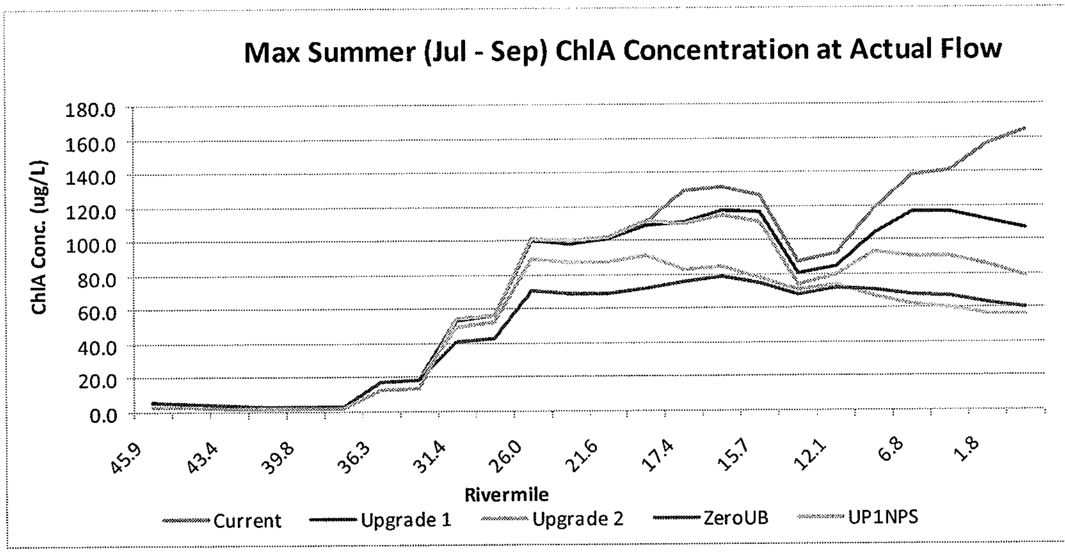

Figure 9: Along stream maximum summer Chl-a concentrations for the actual flow regime

4.4 Cumulative Frequency Nutrient Concentrations and Loads

Cumulative frequency distribution curves were developed for both concentrations and loads at the Blackstone River Outlet (Reach 200, river mile 0.0), the Blackstone at the MA/RI Border (Reach 276, river mile 16.6), and the Blackstone at the outlet of the Upper Blackstone Watershed (Reach 390, river mile 41.7), Figure 10. These locations were chosen for analysis for several reasons. The outlet of the Upper Blackstone Watershed is located approximately three miles downstream of the UBWPAD outlet at the USGS Stream Gauge at Millbury (USGS gauge number 1109730). Evaluation of model results at this location demonstrates the impacts of the upgrades at the UBWPAD almost immediately downstream of the plant. Located at Bridge St in Blackstone, MA, the MA/RI border location allows for the analysis of the impacts of upgrades at the UBWPAD on loadings from MA to RI. The Blackstone River Basin outlet is located at Slater's Mill Dam in Pawtucket, RI. Model results at this location provide an evaluation of load reductions to Narragansett Bay resulting from upgrades at both the UBWPAD and Woonsocket WWTPs.

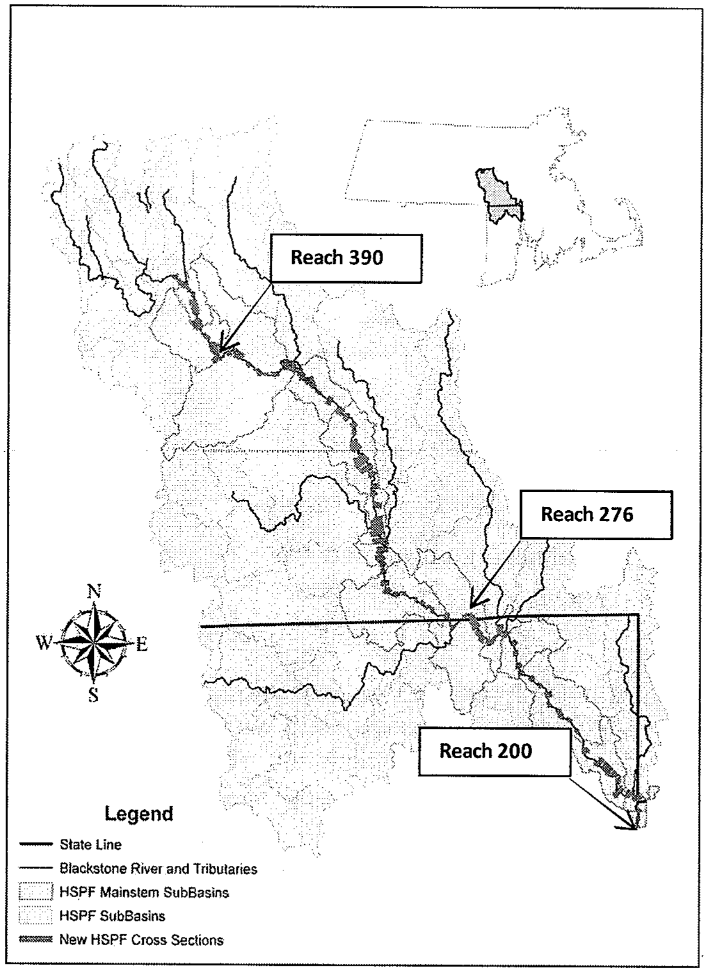

Figure 10: Locations for which cumulative frequency distribution plots are presented

