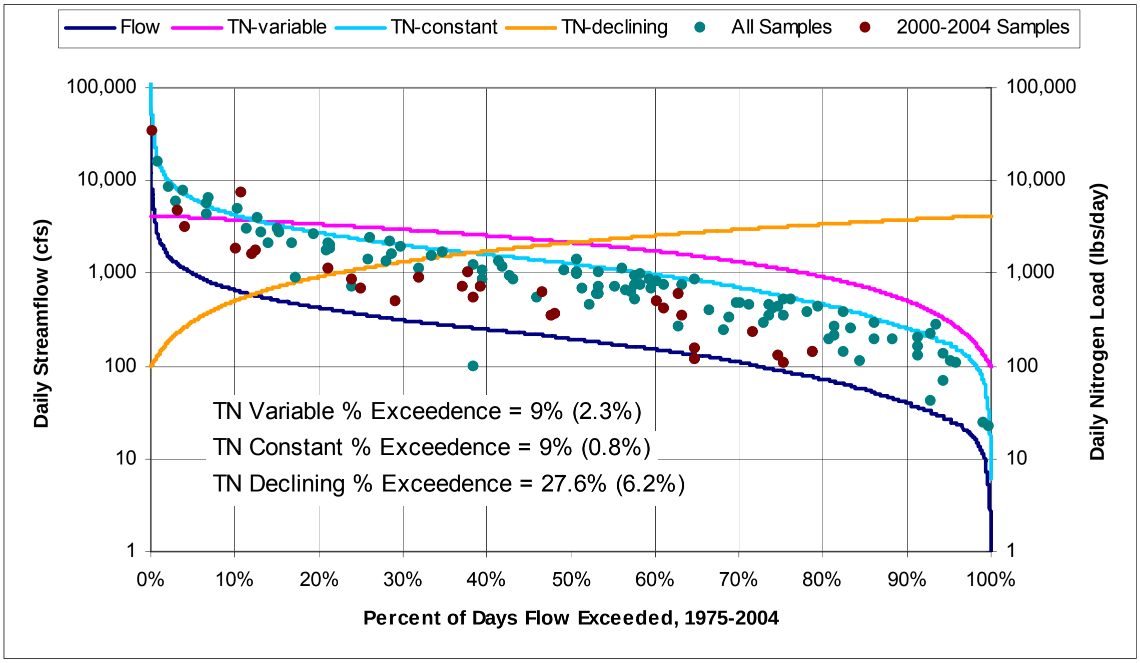


Figure 22. TN Load-Duration Curve for RAP045.08.

