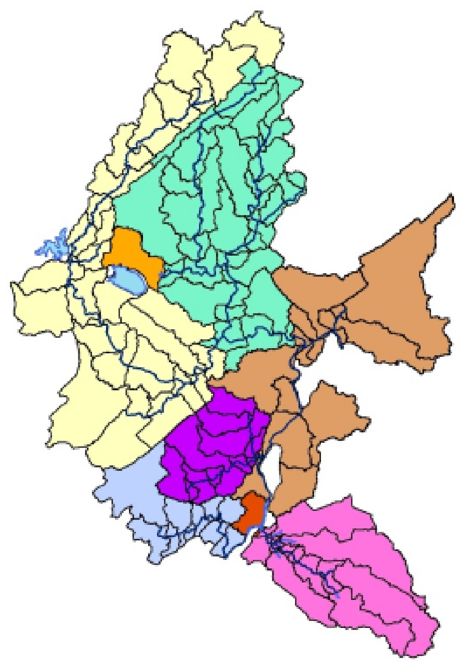
PHASE II FINAL REPORT

RARITAN RIVER BASIN NUTRIENT TMDL STUDY
WATERSHED MODEL AND TMDL CALCULATIONS

VOLUME 1 OF 3



PREPARED FOR:

RUTGERS UNIVERSITY NEW JERSEY ECOCOMPLEX
AND
NEW JERSEY DEP'T ENVIRONMENTAL PROTECTION
DIVISION OF WATER MONITORING AND STANDARDS

AUGUST 2013

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AUGUST 2013

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EXECUTIVE SUMMARY

This study was undertaken to provide the scientific foundation to understand the cause-and-effect relationships between pollutant loads and observed water quality responses for a select set of related water quality impairments in the Raritan River Basin. Defining these relationships provides the Department with the defensible technical basis to address total phosphorus (TP), pH, dissolved oxygen (DO), and total suspended solids (TSS) impairments in streams and lakes within the study area. This will include regulatory actions, implemented through NJPDES permits, and non-regulatory actions involving regional and local partners, targeted funding, and stewardship building.

Phosphorus can cause designated use impairment by stimulating excessive growth of algae and aquatic plants, which can cause oxygen supersaturation during the day and oxygen depletion at night. Large diurnal variations of DO are often associated with large diurnal variations of pH, both of which can be induced by excessive growth in the system. As a result, phosphorus is related, through primary productivity, to both DO and pH. In addition to affecting attainment of DO and pH criteria, excessive productivity can result in non-attainment of the narrative nutrient criteria at N.J.A.C. 7:9B-1.14(d)4.i:

> *"Except as due to natural conditions, nutrients shall not be allowed in concentrations that render the waters unsuitable for the existing or designated uses due to objectionable algal densities, nuisance aquatic vegetation, diurnal fluctuations in dissolved oxygen or pH indicative of excessive photosynthetic activity, detrimental changes to the composition of aquatic ecosystems, or other indicators of use impairment caused by nutrients."*

The study defined critical locations and end points that drive the pollutant load reductions needed in order to attain Surface Water Quality Standards (SWQS) and thereby support designated uses. Based on applicable instream and in-lake water quality criteria in the SWQS [N.J.A.C. 7:9B-1.14(d)], water quality targets were defined in terms of TP, DO, and TSS. In order to address pH impairments, peak diurnal DO thresholds were defined at critical locations to relate predicted DO to the maximum pH criterion of 8.5 s.u.

The Raritan River Basin Model was developed by Kleinfelder/Omni as a diagnostic and predictive tool to inform the management responses developed by NJDEP to address water quality impairments. The Model consists of a family of five watershed area models that are calibrated and validated for nutrients, DO, and TSS. Each watershed area model simulates flow and water quality by integrating hydrologic (runoff and baseflow), pollutant loading (point and nonpoint source), hydraulic (channel characteristics such as depth and velocity), and receiving water quality (pollutant fate and transport) models within a geographically-based modeling framework. The hydrologic and nonpoint source pollutant loading model (HydroWAMIT) was developed specifically for this project in order to simulate important features of the system and to isolate various nonpoint sources. It is coupled with a large-scale application of USEPA's dynamic surface water quality model, Water Analysis Simulation Program (WASP7.1). The Raritan River Basin Model represents a state-of-the-art simulation tool that integrates point and nonpoint sources and captures salient hydrologic properties, hydraulics, and instream kinetics. Watershed modeling analyses were performed to assess the impact of nutrient reductions from point and nonpoint sources on DO, phosphorus concentrations, pH (through relationship with diurnal DO peaks), and TSS in streams and lakes throughout the system.

A phosphorus TMDL Condition was defined as the combination of point and nonpoint source reductions that will satisfy water quality targets throughout the system. Point and nonpoint source reductions varied significantly among the various basins and even from one watershed to the next within a basin. Wastewater treatment plant (WWTP) point source allocations were assigned for both summer and winter based on satisfaction of water quality targets under varying seasonal flows. The model has demonstrated that instream levels of orthophosphorus are critical to attaining water quality objectives; therefore, in addition to TP, effluent loadings for the TMDL Condition were also established for orthophosphorus. Stormwater sources were assigned watershed-specific percent reductions of loads from urban and agricultural land areas. Appendix P provides the effluent concentrations and loads associated with the TMDL Condition for each WWTP point source in each major basin[1], as well as the stormwater source reductions that would be required in each watershed to achieve water quality standards.

The TSS TMDL Condition was based on the stormwater TSS improvements that would result from the implementation of the phosphorus TMDL, which was found to satisfy TSS water quality targets at all subwatershed outlets. Percent reductions of TSS in stormwater from urban

[1] Effluent levels for the lower Millstone River (downstream of Carnegie Lake) and the mainstem Raritan River downstream of the Millstone River are not included in Appendix P, since a TMDL analysis for TP was not performed in this watershed area. The narrative nutrient criteria are met in the lower Millstone River; however, a TMDL analysis in the mainstem Raritan River was deferred because existing data provided inconclusive results that could not be explained from a water quality perspective. Based on the results of follow-up studies in the mainstem Raritan River, it is possible that this area will be affected by a future TMDL based on impact to the mainstem Raritan River.

and agricultural areas were set to the same percent reduction assigned to each subwatershed for TP reductions. This is a conservative assumption, since stormwater management improvements generally reduce TSS in stormwater more than TP. Appendix S provides the stormwater and nonpoint source TSS source reductions required in each watershed.

As required under the Clean Water Act, this study was focused on achieving 100% compliance with applicable surface water quality criteria. The Clean Water Act also requires a Margin of Safety (MOS) in setting the TMDL in order to account for uncertainty in the loading estimates, physical parameters, and the model itself; a MOS of 10% for WWTP point sources and 20% for stormwater and nonpoint sources was applied in order to account for these uncertainties. The TMDL requires major reductions of nonpoint source and stormwater loads; the reason is that stormwater causes storm-induced peaks of both phosphorus and TSS concentrations in the streams. Major reductions are required in order to prevent those peaks from exceeding the water quality targets. Similarly, the TMDL Condition requires significant reductions of TP and orthophosphorus levels from WWTP sources. These reductions are necessary to satisfy the nutrient criteria under all flow conditions and to constrain instream productivity enough to reduce the diurnal pH peaks below the criterion.

The TMDL outcomes for each impairment designation in each subwatershed are provided in Appendix Q. Following the public comment process and approval by EPA, the phosphorus and TSS TMDLs will be implemented through NJPDES permit revisions for wastewater and urban stormwater sources, and programs designed to encourage the application of agricultural BMPs.

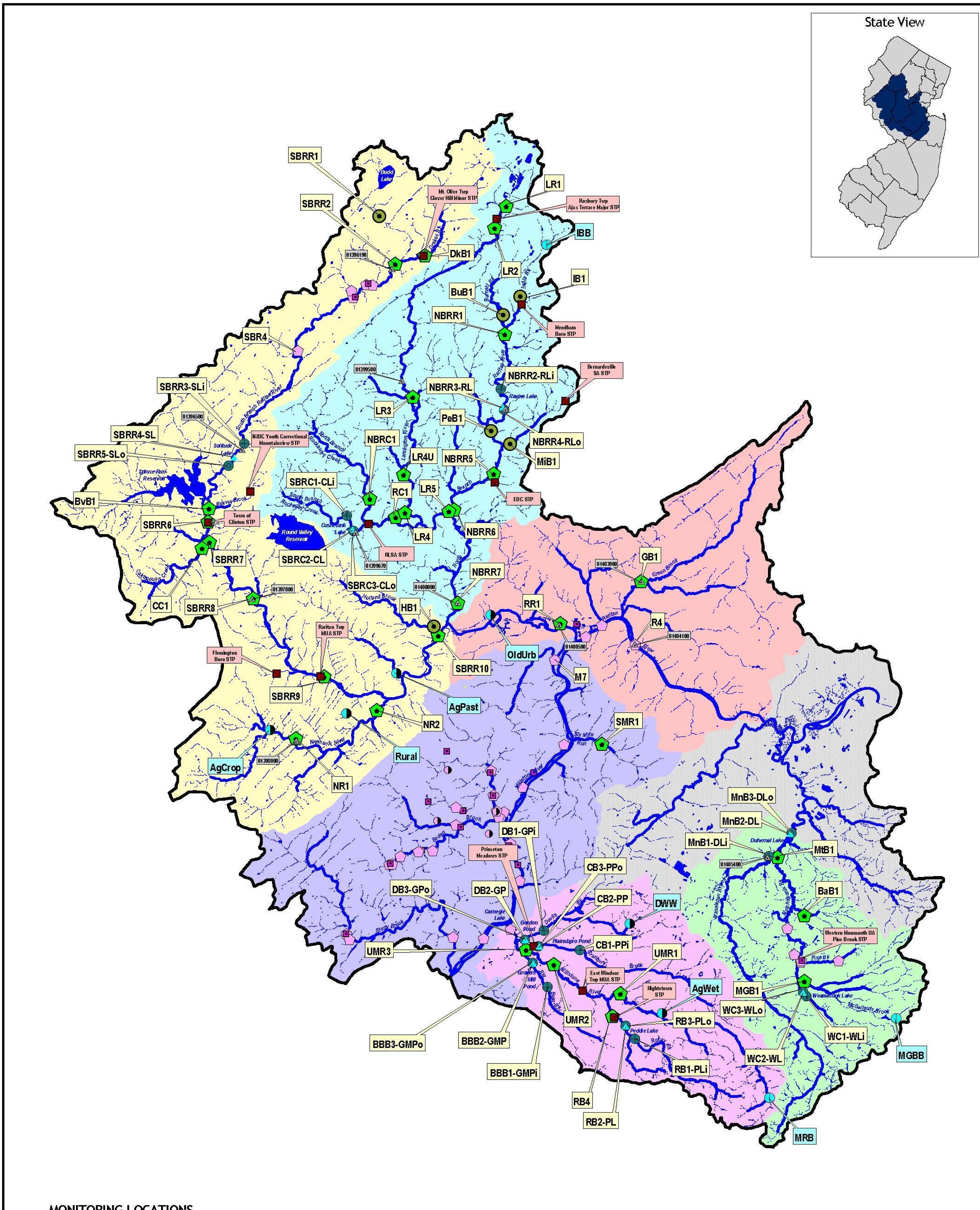
I. INTRODUCTION

A. Project Description

The Raritan River Basin encompasses over 1,100 square miles in the central portion of New Jersey that drain to the Raritan Bay, and includes three of the State of New Jersey's Watershed Management Areas (WMAs): WMA 8 (470 mi²), WMA 9 (350 mi²), and WMA 10 (285 mi²). The Raritan River Basin Nutrient Total Maximum Daily Load (TMDL) Study (hereafter referred to as Raritan TMDL Study) was designed to provide the technical basis for the New Jersey Department of Environmental Protection (NJDEP, also referred to as "the Department") to establish TMDLs as necessary to address phosphorus and other conventional pollutant impairments in the Raritan River Basin. A TMDL specifies the maximum amount of a pollutant that a waterbody can receive while still being in compliance with the applicable water quality standards, and is required for all impaired waters by the Clean Water Act (Section 303d).