Cumulative frequency distributions were calculated from the daily average in-stream concentrations (or load) estimated by the model for a given location over the simulation period. The Weibull formula, Equation 3, was used to compute the frequencies of both the loads and concentrations at all three locations,

$$P = r\frac{1}{n+1}*100 \qquad \text{Equation 3}$$

where, P is the probability (or frequency) of a given load or concentration, r is the rank of load or concentration where 1 is lowest, n is highest and n is the number of samples. Results are presented for TN, TP, and Chl-a concentrations at Millbury, the MA/RI border, and at the basin outlet under the actual flow regime. In addition, the cumulative frequency distribution of TN and TP loads at the basin outlet are presented under actual flow conditions. Cumulative frequency distribution plots for loads at Millbury and the MA/RI border as well as plots for DO are included in Appendix E. As noted previously, model calibration for DO and Chl-a is undergoing further refinement; results for these parameters should thus be considered interim. However, although model calibration refinement may alter specific values, trends and relative behavior under the studied scenarios are anticipated to be similar. Cumulative frequency distribution plots under design flow conditions are included in Appendix F. In general, as more stringent effluent limits are applied, cumulative frequency distribution curves shift to the left, reflecting an overall reduction in concentration or load in the river. Model simulation results under the actual and design flow regimes are comparable for a given scenario.

Two orange lines have been added to the TN and TP figures below to provide a reference for evaluating effectiveness of the analyzed scenarios. The horizontal line references the in-stream concentration values corresponding to the P25, or the 25th percentile. The concentration value corresponding to the point where this line intersects each scenario curve represents the concentration that is *not* exceeded 25% of the time. This value was selected as a reference based on EPA recommended usage of the P25 value of observed data for unimpaired streams and rivers as an appropriate reference, or background, value. In addition, average results were presented earlier in the along stream results and are expected to represent a comparable evaluation of in-stream water quality improvements as the median, or P50, would. The vertical line references the EPA P75 summer reference condition for Ecoregion 14-59, within which the Blackstone lies. This value was selected as representative of some of the highest concentrations observed in unimpaired waters of the region.

Millbury

Scenario results are summarized through cumulative frequency distribution (CFD) curves for TN daily concentration at Millbury on Figure 11 for the actual flow regime. A large shift in the TN daily concentration CFD curve is observed between the Current and Upgrade 1 scenarios. A smaller shift in the CFD occurs between Upgrade 1 and Upgrade 2. Results for the UP1NPS fall between the two, but are very close to the UP1 line. Larger reductions in in-stream concentrations occur as the result of more stringent effluent limits at higher cumulative frequencies, or those that are exceeded less frequently. P25 values based on the daily concentrations at Millbury predicted by the model for each scenario are presented in Table 14 below for TN and TP. Under most scenarios, model results suggest that mean daily concentrations at Millbury remain above the EPA summer P75 value for TN (orange vertical line) of 0.94 mg/L. The only exception to this is the ZeroUB scenario, for which cumulative frequencies below P80 are lower than the EPA summer P75 value.

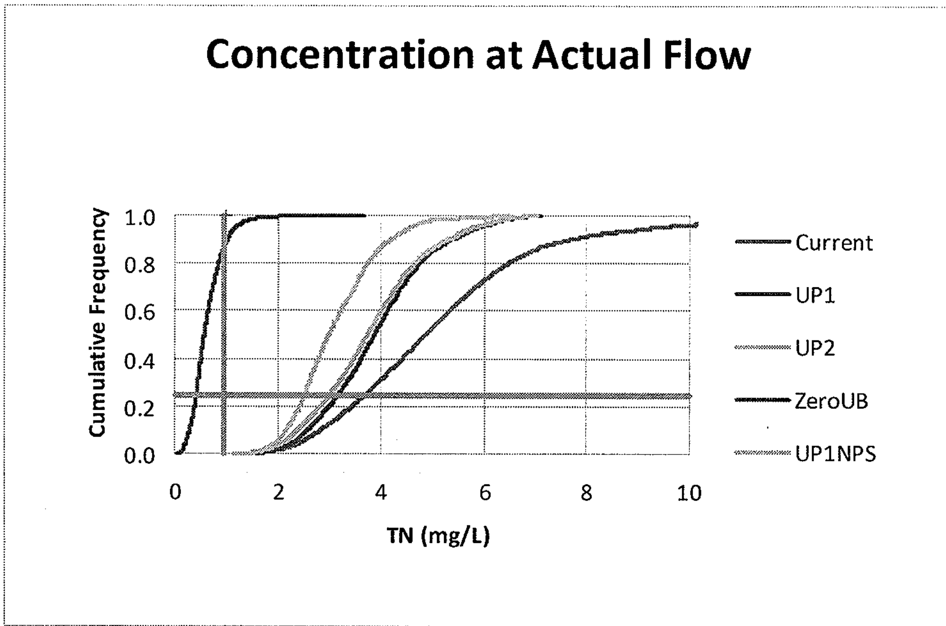

Figure 11: Cumulative frequency distribution of model average daily TN concentrations at Millbury (river mile 41.7) for the actual flow regime

Table 14: Modeled average daily in-stream P25 concentrations for the studied scenarios at Millbury

	Scenario				
Parameter	Current	UP1	UP2	ZeroUB	UP1NPS
TN	3.68 mg/L	3.16 mg/L	2.52 mg/L	0.42 mg/L	3.0 mg/L
TP	0.35 mg/L	0.24 mg/L	0.09 mg/L	0.03 mg/L	0.23 mg/L

The TP cumulative frequency distribution (CFD) curves at Millbury for the studied scenarios are shown on Figure 12 for the actual flow regime. The more stringent effluent limits in UP1 result in a large shift of the CFD to the left such that almost all modeled daily TP concentrations fall below 0.5 mg/L TP. Under most scenarios, model results suggest that mean daily TP concentrations at Millbury remain above the EPA summer P75 value (orange vertical line) of 0.09 mg/L. However, values below P30 for the UP2 scenario fall below this reference concentration as well as values below the P90 for the ZeroUB scenario. P25 values based on the daily concentrations at Millbury predicted by the model for each scenario are presented in Table 16 below.