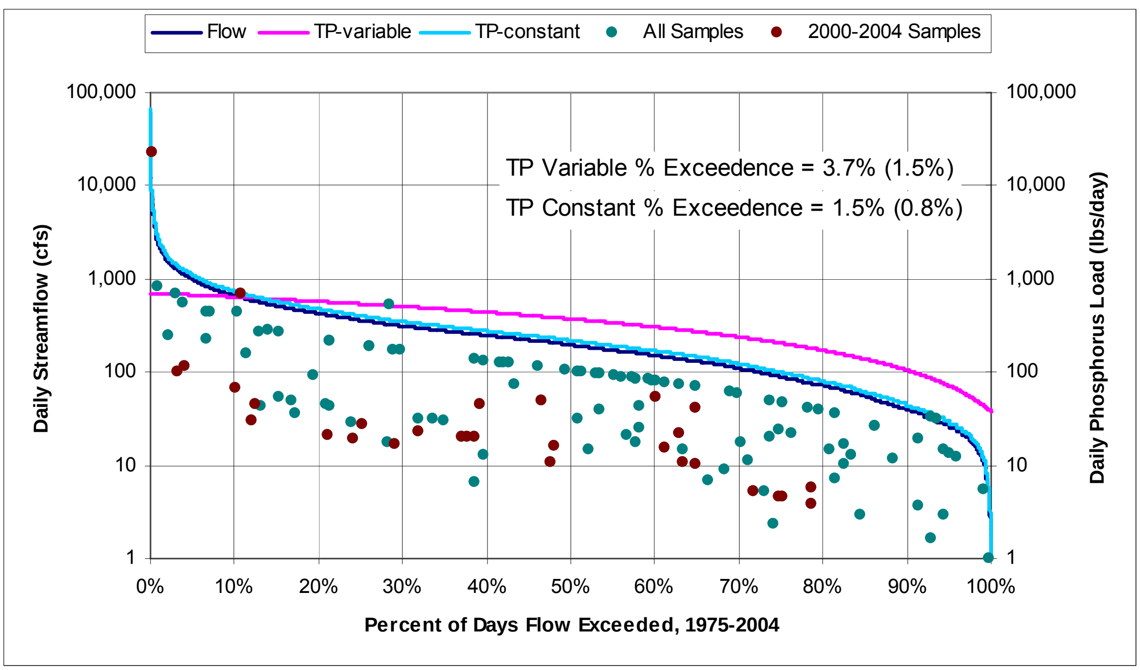


Figure 23. TP Load-Duration Curve for RAP045.08.

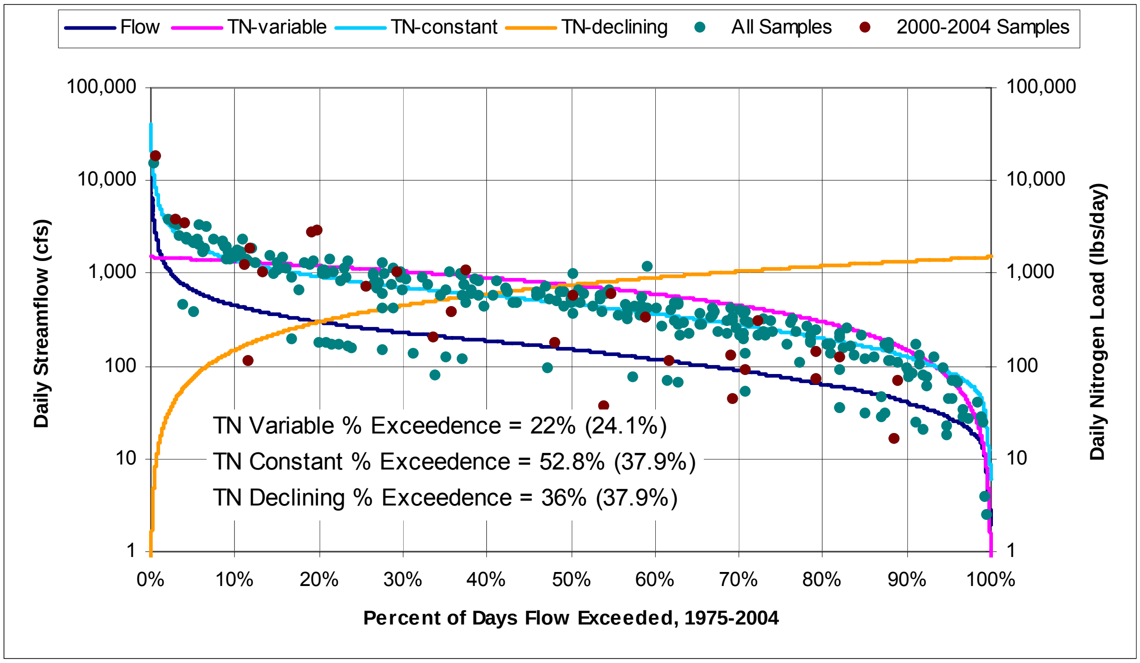


Figure 24. TN Load-Duration Curve for ROB001.90.