Extensive data collection was performed during Phase I, the purpose of which was to augment presently available information in order to provide data necessary to evaluate nutrient chemistry and use impairment, as well as provide data necessary for the modeling work in Phase II. Figure 1 (taken from Phase 1 Report: TRC Omni, December 19, 2005) is provided to illustrate the monitoring station locations and types (e.g. stream, WWTP, and stormwater). Sampling was performed in accordance with the Quality Assurance Sampling Plan prepared by Omni[2] and approved by NJDEP (TRC Omni, May 24, 2004). The data collected during Phase I of the Raritan TMDL Study were presented and summarized in the Phase I Report (TRC Omni, December 19, 2005), along with a preliminary identification of critical locations. The results of Phase II, including model development, TMDL definition, and load allocations, are provided in this report.

[2] Now Kleinfelder/Omni; formerly TRC Omni Environmental Corporation and Omni Environmental LLC.



MONITORING LOCATIONS

- Characterization Station
- Tributary Station
- Lake Inlet
- Lake Station
- Lake Outlet
- Background/Stormwater Station
- Background Station
- STP
- STP - Phosphorus Study
- Phosphorus Study Station
- Phosphorus Study Stormwater Station
- USGS Flow Station

- Main Stem Raritan River
- Matchaponix Brook
- North Branch Raritan River
- South Branch Raritan River
- Lower Millstone River
- Upper Millstone River
- Outside Study Area

Lake
River
Stream

Figure 1

Raritan River Basin Nutrient TMDL Study Monitoring Locations

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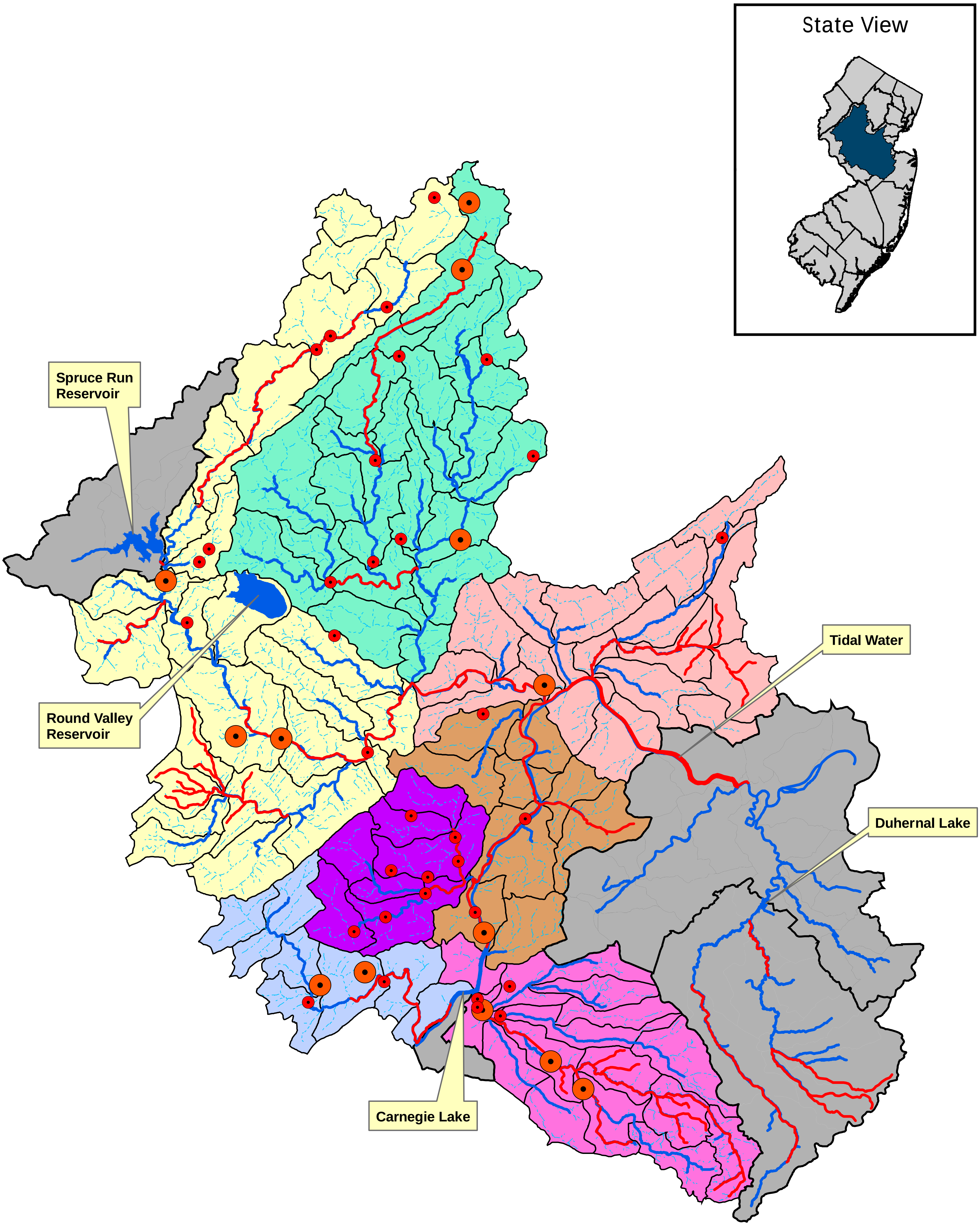
This project complements phosphorus evaluation studies performed in 2000, 2001, and 2003 for substantial portions of the lower Millstone River and mainstem Raritan watersheds (TRC Omni, May 6, 2004; TRC Omni, December 8, 2004) as well as a phosphorus evaluation performed concurrently in 2004 in the South Branch Raritan River (TRC Omni, March 8, 2005). The purpose of these phosphorus evaluations, performed by Omni on behalf of municipal utility authorities, was to evaluate nutrient limitation and use impairment in order to determine the applicability of the phosphorus stream criterion. In accordance with NJDEP guidance that was applicable at the time the studies were performed, nutrient limitation was evaluated using instream nutrient chemistry while use impairment was evaluated using response indicators of productivity under critical conditions, namely diurnal DO, phytoplankton concentration, and periphyton density. Data collected during these studies are available electronically in Appendix T, along with other historic data assembled by Kleinfelder/Omni for this study.

Kleinfelder/Omni worked closely with NJDEP Division of Water Monitoring and Standards to perform this work under a contract with the Rutgers University New Jersey EcoComplex (NJEC). Funding, project oversight, and technical review were provided by NJDEP, while contract management and academic technical review were provided by NJEC. Project presentations were provided to NJDEP and NJEC on September 20, 2006, December 10, 2007, and May 7, 2008. An initial Report was submitted to NJDEP in June 2008. Based on extensive review by NJDEP and NJEC, additional work was performed to complete the project. A final project presentation reflecting the additional work was provided to NJDEP and NJEC on October 1, 2010. A revised Report was submitted to NJDEP in March 2011. Additional technical review by NJDEP and NJEC led to this Final Report, which was finalized in August 2013.

In addition to the technical and administrative oversight provided by NJDEP and NJEC, the project was subjected to extensive public review. Public presentations were provided to interested stakeholders on: August 20, 2007 (Data Summary); September 17, 2007 (Model Calibration and Validation); December 17, 2007 (Water Quality Targets and Future Simulations); June 5, 2013 (Raritan TMDL Stakeholder Meeting); June 18, 2013 (Raritan TMDL Discharger Meeting). These presentations are included with the electronic documentation provided in Appendix T.

B. Area of Interest

The area of interest within the Raritan River Basin was based generally on the extent of watersheds within the basin with stream segments that were designated by NJDEP as impaired by phosphorus, ammonia, nitrate, dissolved oxygen, pH, temperature, and TSS in its 2004 Integrated List of Waterbodies (NJDEP, June 2004), and was subsequently updated to reflect the 2006 and 2008 Integrated Lists (NJDEP, December 2006; and NJDEP, July 2009). Figure 2 shows the general area of interest for the Raritan River Basin Nutrient TMDL Study, subdivided into various study areas: South Branch Raritan River watershed; North Branch Raritan River watershed; mainstem Raritan River watershed; Carnegie Lake watershed (upper Millstone River and Stony Brook watersheds); Beden Brook watershed; and lower Millstone River watershed. Spruce Run Reservoir and its drainage area were excluded from the area of interest for several reasons: 1) Spruce Run Reservoir is a complex water feature, the study of which would necessitate significant additional monitoring effort and different modeling tools; and 2) the continuous stream flow gage in Spruce Run just downstream of the reservoir provides a useful model boundary for the TMDL study, given that there did not appear to be any justification for the significant effort that would be required to include Spruce Run Reservoir. The Duhernal Lake watershed (Matchaponix Brook and Manalapan Brook watersheds) is outside the study area for this report, but will be evaluated in a separate technical report. Figure 3 shows the land use / land cover and stream classifications within the various study areas. Land uses are important because they generate stormwater runoff, which is an important source of pollutants to the surface waters in the Raritan River Basin.