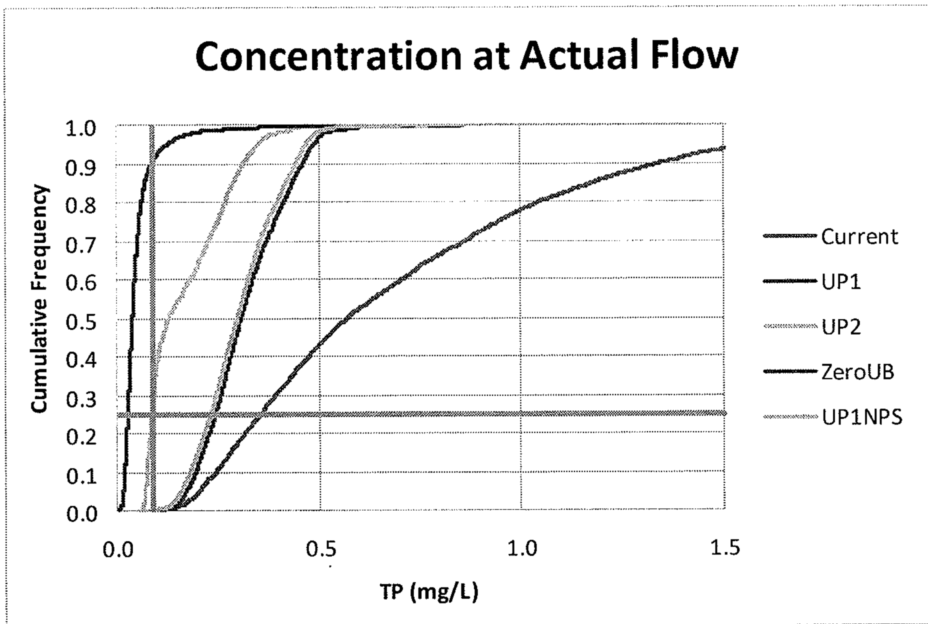

Figure 12: Cumulative frequency distribution of model average daily TP concentrations at Millbury (river mile 41.7) for the actual flow regime

Scenario results are summarized through cumulative frequency distribution (CFD) curves for Chlorophyll a concentration at Millbury on Figure 13 for the actual flow regime. The CFD curves for Chl-A concentration are essentially the same between flow regimes and scenarios at this location. This is due to the proximity of Millbury to the UBWPAD, an associated lack of algal growth at this location, and low Chl-a concentrations upstream of the UBWPAD.

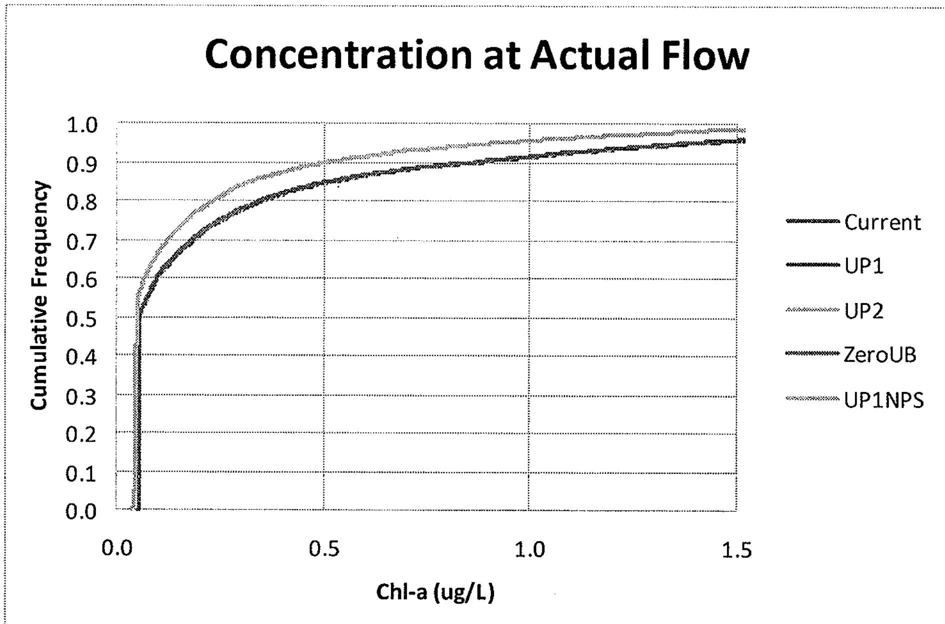

Figure 13: Cumulative frequency distribution of model average daily Chl-a concentrations at Millbury (river mile 41.7) for the actual flow regime

MA/RI Border

Scenario results are summarized through cumulative frequency distribution (CFD) curves for TN daily concentration at the MA/RI border for the actual flow regime on Figure 14. A large shift in the TN daily concentration CFD curve is observed between the Current and Upgrade 1 scenarios. A smaller shift in the CFD occurs between Upgrade 1 and Upgrade 2. Results for the UP1NPS fall about half-way between the two. Larger reductions in in-stream concentrations occur at higher cumulative frequencies, or those that are exceeded less frequently. P25 values based on the daily concentrations at the border predicted by the model for each scenario are presented in Table 15 below for TN and TP. In comparison to the curves at Millbury, most of the CFDs at the MA/RI border are shifted towards lower in-stream TN concentrations, reflecting along stream dilution and attenuation. However, the ZeroUB scenario has actually shifted towards higher concentrations, reflecting the cumulative impacts of NPS nitrogen sources on the scenario. Model results suggest that mean daily concentrations under all scenarios remain above the EPA summer P75 value for TN (orange vertical line) of 0.94 mg/L. The only exception to this is the ZeroUB scenario, for which cumulative frequencies below P10 are lower than the EPA summer P75 value.