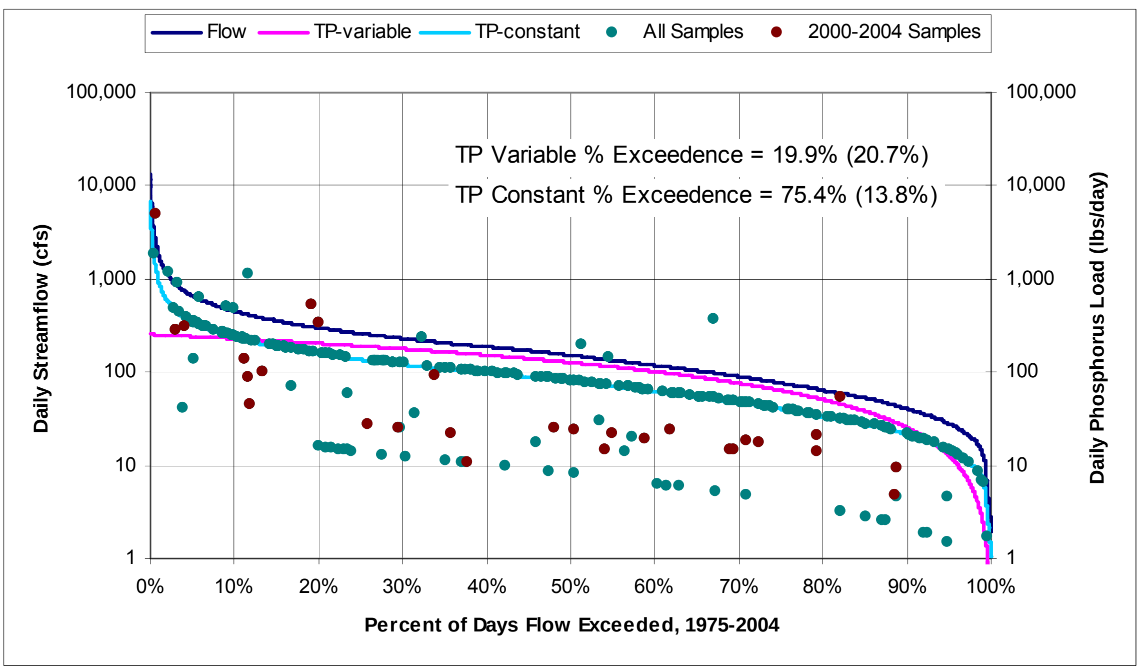


Figure 25. TP Load-Duration Curve for ROB001.90.

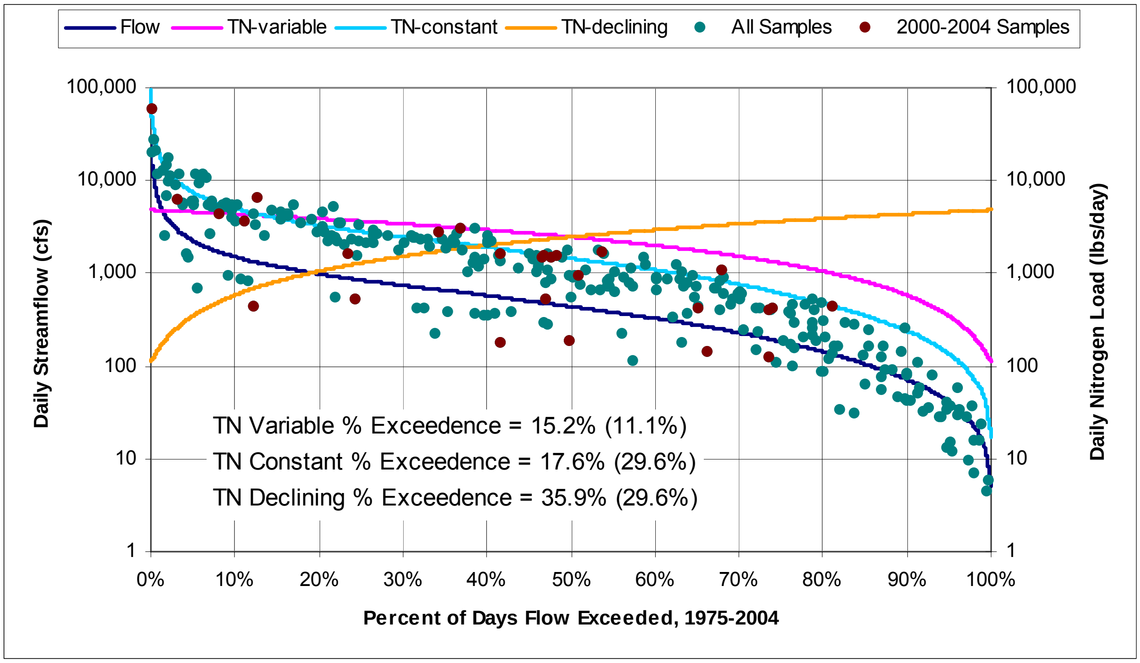


Figure 26. TN Load-Duration Curve for RPP147.10.