Sources:
NJDEP, NJGS, 2006. DEPHUC14
NJDEP, OIRM, BGIS, 2008. Streams Update for New Jersey

- Major Dischargers
- Minor Dischargers
- Raritan River Basin Integrated List 2004 Phosphorus Impaired Segments
- Lake
- River
- Stream
- South Branch Raritan River Watershed
- North Branch Raritan River Watershed
- Mainstem Raritan River Watershed
- Upper Millstone River Watershed
- Stony Brook Watershed
- Beden Brook Watershed
- Lower Millstone River Watershed
- Outside Area of Interest

Figure 2

Raritan River Basin Nutrient TMDL Study Area of Interest

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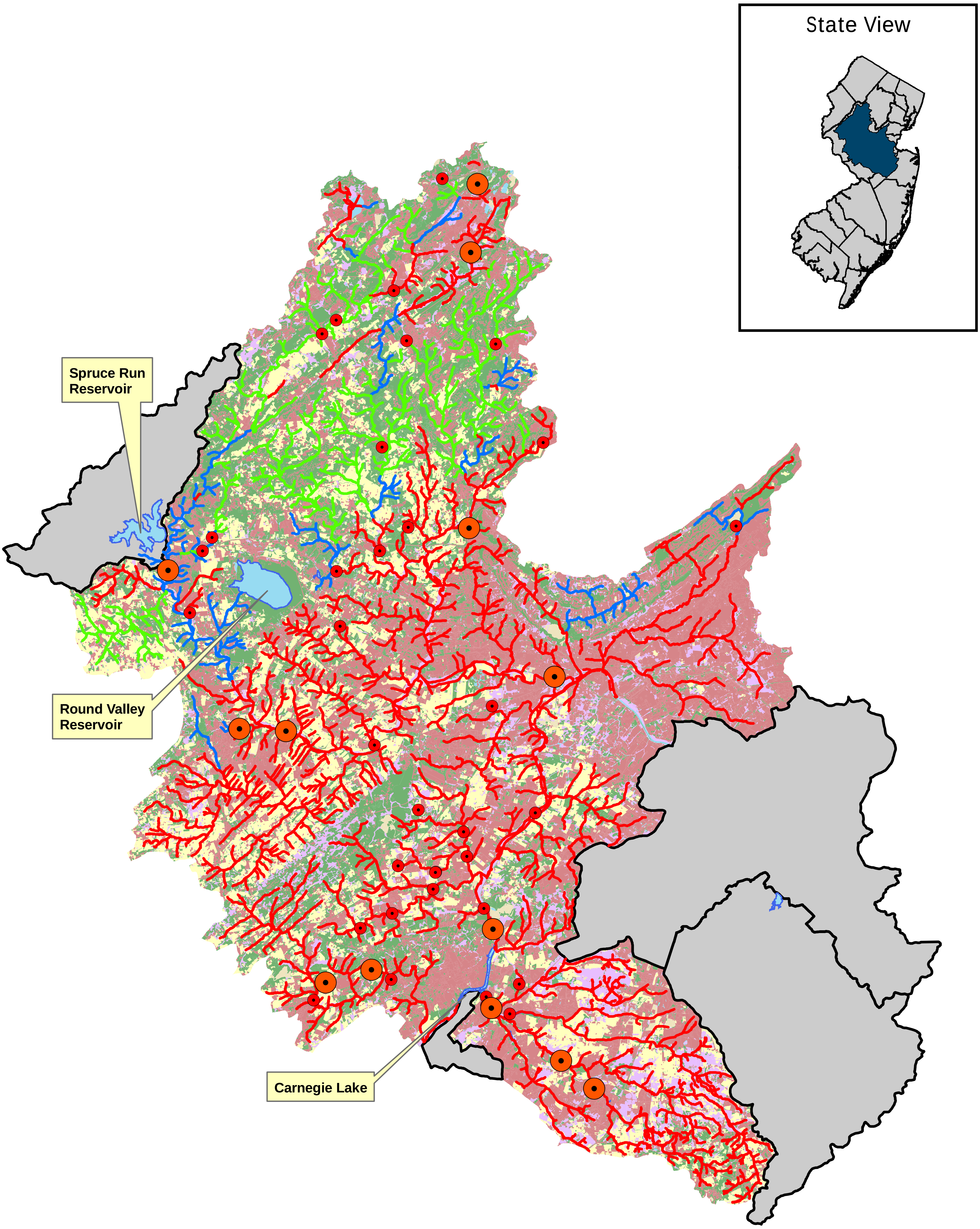

Sources:
NJDEP, NJGS, 2006. DEPHUC14
NJDEP, OIRM, BGIS, 2008. Streams Update for New Jersey
NJDEP, OIRM, BGIS, 2002 Land Use, 2007 Updates

Major Dischargers
Minor Dischargers

Land Use / Land Cover 2002 by Type
- AGRICULTURE
- BARREN LAND
- FOREST
- URBAN
- WATER
- WETLANDS

Streams by Trout Classification
- Freshwater - Non-Trout
- Freshwater - Trout Maintenance
- Freshwater - Trout Production

Figure 3

Raritan River Basin Nutrient TMDL Study Land Use / Land Cover & Stream Classifications

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There are three major water supply features that comprise the Raritan Basin Water Supply System, which is managed by the New Jersey Water Supply Authority (NJWSA): Spruce Run Reservoir, Round Valley Reservoir, and the Delaware and Raritan Canal. In addition, there is a major drinking water supply intake at the confluence of the Raritan and Millstone Rivers at Manville. Spruce Run Reservoir is the primary water supply storage for the system. It fills naturally from the Spruce Run and Mulhockaway Creek watersheds, and is released into the South Branch Raritan River to supply water at the Millstone/Raritan confluence intake, and to meet passing flow requirements at Stanton and Manville. Round Valley Reservoir receives very little natural inflow, since 90% of its watershed is the reservoir itself. As needed, water from the South Branch Raritan River is pumped to Round Valley Reservoir from the Hamden pump station. During low flow periods when additional water is needed to maintain passing flow at Manville, water is released from Round Valley Reservoir to the South Branch Rockaway Creek, where it flows through the Rockaway Creek, Lamington River, and North Branch Raritan River. Alternatively, water from Round Valley Reservoir is occasionally released into the South Branch Raritan River at Hamden to maintain passing flows at Stanton. The preceding overview is a gross simplification of the Raritan Basin Water Supply System; the Raritan River Basin comprises a substantial drinking water resource, and there are diversions and releases throughout the system that affect flow and water quality. The most important of these, from a flow and water quality perspective, are the releases from Spruce Run Reservoir and Round Valley Reservoir into the South Branch Raritan River and South Branch Rockaway River, respectively. These releases are typically used during low flow periods to maintain minimum passing flows and to augment the flow of water available at the intake at the confluence of the Millstone and Raritan Rivers.

There are also numerous municipal and industrial wastewater treatment plant discharges (i.e., point sources) permitted within the study areas, as shown in Figures 2 and 3. Table 1 lists the wastewater treatment plants (WWTPs) that lie within the various study areas.

Table 1: WWTP Discharges Permitted Within Raritan River Basin TMDL Study Area

NJPDES ID	Facility Name	Receiving Water	Permitted Flow (MGD)
South Branch Raritan River Watershed			
NJ0028304	Day's Inn - Roxbury – Ledgewood	Ledgewood Brook	0.04
NJ0021954	Mt Olive Twp - Clover Hill STP	Drakes Brook	0.5
NJ0023493	Washington Twp-Schooley's Mt	Raritan River S B	0.5
NJ0109061	Washington Twp-Long Valley	Raritan River SB	0.244
NJ0028487	NJDC Youth Correct-Mountainview	Beaver Brook	0.26
NJ0078018	Clinton West[1]	Beaver Brook	0.25
NJ0035084	Exxon Research & Eng Co	Beaver Brook	0.22
NJ0020389	Town of Clinton WTP	Raritan River SB	2.03
NJ0100528	Glen Meadows/Twin Oaks	Raritan River SB via unnamed trib	0.025
NJ0028436	Flemington Boro (wet weather only)	Bushkill Brook	3.85
NJ0022047	Raritan Twp MUA	Raritan River SB	3.8
North Branch Raritan River Watershed			
NJ0000876	Hercules Kenvil Works Facility	Lamington River via ditch	0.135
NJ0022675	Roxbury Twp-Ajax Terrace	Lamington River	2.0
NJ0026824	Chester Shopping Center	Tiger Bk (Lamington R) via ditch	0.011
NJ0022781	Valley Rd Sewer Co – Pottersville	Lamington River	0.048
NJ0021865	Fiddler's Elbow CC – Reynwood	Lamington River	0.03
NJ0102563	Route 78 Office Area – Tewksbury[1]	North Branch Rockaway Creek	0.09653
NJ0023175	Clinton Twp BOE - Round Valley	South Branch Rockaway Creek	0.009
NJ0098922	Readington-Lebanon SA	Rockaway Creek S B	1.45
NJ0021334	Mendham Boro	India Brook (Raritan River NB)	0.45
NJ0026387	Bernardsville	Mine Brook	0.8
NJ0033995	Environmental Disposal Corporation	Raritan River NB via unnamed trib	2.1
Upper Millstone River Watershed			
NJ0004243	Elementis	Millstone River	0.036
NJ0029475	Hightstown Boro Advanced WWTP	Rocky Brook	1
NJ0023787	East Windsor Twp MUA	Millstone River (Raritan R)	4.5
NJ0024104	Princeton Meadows STP	Cranbury Brook	1.64
NJ0023922	USDOE PPPL	Bee Brook to Millstone R.	0.637
NJ0000272	David Sarnoff Research	Millstone River (Raritan R)	0.096
NJ0031445	Firmenich Inc.	Millstone River (Raritan R)	0.036

Table 1: WWTP Discharges Permitted Within Raritan River Basin TMDL Study Area

NJPDES ID	Facility Name	Receiving Water	Permitted Flow (MGD)
Stony Brook Watershed			
NJ0000795	Bristol-Myers Squibb Co.	Stony Brook via unnamed trib	0.1724
NJ0035319	Stony Brook RSA – Pennington	Stony Brook	0.445[2]
NJ0000809	Hopewell Business Park[3]	Cleveland Brook	0.128
NJ0022110	Educational Testing Service	Stony Brook	0.08
Beden Brook Watershed			
NJ0035301	Stony Brook RSA – Hopewell	Beden Brook	0.3
NJ0069523	Montgomery Twp - Cherry Valley	Beden Brook	0.286
NJ0022390	Montgomery Twp - Skillman Village[4]	Rock Brook	0.5
NJ0023663	Carrier Foundation Rehab STP	Cruser Bk via unnamed trib	0.04
NJ0060038	Montgomery Twp - Pike Brook	Pike Run	0.67
NJ0026140	J & J Consumer Products	Back Brook via drainage ditch	0.0625
NJ0067733	Montgomery Twp – Oxbridge	Pike Run	0.088
Lower Millstone River Watershed			
NJ0031119	Stony Brook RSA-River Road	Millstone River (Raritan R)	13.06
NJ0026905	Montgomery Twp-Stage II	Millstone River (Raritan R)	0.48
NJ0050130	Montgomery Twp – Riverside	Millstone River (Raritan R)	0.145
NJ0023019	Industrial Tube Corp	Royce Brook via unnamed trib	0.012
NJ0020036	VA Supply Depot	Millstone River	0.08
Mainstem Raritan River Watershed			
NJ0024864	Somerset Raritan SA	Cuckels Bk (Raritan R)	24.3
NJ0026727	Colorado Café	Green Brook	0.0175

1 – permitted but not constructed
2 – pending formal approval of expansion from 0.3 MGD to 0.445 MGD.
3 – formerly Lucent Technologies, Inc
4 – formerly NPDC

C. TMDL Approach

A TMDL represents the assimilative or carrying capacity of a waterbody, taking into consideration point and nonpoint sources of pollutants of concern, natural background and surface water withdrawals. The amount of a pollutant a water body can assimilate without violating water quality standards is quantified, and that load capacity is allocated among known point sources in the form of wasteload allocations (WLAs), nonpoint sources in the form of load allocations (LAs), a margin of safety, as well as an optional reserve capacity to accommodate future loadings. A TMDL is developed as a mechanism for identifying all the contributors to surface water quality impacts and establishing load reductions as necessary to meet SWQS.