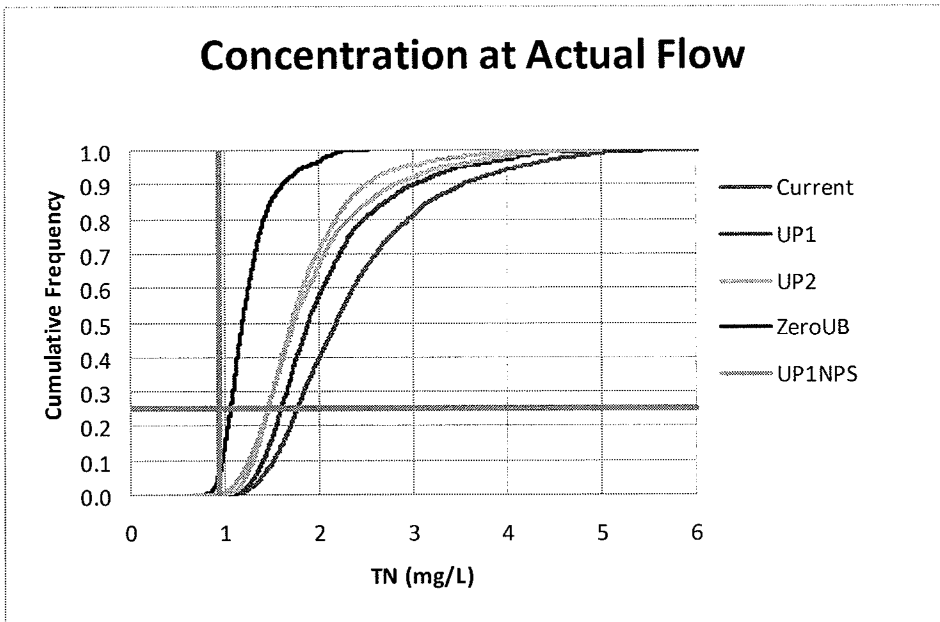

Figure 14: Cumulative frequency distribution of model average daily TN concentrations at the MA/RI border (river mile 16.6) for the actual flow regime

Table 15: Modeled average daily in-stream P25 concentrations for the studied scenarios at the MA/RI border

	Scenario				
Parameter	Current	UP1	UP2	ZeroUB	UP1NPS
TN	1.8 mg/L	1.6 mg/L	1.5 mg/L	1.1 mg/L	1.5 mg/L
TP	0.14 mg/L	0.11 mg/L	0.09 mg/L	0.07 mg/L	0.10 mg/L

The TP cumulative frequency distribution (CFD) curves at the MA/RI for the studied scenarios are shown on Figure 15 for the actual flow regime. The more stringent effluent limits in UP1 result in a large shift of the CFD to the left such that almost all modeled daily TP concentrations fall below 0.3 mg/L TP. Under most scenarios, model results suggest that mean daily TP concentrations at the border remain above the EPA summer P75 value (orange vertical line) of 0.09 mg/L. P25 values based on the daily concentrations at the MA/RI predicted by the model for each scenario are presented in Table 15. Relative differences in concentration between the scenarios for a given cumulative frequency are smaller at this location than at Millbury. CFDs based on load (see Appendix E) also begin to converge, but not as drastically.

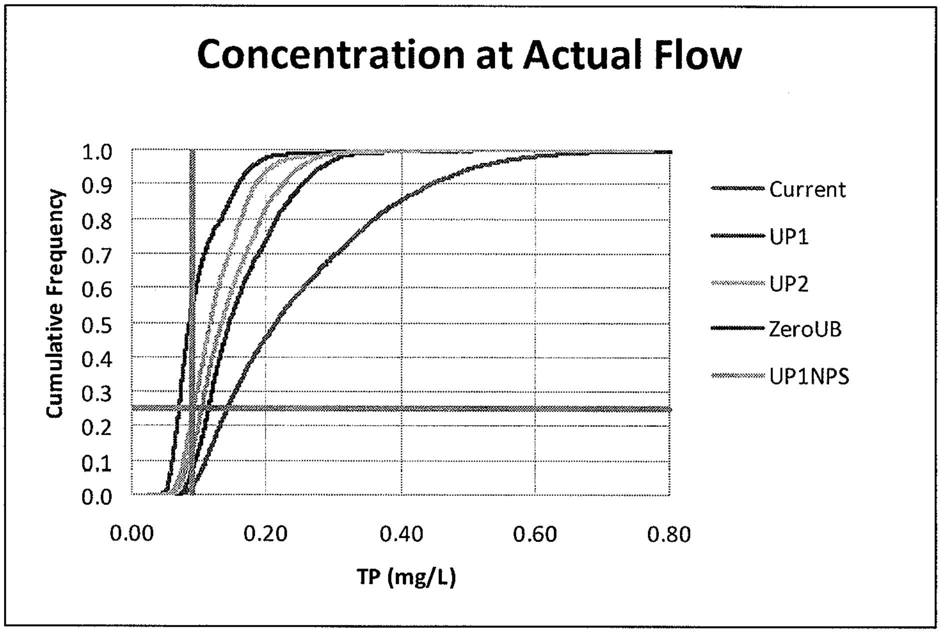

Figure 15: Cumulative frequency distribution of model average daily TP concentrations at the MA/RI border (river mile 16.6) for the actual flow regime

Scenario results are summarized through cumulative frequency distribution (CFD) curves for Chlorophyll a concentration at the MA/RI border on Figure 16 for the actual flow regime. Note that a log-scale has been used for the x-axis so that the entire range of concentrations is viewable. The CFD curves for Chl-a concentration are very similar between flow regimes and scenarios, but a general shift to lower concentrations occurs, particularly between Upgrade 1 and Upgrade 2. The curve for the UP2 scenario is comparable to the ZeroUB scenario. For all scenarios, at least 90% of the observed Chl-a values are less than 20 μg/L at this location. Further refinements to the Chl-a calibration are expected, so these results should be considered interim. However, although model calibration refinement may alter specific values, trends and relative behavior under the studied scenarios are anticipated to be similar.