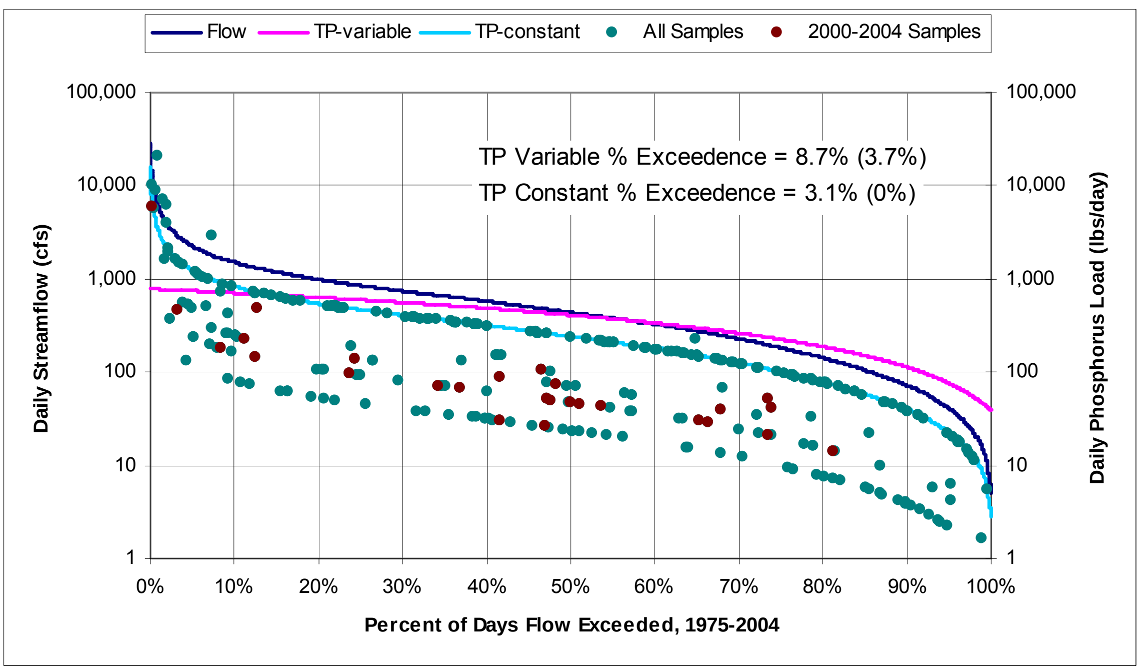


Figure 27. TP Load-Duration Curve for RPP147.10.

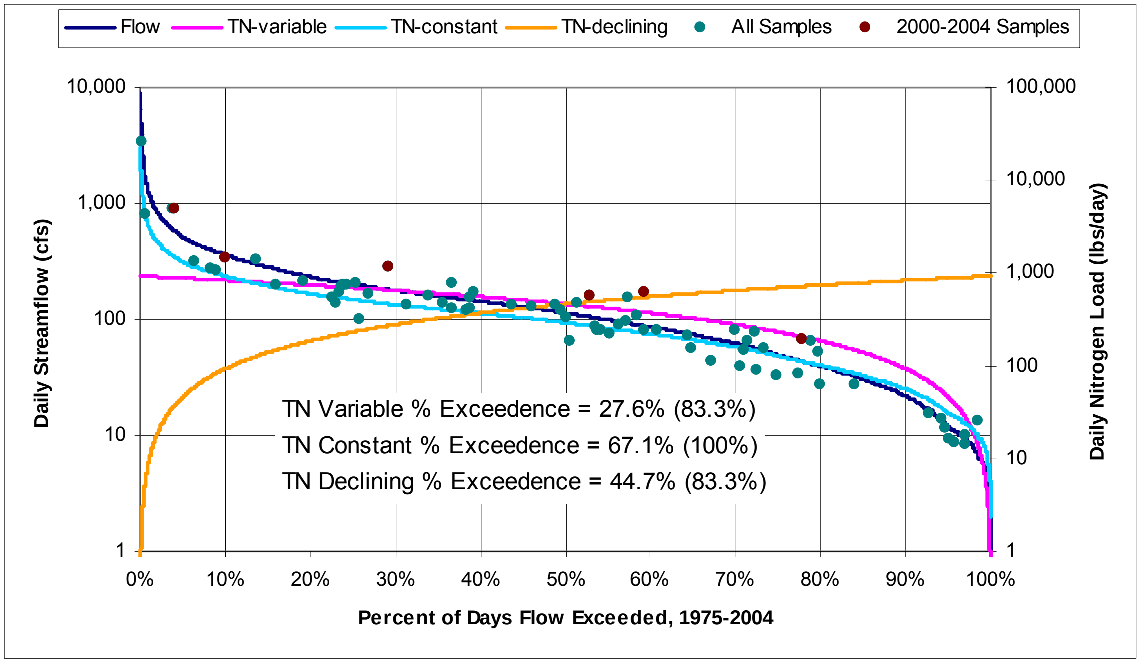


Figure 28. TN Load-Duration Curve for THO006.50.