Watershed modeling tools were developed in order to relate nutrients and TSS sources to water quality targets, specifically phosphorus, DO, nitrate, and TSS concentrations. Phosphorus TMDLs were developed as necessary to address phosphorus, pH, and DO impairments. TSS TMDLs were developed as necessary to address TSS impairments.

II. WATER QUALITY ASSESSMENT

A. Pollutants of Concern

Pollutants of concern for this study include total phosphorus (TP), pH, dissolved oxygen (DO), nitrate, and total suspended solids (TSS). Each of these pollutants is the basis for use impairment designation at one or more locations throughout the Raritan River Basin. A complete list of watershed impairment designations is provided in Appendix A.

The mechanism by which phosphorus can cause use impairment is via excessive primary productivity. Phosphorus is an essential nutrient for plants and algae, but is considered a pollutant because it can stimulate excessive growth (primary production) leading to accelerated eutrophication. Symptoms of eutrophication (primary impacts) include oxygen supersaturation during the day and oxygen depletion during the night, both driven by excessive growth of algae and aquatic plants. Large diurnal variations of DO are often associated with large diurnal variations of pH, both of which can be induced by excessive primary productivity. As a result, phosphorus is related, through primary productivity, to both DO and pH.

pH is a measure of the concentration of hydrogen ions and therefore the acidity of water. High pH indicates a low concentration of hydrogen ions and therefore basic conditions. Low pH indicates a high concentration of hydrogen ions and therefore acidic conditions. A pH of 7 is exactly neutral, and each unit higher or lower represents a 10-fold decrease or increase in acidity. Aquatic life impairments can be caused by high or low pH conditions. Photosynthesis uses up dissolved carbon dioxide in water. Since carbon dioxide forms carbonic acid in water, the removal of carbon dioxide due to photosynthesis reduces the acidity of the water and therefore increases pH. Respiration and decomposition, which produce carbon dioxide, increase acidity and therefore decrease pH. Because photosynthesis occurs only during the day, photosynthesis and respiration can induce large diurnal pH swings. Occasionally, these daytime pH peaks can exceed levels that are associated with aquatic life impairment.

Dissolved oxygen was identified as a critical parameter of concern because it is a direct cause of aquatic life use impairment. The SWQS define dissolved oxygen criteria in terms of minimum thresholds that vary according to stream classification. Generally, one or both of the following factors can cause low dissolved oxygen conditions:

- excessive oxygen-demanding substances exposed to the water column, usually expressed as carbonaceous oxygen demand, nitrogenous oxygen demand, and/or sediment oxygen demand (SOD); and/or
- excessive plant and algal growth, leading to oxygen deficits in the pre-dawn hours when respiration and decomposition are not overshadowed by photosynthesis.

Secondary treatment of municipal wastewater has greatly reduced the occurrence of oxygen depletion caused by excessive oxygen-demanding substances in the water column. Understanding the impacts of excessive plant and algal growth as well as oxygen demands such as ammonia nitrification and SOD on dissolved oxygen was among the primary goals of this research, and drove the development of TMDLs.

The 10 mg/l criterion for nitrate-nitrogen is based on its toxicity in drinking water, not its potential to contribute to eutrophication. Generally, nitrate concentrations throughout the study areas in the Raritan River Basin are well below any level of concern for drinking water toxicity. However, nitrate is also important as one of the nutrients that helps stimulate plant and algal growth.

Total Suspended Solids (TSS) was identified as a pollutant of concern because several streams were designated by NJDEP as impaired by TSS (NJDEP, 2006; and NJDEP, 2009). The Phase I Raritan TMDL Study (TRC Omni, December 19, 2005) also noted high TSS concentrations during high flow conditions and during storm events. As described in the Phase I report (TRC Omni, December 19, 2005), concentrations of TSS during high flow events were observed to increase at more downstream locations. TSS is important because high concentrations can impair aquatic life, especially fish.

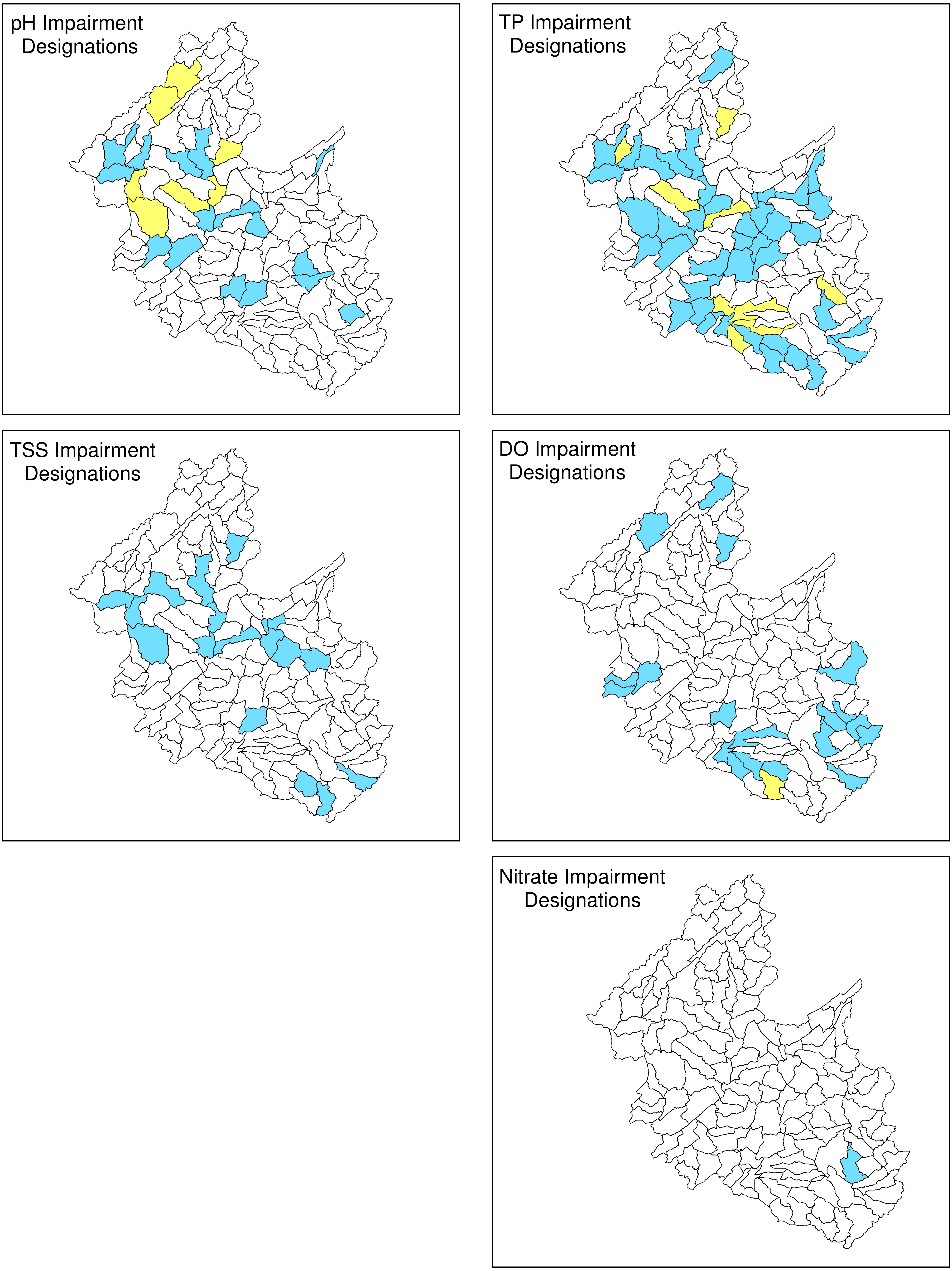
B. Impairment Designations

Section 305(b) of the Federal Clean Water Act (CWA) requires the State of New Jersey to prepare and submit to the United States Environmental Protection Agency (USEPA) a Water Quality Inventory Report that summarizes the overall water quality of the State's waters. The State is also required under Section 303(d) of the CWA to prepare and submit to USEPA a List of Impaired Waterbodies that identifies waters that do not meet or are not expected to meet Surface Water Quality Standards (SWQS) after implementation of technology-based effluent limitations or other required controls. The waterbodies designated as impaired require TMDL evaluations.

In 2002, NJDEP began integrating the Water Quality Inventory Report (305(b) Report) and the List of Impaired Waterbodies (303(d) List) into one report entitled the Integrated Water Quality Monitoring and Assessment Report, commonly called the Integrated List of Waterbodies. This integrated report assigns waterbodies to one of five Sublists according to the degree of designated use impairments. Sublist 5 constitutes the traditional List of Impaired Waterbodies for which one or more TMDL evaluations are needed.

NJDEP's 2010 List of Impaired Waterbodies (NJDEP, 2010) was utilized in order to generate a list of subwatersheds (HUC-14) that require a TMDL evaluation and response for the pollutants of concern (phosphorus, TSS, pH, DO, and nitrate). In addition, NJDEP performed a supplemental data review based on data obtained during Phase 1 of the Raritan TMDL Study (TRC Omni, December 19, 2005), in order to augment the impairment designations. Responses to impairment designations include: establish TMDL to address impairment, delist waterbody based on the TMDL evaluation, or recommend a specific management action that will address the impairment. The purpose of generating a list of impairment designations was to identify all locations where a response to impairment is needed. Figure 4 shows the watershed impairment designations in the Raritan River Basin for each pollutant of concern, and the watersheds are listed individually, along with the basis for each impairment designation, in Appendix A. The TMDL outcomes[3] for each impairment designation are provided in Appendix Q.

[3] The study does not formally address all impairments in all subwatersheds. The reason is that the spatial extent and technical approach were developed based on previous iterations of the Department's water quality assessment that were available at that time. The study addresses as many of the newly designated impairments as possible given the constraints of the spatial extent and technical approach that were based on previous impairment assessments.



Basis for Impairment Designation

- 2010 303(d)
- Supplemental Data Review by NJDEP

Sources:
NJDEP, NJGS, 2006. DEPHUC14
NJDEP, OIRM, BGIS, 2008. Streams Update for New Jersey

Figure 4

Raritan River Basin Nutrient TMDL Study Impaired Watershed Designations

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C. Water Quality Targets

In order to prevent excessive primary productivity and consequent impairment of recreational, water supply and aquatic life designated uses, the New Jersey Surface Water Quality Standards[4] [N.J.A.C. 7:9B-1.14(d)4] state:

i. Except as due to natural conditions, nutrients shall not be allowed in concentrations that render the waters unsuitable for the existing or designated uses due to objectionable algal densities, nuisance aquatic vegetation, diurnal fluctuations in dissolved oxygen or pH indicative of excessive photosynthetic activity, detrimental changes to the composition of aquatic ecosystems, or other indicators of use impairment caused by nutrients.

ii. Phosphorus (mg/L)

(1) Non Tidal Streams: Concentrations of total P shall not exceed 0.1 in any stream, unless watershed-specific translators are established pursuant to N.J.A.C. 7:9B-1.5(g)2 or if the Department determines that concentrations do not render the waters unsuitable in accordance with (d)4i. above.