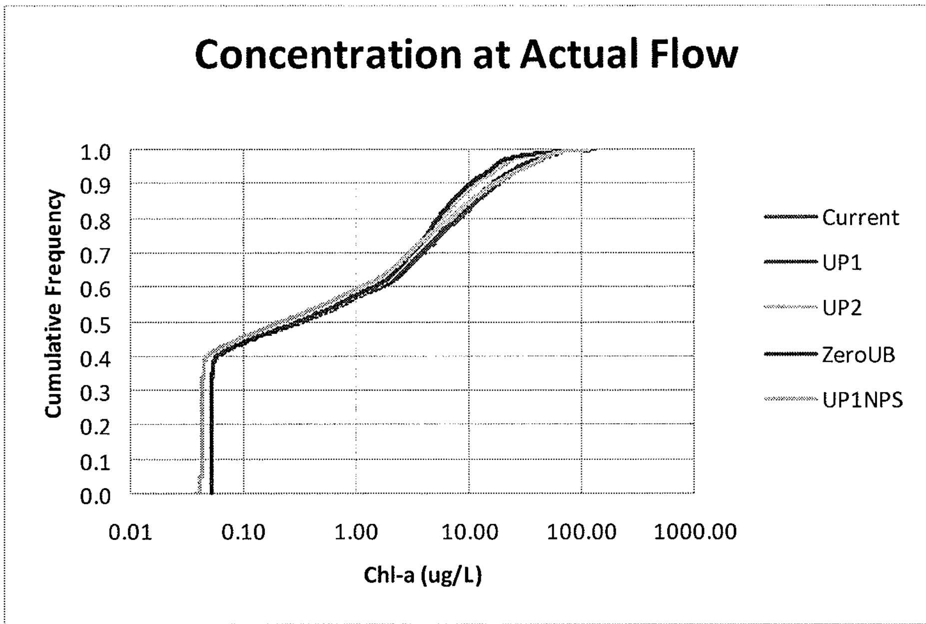

Figure 16: Cumulative frequency distribution of model average daily Chl-a concentrations at the MA/RI border (river mile 16.6) for the actual flow regime

Blackstone River Outlet

Scenario results are summarized through cumulative frequency distribution (CFD) curves for TN daily concentration at the basin outlet for the actual flow regime on Figure 17. The CFD curve for TN daily loads is shown on Figure 18. As observed for the other locations, a shift in the TN daily concentration CFD curve is observed between the Current and Upgrade 1 scenarios. A smaller shift in the CFD occurs between Upgrade 1 and Upgrade 2. Results for the UP1NPS scenario are comparable to those of UP2 across most of the cumulative frequencies. Larger reductions in in-stream concentrations occur at higher cumulative frequencies, or those that are exceeded less frequently. P25 values based on the daily concentrations at the border predicted by the model for each scenario are presented in Table 16 below for TN and TP. In comparison to the curves at Millbury and the MA/RI border, most of the CFDs at the MA/RI border are shifted towards lower in-stream TN concentrations, reflecting along stream dilution and attenuation. Changes in in-stream concentrations are relatively smaller than those observed further upstream across a range of frequencies. For example, under the UP1 scenario, 70% of the in-stream TN concentrations are below 2.0 mg/L. However, under the UP2 scenario, 70% of the concentrations are less than 1.9 mg/L, a difference of only 0.1 mg/L TN. In addition, the ZeroUB scenario has shifted closer towards the UP2 scenario results, reflecting the cumulative impacts of NPS nitrogen sources on the scenario. Model results suggest that mean daily concentrations under all scenarios remain above the EPA summer P75 value for TN (orange vertical line) of 0.94 mg/L. The results for TN load are similar. The P25, median, and P75 daily loads from the basin are summarized in Table 17.

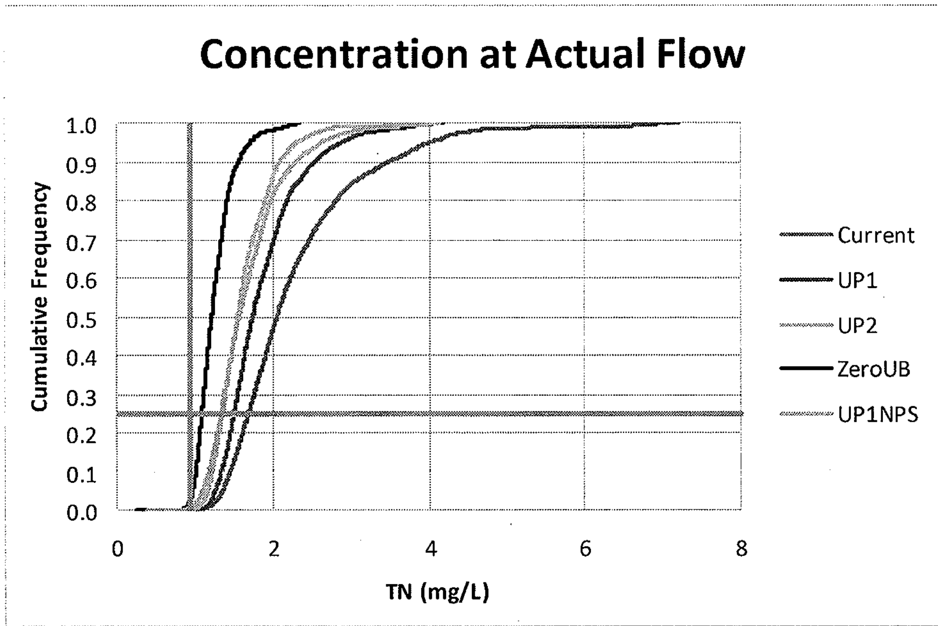

Figure 17: Cumulative frequency distribution of model average daily TN concentrations at the basin outlet for the actual flow regime