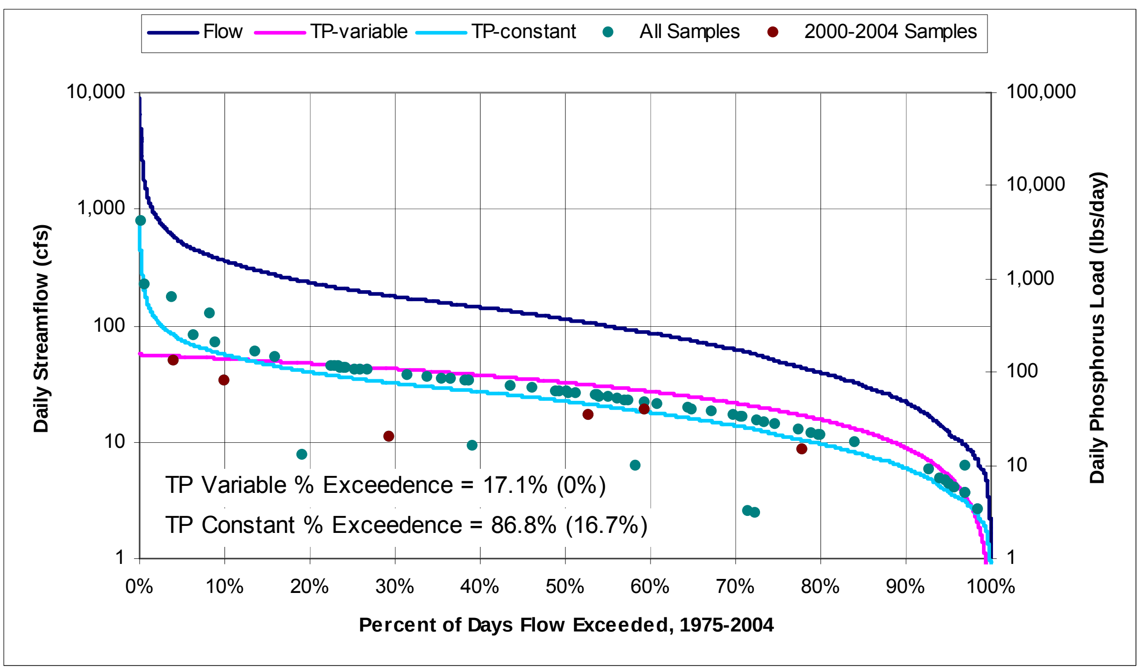


Figure 29. TP Load-Duration Curve for THO006.50.

II.B. Downstream-Loading Component of Nutrient Criteria for Freshwater Rivers and Streams: Recommended Approach

Background

The AAC has recommended that DEQ establish nutrient criteria for rivers and streams by addressing independently the two effects of nutrient over enrichment described by EPA: localized and downstream effects. Such criteria would be comprised of

1) localized components intended to protect designated uses within any stream segment that is monitored and assessed, and
2) downstream-loading components intended to be protective of designated uses in water bodies located downstream of any given stream segment.

This section describes an approach to the downstream-loading component of nutrient criteria for streams and rivers in Virginia.

Recommended Approach

The committee recommends that the downstream-loading component of Virginia's nutrient criteria be developed as narrative criteria. The narrative criteria applied to each stream segment would be comprised of clear statements requiring that nutrient levels in any given stream segment be protective of designated uses in all downstream water bodies that receive waters carried by that stream segment. Should a water body located downstream from a given stream segment be found to suffer a nutrient impairment, a water-quality management process would be initiated for the impaired water body. That process would consider all nutrient sources, as well as other stressors, that contribute to the impaired water body and would take action to mitigate the impairment by addressing any sources found to contribute to the impairment.

Rationale

There are several reasons for recommending this approach. First, assuming the water quality management processes referenced by the narrative criteria are effective, the narrative criteria would be capable of protecting the downstream receiving waters from impairment.