(2) Lakes: Concentrations of total P shall not exceed 0.05 in any lake, pond or reservoir, or in a tributary at the point where it enters such bodies of water, unless watershed-specific translators are developed pursuant to N.J.A.C. 7:9B-1.5(g)2 or if the Department determines that concentrations do not render the waters unsuitable in accordance with (d)4i. above.

Paragraph i above describes the narrative nutrient criteria, whereas paragraph ii lists the numeric criteria for phosphorus. Except as noted in Section II.D, the 0.1 mg/l instream phosphorus criterion was applied as a water quality target to streams throughout the study areas. Watershed-specific translators were not utilized for this TMDL study, although compliance with the maximum pH criterion was utilized as an additional target as described below.

[4] Re-adopted November 16, 2009; Last Amended April 4, 2011 (43 N.J.R. 833(a))

The Raritan River TMDL Study explicitly considered the following lakes: Solitude Lake, Ravine Lake, Cushetunk Lake, Peddie Lake, Plainsboro Pond, Grovers Mill Pond, Gordon Pond, and Carnegie Lake. The 0.05 mg/l phosphorus criterion was applied as the phosphorus water quality target for Solitude Lake, Ravine Lake, and Cushetunk Lake.

The natural condition of lakes in the upper Millstone River watershed (Peddie Lake, Plainsboro Pond, Grovers Mill Pond, Gordon Pond, and Carnegie Lake) was determined to exceed the 0.05 mg/l criterion (see Section IV.C.5 for description of natural condition simulation). In accordance with N.J.A.C. 7:9B-1.5(c)1, the phosphorus criterion associated with the natural condition for each of these lakes was applied as the water quality target for phosphorus.

The SWQS minimum DO criteria were applied as water quality targets for DO. Specifically, minimum DO criteria of 4.0 mg/l, 5.0 mg/l, and 7.0 mg/l were applied to waters classified as freshwater non-trout (FW2-NT), freshwater trout maintenance (FW2-TM), and freshwater trout production (FW2-TP), respectively. Similarly, the SWQS maximum TSS criteria were applied as water quality targets for TSS. The maximum TSS criteria of 40 mg/l and 25 mg/l were applied to nontrout waters (FW2-NT) and trout waters (FW2-TM and FW2-TP), respectively.

The SWQS specify an acceptable pH range of 6.5 to 8.5 s.u. for all freshwater surface waters. The maximum pH of 8.5 s.u. was applied as a water quality target, since diurnal productivity-induced swings during summer low-flow conditions cause pH to exceed 8.5 s.u. at many locations in the Raritan River Basin. However, the water quality model used (Section III.C) simulates DO, but not pH. In fact, while there are geochemical-based models that simulate average pH, the state-of-the-art for water quality modeling at the time this research was performed did not simulate diurnal variation of pH. As described previously in Section II.B, photosynthesis pumps DO into the water column and utilizes carbon dioxide, which increases pH during the day. High productivity results in diurnal swings of DO and pH. In fact, DO and pH diurnal swings are well correlated, both being caused directly by the diurnal photosynthesis and respiration cycles.

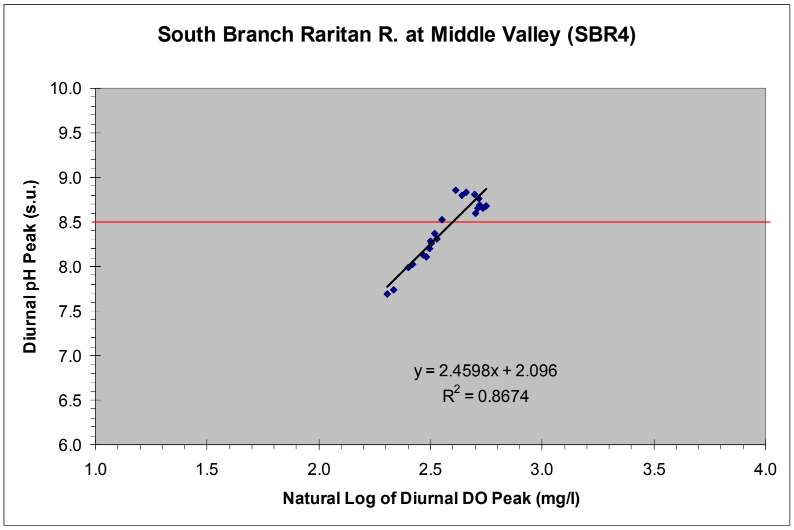
In order to relate model predictions of diurnal DO to the maximum pH target of 8.5 s.u., site-specific correlations between diurnal pH peaks and diurnal DO peaks were developed based on data from diurnal monitoring performed during late summer low-flow periods (after July 15). This period was the most data-rich in terms of diurnal data, and data were insufficient to develop correlations for other time periods. All available diurnal data collected between July 15 and September 30, and which displayed discernible DO peaks, were utilized. Correlations between diurnal pH peaks and diurnal DO peaks (expressed as natural logs) were used to develop site-specific maximum DO targets at three key locations in the North and South Branch Raritan River watersheds that were designated as impaired due to high pH peaks. These locations were selected due to the strength of the correlations, the degree of impairment, and the fact that these three locations serve as control points to restrain productivity throughout the North and South Branch Raritan River basin. The maximum DO targets specify the summer DO above which the pH would be expected to exceed the 8.5 s.u. maximum criterion. Since DO is also influenced by many factors including temperature, these maximum DO targets are valid only during low-flow periods from mid-July through September. This temporal window is being used as a control point to restrain productivity during other seasons, which is generally less critical. Future simulations (Section V) demonstrate that the use of a temporal control point (mid-July through September) will also dramatically restrain diurnal swings during other time periods. It is important to understand that the maximum DO targets are intended to address situations in which excessive productivity is driving pH peaks. They are not suitable to address high pH that is driven by factors other than summer photosynthesis-induced diurnal variations. The site-specific maximum DO targets used to relate summer DO simulations to the maximum pH water quality target of 8.5 s.u. are provided in Table 2, and the correlations are shown in Figure 5. All data, including data excluded due to being outside the temporal range or lacking a discernible peak, are provided electronically in Appendix T.

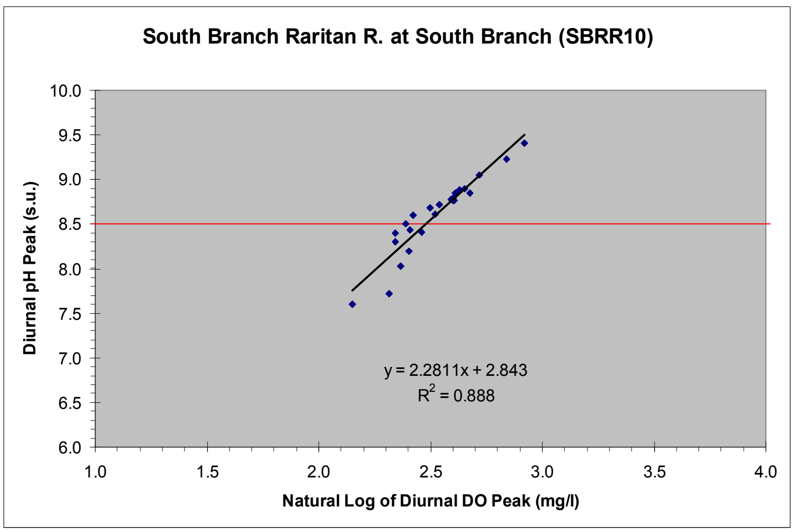
Table 2: Maximum Late Summer DO Targets to Meet Maximum pH Criterion

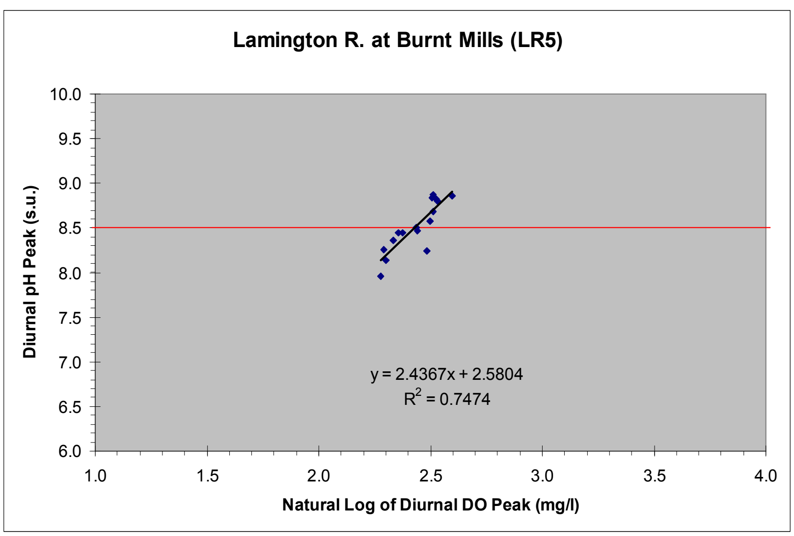
Location	R-Squared (RSQ*)	DO Target (pH Threshold)
South Branch Raritan R. at Middle Valley (SBR4)	0.87	13.5
South Branch Raritan R. at South Branch (SBRR10)	0.89	11.9
Lamington R. at Burnt Mills (LR5)	0.75	11.4

* 1.0 represents perfect correlation between peak pH and natural log of peak DO.

Figure 5: Correlations Between Diurnal pH and DO Peaks







D. Evaluation of Narrative Nutrient Criteria

It is important to evaluate whether phosphorus concentrations "render the waters unsuitable" [N.J.A.C. 7:9B-1.14(d)4i] and therefore whether the numeric criterion properly applies as a water quality target to any particular segment. This evaluation is important because the numeric criteria [N.J.A.C. 7:9B-1.14(d)4ii] are dependent on the narrative criteria; if a positive demonstration is made that the narrative criteria are met, then there is no need to rely on the numeric criteria. Accordingly, the 0.1 mg/l instream TP criterion was generally applied as a water quality target for all streams, unless a demonstration was made that nutrient concentrations are not rendering the waters unsuitable for existing or designated uses in a particular watershed, or where existing information is inconclusive and additional studies are underway.

Two references are most relevant to making a determination as to whether phosphorus is "rendering the waters unsuitable" and therefore whether the narrative nutrient criteria are satisfied for a particular waterbody. The Technical Manual for Phosphorus Evaluations (NJDEP, August 2008) was developed by NJDEP as a tool for NJPDES permittees to evaluate whether the instream numeric phosphorus criterion should be applied to the receiving water for their discharge. More recently, NJDEP published its 2010 Methods Document (NJDEP, September 2010), which describes the methodology used by the Department to assess whether nutrient concentrations are "rendering the waters unsuitable" and therefore whether the narrative nutrient criteria are satisfied. The two methodologies are similar, although the 2010 Methods Document reflects that Department's most current methodology and is most relevant for deciding where to apply the instream phosphorus criterion as a water quality target. Specifically, Table 4.4 on page 16 of the 2010 Methods Document provides the most succinct and relevant methodology. If the DO swing during summer diurnal surveys is not greater than 3 mg/l/d, then phosphorus is not considered to be a cause of any aquatic life use impairment that may exist. If the DO swing exceeds 3 mg/l/d, but dissolved oxygen criteria are satisfied, then periphyton density is used to determine whether phosphorus is causing aquatic life use impairment. Specifically, if the average periphyton density from a minimum of three sampling events is 150 mg/m² chlorophyll-a or less, then phosphorus is not considered to be a cause of any aquatic life use impairment that may exist. If, using the NJDEP methodology, phosphorus is determined not to be causing impairment of aquatic life uses, then the instream phosphorus criterion of

0.1 mg/l was not applied as a water quality target. While not specifically included in the Department's current Methods Document, excursions of the maximum pH criterion, when associated with diurnal DO swings in excess of 3 mg/l/d, were used as an additional indicator of nutrient impacts. Results and assessment basis in terms of the application of the 0.1 mg/l TP criterion as a water quality target are described below for each of the study areas.