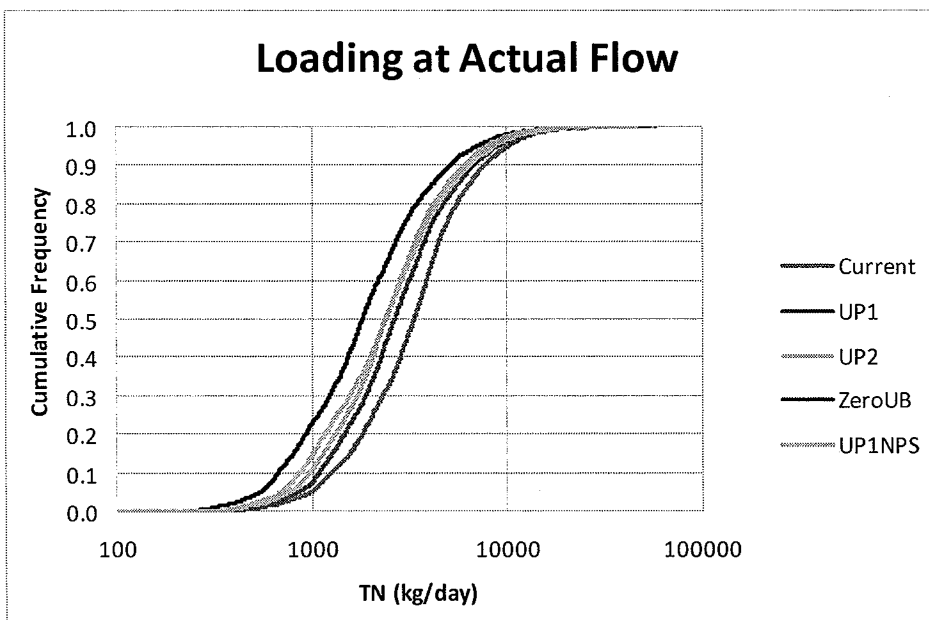

Figure 18: Cumulative frequency distribution of model average daily TN loads at the basin outlet for the actual flow regime

Table 16: Modeled average daily in-stream P25 concentrations for the studied scenarios at the MA/RI border

	Scenario				
Parameter	Current	UP1	UP2	ZeroUB	UP1NPS
TN	1.7 mg/L	1.5 mg/L	1.4 mg/L	1.1 mg/L	1.3 mg/L
TP	0.16 mg/L	0.11 mg/L	0.09 mg/L	0.07 mg/L	0.10 mg/L

Table 17: Modeled average daily loads, kg/day, from the basin for a range of frequencies

		Scenario				
Parameter	***Freq.***	***Current***	***UP1***	***UP2***	***ZeroUB***	***UP1NPS***
TN	.25	2,040	1,670	1,350	1,080	1,500
	.50	3,330	2,640	2,370	1,800	2,380
	.75	4,920	4,170	3,890	3,300	3,730
TP	.25	252	135	91	89	118
	.50	363	199	169	134	178
	.75	544	306	273	218	273

The TP cumulative frequency distribution (CFD) curves at the outlet for the studied scenarios are shown on Figures 19 and 20 for the actual flow regime. The more stringent effluent limits in UP1 result in a large shift of the CFD to the left such that almost all modeled daily TP concentrations fall below 0.2 mg/L TP. Under most scenarios, model results suggest that mean daily TP concentrations at the border remain above the EPA summer P75 value (orange vertical line) of 0.09 mg/L. P25 values based on the daily concentrations at the MA/RI predicted by the model for each scenario are presented in Table 16 and are almost equivalent for the scenarios. There are greater differences at higher frequencies. For example, the P70 concentration for UP1 is approximately 0.17 mg/L while for UP2 it is approximately 0.12 mg/L. Relative differences in concentration between the scenarios for a given cumulative frequency are smaller at this location than at Millbury and the border. CFDs based on load also converge, but not as drastically.

Scenario results are summarized through cumulative frequency distribution (CFD) curves for Chl-a concentrations at the Blackstone River outlet on Figure 21 for the actual flow regime. Note that a log-scale has been used for the x-axis so that the entire range of concentrations is viewable. The CFD curves for Chl-a concentration are very similar between flow regimes and scenarios, but a general shift to lower concentrations occurs, particularly between Upgrade 1 and Upgrade 2. The concentrations of Chl-A observed at the outlet are shifted to higher Chl-a values than upstream. For example, at the MA/RI border, at least 90% of the Chl-a values for all scenarios were less than 20 μg/L. A vertical line representing a concentration of 20 μg/L Chl-a has been added to Figure 21. At the outlet, most of the scenario lines intersect with a cumulative frequency of approximately 75% at this concentration. This shift to higher concentrations is likely due to the longer residence times available to the algal blooms for growth. The curve for UP1NPS falls to the left of the ZeroUB curve at times, suggesting that targeted downstream NPS management may be an effective option for lowering Chl-a concentrations in the Rhode Island portions of the river. These results are interim, however, and further study is necessary. However, although model calibration refinement may alter specific values, trends and relative behavior under the studied scenarios are anticipated to be similar.