Second, use of narrative criteria as the downstream-loading component of nutrient criteria would require fewer of DEQ's resources than would numeric criteria. We make the preceding statement considering that nutrient criteria implementation requires regulatory development, and the following:

1. Numeric-load limits for downstream receiving waters would require allocation of the water bodies' total allowable loads to individual upstream segments, an activity that is well suited to a comprehensive watershed management process that may include TMDL development. If the numeric downstream-loading components of nutrient criteria were established, it would be necessary for DEQ to conduct this loading-allocation procedure for all of the state's receiving water bodies regardless of impairment status. The process would be complicated because most stream segments contribute waters to numerous downstream water bodies.

2. Numeric downstream-loading components of nutrient criteria applied to specific stream segments (to protect downstream waters from nutrient impairment) would need to be responsive to other water management activities. Thus, some of the numeric downstream-loading components established through an initial round of loading-allocation activities (as described in 1 above) would likely require subsequent revisions. For example:

   - For basins where allowable loadings have been assigned (*e.g.*, Chesapeake Bay tributaries), future developments may cause those allowable loadings to change. For example, the current Tributary Strategy "cap loads" have been allocated and assigned based on assumptions that include application of specific non-point-source Best Management Practices; as time passes, those assumptions and the resulting allocations may change.
   - Implementation of "nutrient trading" in the Chesapeake Bay Watershed may also cause changes in how major Bay tributary cap loads are allocated among stream segments within tributary basins.
   - If a receiving water body is defined as nutrient impaired, the resultant water quality management plan may require an adjustment of its nutrient-loading limits as a means of restoring its capability to support its designated uses. Such an adjustment would also affect numeric downstream-loading components of contributing stream segments.

3. The AAC has recommended that localized nutrient criteria for wadeable rivers and streams in Virginia be established as a process that includes screening values instead of strict numeric criteria. Although we have not recommended how localized criteria should be defined for non-wadeable streams, it is possible that we would recommend application of a similar logic. Because screening values are not intended for interpretation as thresholds for impairment, localized criteria established through a screening-value process would not provide a basis for defining numeric downstream-loading components for contributing stream segments.

4. Regulatory development and revision processes for water quality uses and criteria in specific waters are resource intensive and can consume large amounts of DEQ's analytical resources and staff time. These processes require the same types and levels of technical analysis required for developing and implementing water quality management plans. In contrast to the regulatory development required to define numeric downstream-loading components of nutrient criteria, the use and application of narrative criteria would require water-quality management plans only for stream systems that contain and contribute to impaired stream segments.

We consider a process that achieves the goals of the Clean Water Act and better allocates DEQ's resources as a superior process. Consumption of DEQ's resources through extensive regulatory development can be expected to detract from the resources available for water-quality protection activities such as water-quality monitoring and assessment, and enforcement of standards.

Conditions and Caveats

We make the recommendation for a narrative downstream-loading component of nutrient criteria with several conditions and caveats. As stated above, it is intended for application within a context that also includes:

1. localized criteria that have numeric components and clearly defined impairment-designation processes, and
2. water-quality management processes (including TMDLs) that are effective in addressing and mitigating impairments.

We suggest that DEQ accept the recommendation only if DEQ is also willing to accept a logical consequence: implementation of the downstream-loading component as narrative criteria, as suggested above, would likely affect Virginia's TMDL process. We make this statement considering that almost all nutrient problems occur due to nutrient contributions from both localized and upstream nutrient sources, and that the most nutrient-sensitive regions of many surface water systems are often the furthest downstream.

An inherent assumption of this recommendation is that the water-quality management process referenced by the narrative criteria would be effective. The effects of elevated nutrient concentrations in individual water bodies are responsive to water-body characteristics and therefore highly variable among water bodies and difficult to predict. We believe that an effective way to enact narrative criteria would be to link them with a flexible and responsive water-quality management framework, such as the adaptive TMDL implementation framework that was recently endorsed by the U.S. EPA.[1] An adaptive implementation approach utilizes new information made available from monitoring activities conducted after initial TMDL implementation to refine further water-quality management actions so as to achieve water-quality management goals. We cite adaptive implementation as an example of the flexible and responsive water-quality management process that we believe would complement a decision by DEQ to rely on a narrative mechanism to define the downstream-loading component of nutrient criteria. Furthermore, we believe that adaptive implementation would enhance the potential for a narrative criteria mechanism to be effective.

1. See: Memorandum, EPA Assessment and Watershed Protection Division to Regions I-X Water Division Directors. "Clarification Regarding 'Phased' Total Maximum Daily Loads." 2 August 2006.

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