1. Raritan River watersheds upstream of the Millstone River confluence

As described in the Phase 1 Data Summary and Analysis Report (TRC Omni, December 19, 2005) the North and South Branches of the Raritan River include many locations that exhibit extremely large diurnal DO swings driven primarily by submerged aquatic vegetation. For instance, the South Branch Raritan River (SBRR10) was observed to exhibit diurnal DO swings of 11 mg/l/d, coincident with diurnal pH swings with peaks well above the maximum pH criterion of 8.5 s.u. In addition, a phosphorus evaluation study performed for the upper South Branch Raritan River (TRC Omni, March 8, 2005) concluded that phosphorus concentrations were rendering the water unsuitable, and identified SBR4 as a critical location. There is no basis to demonstrate that high phosphorus concentrations do not render the waters unsuitable; therefore, NJDEP applied the 0.1 mg/l TP criterion as a water quality target throughout the Raritan River watersheds upstream of its confluence with the Millstone River.

2. Upper Millstone River watershed

The upper Millstone River shares some of the same soil formations that are found in the Manalapan and Matchaponix Brook watersheds, and therefore some of the same phosphorus chemistry characteristics that were observed in the Matchaponix Brook (TRC Omni, April 11, 2005). Specifically, total phosphorus concentrations, even in relatively pristine areas, are higher than in other regions of the Raritan River Basin; available orthophosphorus concentrations, on the other hand, are generally very low. Like the Matchaponix Brook, the upper Millstone River exhibits high iron concentrations, which binds phosphorus in particulate form and renders it unavailable to plants and algae.

No phosphorus evaluation studies were performed within the upper Millstone River watershed. However, stream data collected during Phase I of the Raritan TMDL Study (TRC Omni, December 19, 2005) revealed moderate diurnal DO swings, low pH with very minor diurnal pH swings, and low algal indicators. While DO swings occasionally exceeded 3 mg/l (slightly) in the upper Millstone River (UMR2 and UMR3), none of the sampling locations in the upper Millstone River watershed exhibited periphyton densities in excess of 150 mg/m² chl-a. As noted in the Phase I report (TRC Omni, December 19, 2005), the upper Millstone River exhibits significant amounts of macrophyte growth; however, lacking a translation of the narrative nutrient criteria with respect to nuisance aquatic vegetation, it is uncertain whether the plant growth represents a violation of the narrative nutrient criteria. As explained in more detail in Section V.C.2.a, simulation results demonstrate that:

- the low DO observed at station UMR3 is caused by ammonia and would not be improved by phosphorus reductions; and
- natural levels of phosphorus in the upper Millstone River watershed are sufficient to drive the level of productivity observed in the streams.

For the reasons described above, the 0.1 mg/l criterion was not applied as a water quality target to streams in the upper Millstone River watershed. Instead, the TMDL for the upper Millstone River watershed was driven by impacts to lakes within the watershed and Carnegie Lake, into which the upper Millstone River drains. However, the TP reductions required to meet the SWQS in Carnegie Lake will result in phosphorus concentrations that are well below 0.1 mg/L throughout the upper Millstone River watershed. Streams within this watershed will continue to be monitored with respect to attainment of the narrative nutrient criteria.

3. Stony Brook and Beden Brook watersheds

Data were collected in both the Stony Brook and Beden Brook watersheds in 2003 as part of the <u>Lower Millstone / Raritan River Watershed Phosphorus Evaluation Study</u> (TRC Omni, May 6, 2004). The phosphorus evaluation was performed using the Technical Manual in use at the time the study was performed (NJDEP, March 2003). Stream locations in both Stony Brook and Beden Brook exhibited diurnal DO swings of 9 mg/l/d and 10 mg/l/d (SB3 and BB1, respectively), coincident with diurnal pH peaks over 9 s.u. There is no basis to demonstrate that high phosphorus concentrations do not render the waters unsuitable; therefore, NJDEP applied the 0.1 mg/l TP criterion as a water quality target throughout the Stony Brook and Beden Brook watersheds. Note that the TMDL for the Stony Brook watershed was also driven by the load delivered to Carnegie Lake from the Stony Brook watershed.

4. Lower Millstone River

The lower Millstone River extends from Carnegie Lake to the Raritan River. The Lower Millstone / Raritan River Watershed Phosphorus Evaluation Study (TRC Omni, May 6, 2004) was performed using the Technical Manual in use at the time the study was performed (NJDEP, March 2003). None of the productivity indicators (low DO induced by diurnal DO swing, high phytoplankton, and high periphyton) collected during the study suggest that phosphorus is rendering the waters unsuitable. The lower Millstone River exhibits very little diurnal DO variation even during summer low-flow conditions. Diurnal pH variation in the lower Millstone River is barely discernible, and pH is close to neutral.

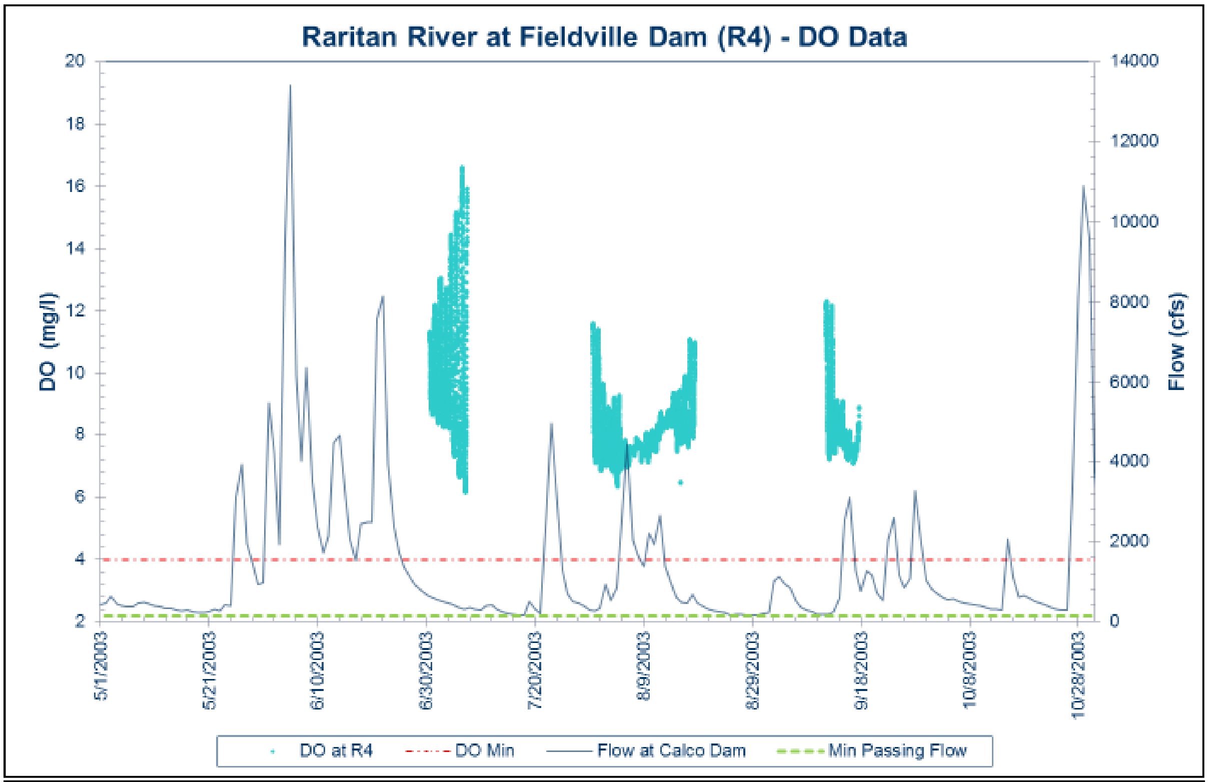
Diurnal monitoring was performed as three locations in the lower Millstone River (M2, M4, and M7) during three diurnal events in 2003. Diurnal DO patterns were barely perceptible, and the swing did not exceed 3 mg/l/d during any event at any location. These data are reproduced from the phosphorus evaluation study (TRC Omni, May 6, 2004) and provided in Appendix B. In accordance with the 2010 Methods Document, since the DO swing during summer diurnal surveys is not greater than 3 mg/l/d, phosphorus is not considered to be a cause of any aquatic life use impairment that may exist. As a result, the narrative nutrient criteria are satisfied, and the instream phosphorus criterion of 0.1 mg/l was therefore not applied as a water quality target. It is important to note that the lower Millstone River drains to the mainstem Raritan River. As described below, the mainstem Raritan River downstream of the Millstone River confluence is the subject of further investigations to evaluate nutrient impacts. Should subsequent investigations determine that nutrient reductions are required to address nutrient impacts in the mainstem Raritan River downstream of the Millstone River confluence, it is very likely that nutrient sources in the lower Millstone River would be impacted. In other words, although the narrative nutrient criteria are satisfied within the lower Millstone River, it is possible that a future TMDL to address nutrient impacts in the mainstem Raritan River would result in nutrient source reductions in the lower Millstone River as well.