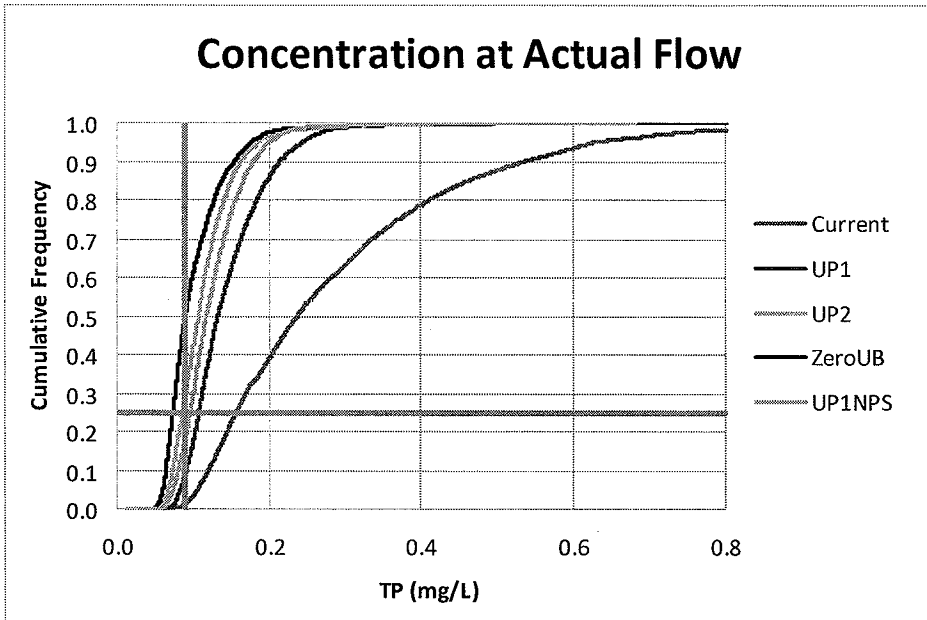

Figure 19: Cumulative frequency distribution of model average daily TP concentrations at the basin outlet for the actual flow regime

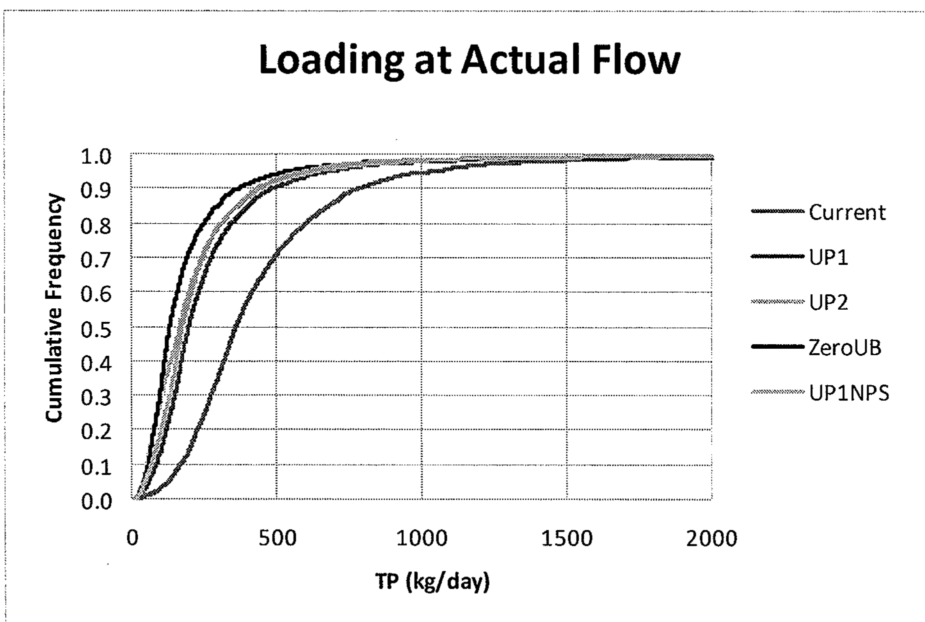

Figure 20: Cumulative frequency distribution of model average daily TP loads at the basin outlet for the actual flow regime

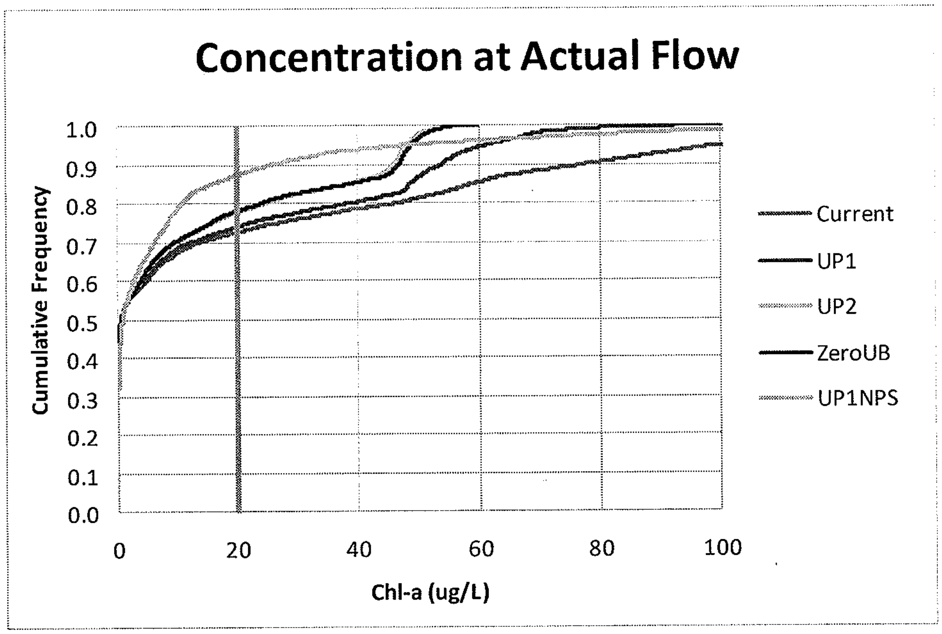

Figure 21: Cumulative frequency distribution of model average daily Chl-a concentrations at the basin outlet for the actual flow regime