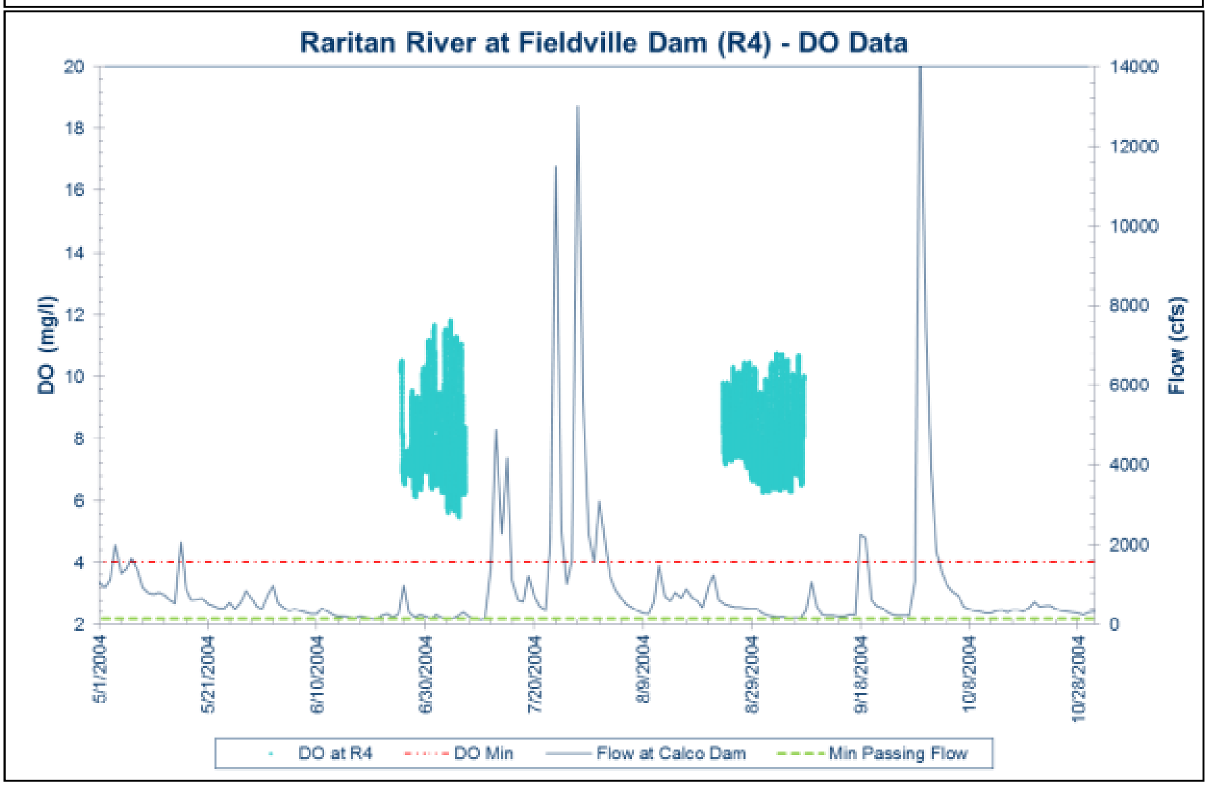
5. Mainstem Raritan River downstream of Millstone River confluence

The Lower Millstone / Raritan River Watershed Phosphorus Evaluation Study (TRC Omni, May 6, 2004) and Supplemental Report (TRC Omni, December 8, 2004) evaluated streams in the Lower Millstone / Raritan River watershed using the Technical Manual in use at the time the study was performed (NJDEP, March 2003). The mainstem Raritan River downstream of the Millstone River exhibits higher oxygen levels and much more diurnal DO and pH variation during summer low-flow conditions than the lower Millstone River. Extensive monitoring performed (TRC Omni, December 8, 2004) at the most critical location, the Raritan River at Fieldville Dam, confirm that DO remains above the minimum DO criteria and algal indicators remain below levels associated with impairment. However, during one monitoring event in early July of 2003, diurnal pH peaks exceeded 8.5 s.u., the maximum pH criterion for surface waters in the SWQS.

For this reason, the Raritan River at Fieldville Dam was designated as a critical location, and extensive diurnal monitoring was performed during the summers of 2003, 2004, and 2005 in order to provide the most rigorous system understanding and model calibration. However, these data provided inconclusive results that could not be explained from a water quality perspective. Specifically, it is not possible at this time to reconcile the large diurnal swings observed in early July 2003 with the comparatively modest diurnal swings observed at the same time in 2004 under much more critical conditions (lower flow, longer period since last storm), as shown in Figure 6. The elevated pH values and large diurnal DO swings observed in early July 2003 remain unexplained, and were therefore not successfully simulated. Data analysis and modeling in this area could not explain the pattern of responses observed, suggesting the influence of an unknown factor variable that is not understood at this time. As a result, NJDEP has determined to defer the TMDL for this part of the watershed until additional information can be developed and analyzed.

Figure 6: Diurnal DO in Mainstem Raritan River

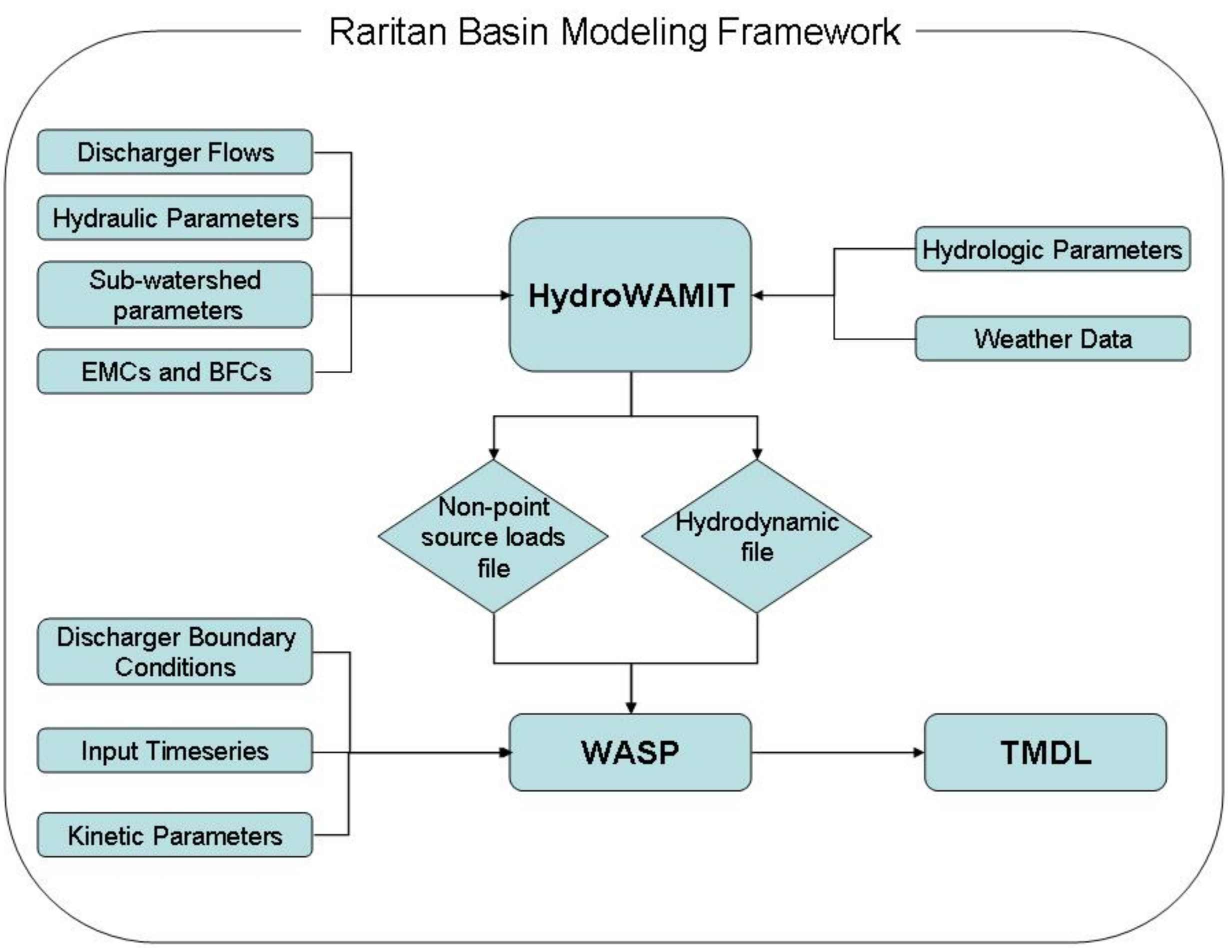




III. WATERSHED MODEL DEVELOPMENT

To simulate the dynamics of nutrient cycling and its effects on water quality variables in the Raritan River Basin, a modeling framework using HydroWAMIT (Cerucci and Jaligama, 2008) and the Water Quality Analysis Simulation Program 7.1 (WASP7.1) (Di Toro et al., 1983, Ambrose, R.B. et al., 1993, Wool et al., 2003) was adopted. HydroWAMIT, a hydrologic model developed by Kleinfelder/Omni, provides hydrodynamic and nonpoint[5] source inputs to WASP7.1, developed by EPA. WASP7.1 includes routines for simulating the fate and transport of conventional water quality constituents required for the TMDL analyses. The main components of the Raritan River Basin Model framework and their relationships are shown in Figure 7.

Figure 7: Raritan River Basin Model Framework



[5] In the context of model development, "nonpoint" refers to stormwater (point and nonpoint) sources and baseflow sources.

HydroWAMIT uses a series of inputs to provide hydrodynamic and nonpoint source loads for the water quality model. Basic inputs to HydroWAMIT are point source flows, cross section geometry of streams, land use distribution within contributing subwatersheds, weather data, hydrologic parameters and the concentration of pollutants associated with surface runoff and baseflow. HydroWAMIT simulates stream flows, surface runoff and baseflow based on local weather inputs and hydrologic input parameters.

Files with hydrodynamic simulations in the stream network and nonpoint source loads from contributing source areas are the main outputs provided by HydroWAMIT. WASP7.1 uses the hydrodynamic and nonpoint source files as inputs for the water quality simulations. WASP7.1 also requires boundary concentrations for water quality constituents from point source dischargers, time series of stream temperature, solar radiation, and kinetic parameters.

WASP7.1 is a complex dynamic water quality model that provides continuous concentrations of water quality constituents for the segments defined in a stream network. The setup of WASP7.1 involves a number of tasks. These tasks include setting up a stream network, defining model time step, performing stability tests, gathering important discharger input data, compiling the relevant data, developing continuous time series of input data based on discrete datasets, and generalizing local data to multiple elements of the stream network.