4.5 Delivery of Nutrients to Narragansett Bay

While in Massachusetts the focus for water quality improvement is on in-stream concentrations, delivery of nutrients to Narragansett Bay is an additional concern. Figures 22 and 23 present the modeled reduction in annual TN and TP load to the bay as lower effluent limits are imposed. Annual variability is due mainly to hydrologic variability, although some impacts of improved effluent data availability and point source improvements over the simulation period are likely present. Table 18 summarizes the average annual TN and TP load to Narragansett Bay over the simulation period under the five scenarios. The reductions are summarized on a percent basis in Table 19 for TN and Table 20 for TP. For comparison purposes, the percent reduction of external sources (PS and NPS) is included in these tables. In general, stricter effluent limits result in a larger reduction of TP load to the Bay than TN. Under the UP1 limits, annual TN load to the Bay is reduced by 15% on average while annual TP load is reduced by 38% on average. These reductions are less than the corresponding percent reductions in PS contributions (26% and 57%, respectively) due to a combination of in-stream processes and NPS contributions. Under the UP1 scenario, point source controls are about 60% as effective on a percent basis at the basin outlet. Under the UP2 limits, annual TN load to the Bay is reduced by 22% on average while annual TP load is reduced by 46% on average. As for TN, these reductions are less then the corresponding percent reductions in PS contributions (39% and 71%, respectively). Under the UP2 scenario, point source controls are also about 60% as effective on a percent basis at the basin outlet. The UP1NPS scenario results suggest that targeted NPS reductions may be a more efficient mechanism for reducing overall loads to Narragansett Bay. Additional alternative scenarios should be analyzed to study this potential. In addition, the model results should be used to analyze the impacts of in-stream processes on load and along stream attenuation. Changes in seasonal load are also of interest but are not available at this time.

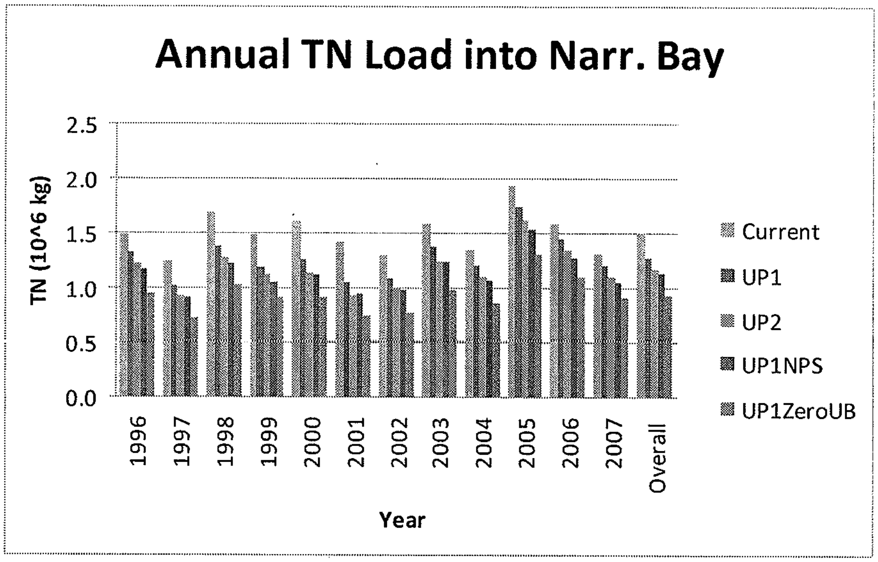

Figure 22: Variation in annual TN load from the Blackstone River to Narragansett Bay in millions of kg

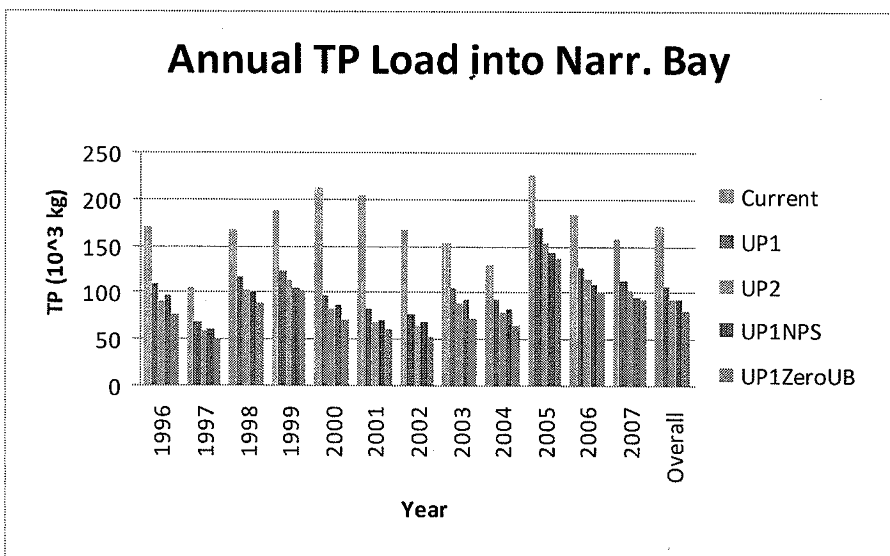

Figure 23: Variation in annual TP load from the Blackstone River to Narragansett Bay in millions of kg