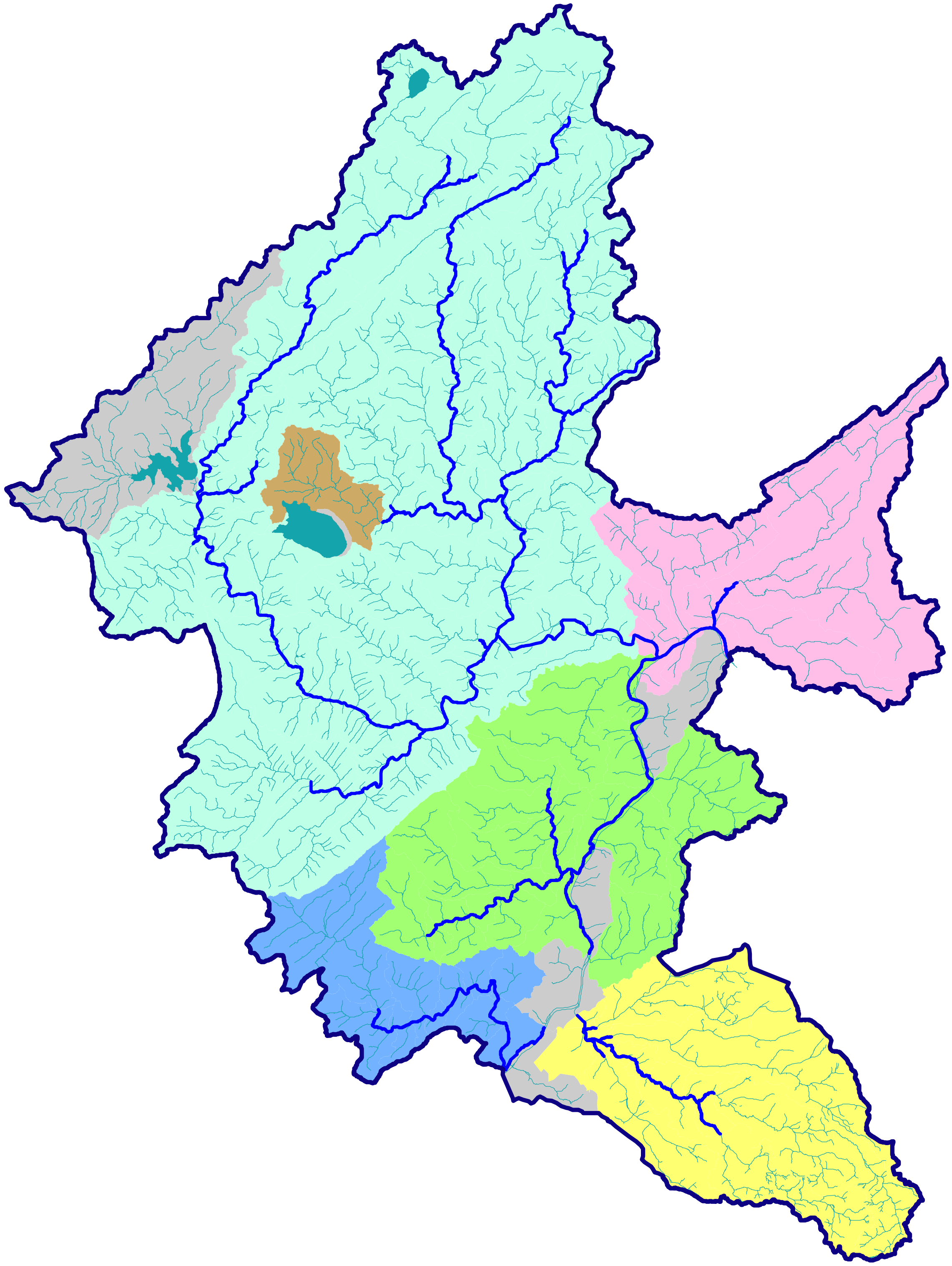
The model setup is followed by the model calibration and validation. Model calibration consists of adjusting the relevant kinetic parameters in order to optimize the simulation performance of the water quality constituents. This process is performed by comparing the simulation outputs and available observed data. Model validation follows model calibration. It consists of comparing an independent dataset of observed data with the simulation outputs from the already calibrated model. The model calibration and validation tasks require enormous effort. The simulated and observed data are compared using statistics and graphs for each calibration and validation station. A total of 75 water quality stations were used for calibrating the Raritan River Basin Model.

Water quality data in the streams and rivers of the Raritan River Basin used for calibration and validation are available at a number of stations from different sources and from different timeframes. In order to compile all this information it was necessary to develop a digital database. This database is linked to the Geographical Information System (GIS), and provides effective means to query the observed data. In addition, algorithms were developed for querying the model output data and the respective observed data from spreadsheets in order to display plots of the observed and simulated data together, and to derive statistics for all the calibration and validation stations. The calibration / validation database is provided electronically in Appendix T.

Reliable simulations of HydroWAMIT and WASP7.1 obtained by this modeling framework were used as a basis for the Raritan TMDL Study. Multiple simulations that use different assumptions regarding point and non-point source inputs were performed to determine the carrying capacity of the streams. The methods used to obtain and to process the relevant input data, discussion of the model testing, calibration and validation, and the final model results are presented and discussed in this section.

A. Spatial Extent of the Model

The non-tidal portion of the Raritan River basin covers a total area of approximately 865 square miles. It was subdivided for hydrologic simulation modeling purposes into five watershed area models: North and South Branch Raritan River (NSBranch), Upper Millstone River (UpperMills), Stony Brook (Stony), Beden Brook/Lower Millstone River (BBLowerMills), and Mainstem Raritan (Mainstem). Figure 8 shows the five major watershed areas defined for the Raritan River Basin Model. This subdivision was necessary due to the large size of the Raritan River Basin. The separation into five watershed area models provides a flexible structure and allows the kinetic coefficients for the water quality parameters to be better represented during the water quality simulations.



Sources:
NJDEP, NJGS, 2006. DEPHUC14
NJDEP, OIRM, BGIS, 2008. Streams Update for New Jersey

Model Segment
Model Subbasin
Beden Brook/Lower Millstone
Upper Millstone River
North & South Branch Raritan
Main Stem Raritan
Stony Brook
Cushetunk Lake Sub-Model
Not Modeled

Figure 8
Raritan River Basin Nutrient TMDL Study Watershed Area Model Extents

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The simulated streams and rivers are represented by branches in the model. The simulated branches and their spatial extents are a function of the features that need to be represented in the model. These features include discharges, diversions, reservoir releases, and water quality sampling stations. The branches are subdivided into segments and nodes. A segment is defined as the stretch of the stream between nodes and the nodes are the input/output boundaries to the model. A node also defines the location of boundary flow inputs. Each branch contains a variable number of nodes. Boundary flows include discharger flows, diversions, reservoir releases and incremental watershed flows. Also shown as "Future Loads" in the maps in the ensuing sections are the small WWTP dischargers that were included in the future simulations of the model to establish the TMDL (see Section IV.D.1 and Table 31). While not significant for calibration purposes due to extremely small actual flows, the load from these "minor"[6] dischargers becomes more important under future reduced phosphorus simulations and assumed permitted flow conditions. The following sections provide a detailed description of the major watershed areas and the spatial extent of all the branches and watersheds.

1. North and South Branch Raritan River Watershed Area Model

The North/South Branch watershed area model consists of a 488 square mile drainage area upstream of the USGS gage 01400500 – Raritan River at Manville. This area was subdivided into 60 subwatersheds of variable sizes in order to capture the spatial variability of watershed parameters and incremental watershed flows. From the 60 subwatersheds delineated in the North/South Branch watershed area model, flows are not simulated for two subwatersheds as they represent the drainage areas of two gaged headwaters: Spruce Run and South Branch Rockaway Creek (Cushetunk Lake watershed). The Cushetunk Lake watershed was the subject of a separate modeling effort that resulted in a modified TMDL boundary condition (see Section V.C.1.c). The yields from these headwaters are used as boundary conditions to the model. Twenty three branches are simulated in the North/South Branch watershed area model. The outlet of the North/South Branch watershed area model is USGS gage 01400500 at Manville. Figure 9 shows the modeled branches, the subwatersheds and point source inputs to the North/South Branch watershed area model.

[6] "Minor" in this context is not the same as the Major/Minor discharger type in NPDES nomenclature. Here "Minor" means the discharge was not included in the flow and water quality model calibration, but was added to future simulations as a load only.

2. Upper Millstone River Watershed Area Model

The Upper Millstone watershed area model is defined by the 98 square mile drainage area of the Millstone River upstream of Carnegie Lake (watershed outlet at upper Millstone River US-1 Bridge). This area is subdivided into 13 subwatersheds and nine branches. Figure 10 shows the modeled branches, the subwatersheds and point sources simulated in the Upper Millstone watershed area model.

3. Stony Brook Watershed Area Model

The Stony Brook watershed area model is the smallest among the watershed area models with an area of 47 square miles. It includes 10 subwatersheds and only one branch representing the Stony Brook. The branch starts approximately 0.2 mile upstream of the Baldwin's Creek and ends 15 miles downstream, near the inlet to Carnegie Lake. Figure 11 shows the modeled branches, the subwatersheds and point source inputs to the Stony Brook watershed area model.

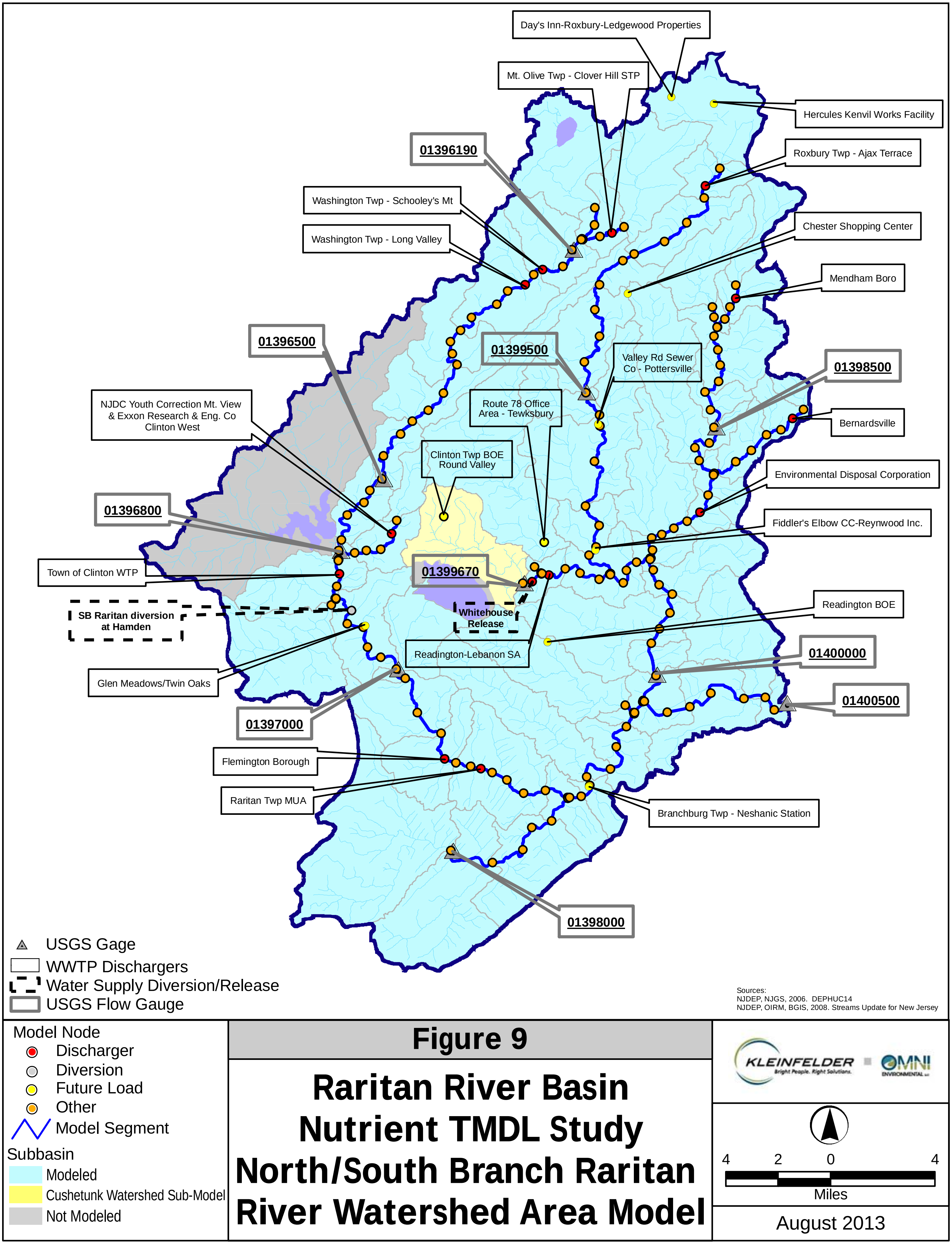

Figure 9

Raritan River Basin Nutrient TMDL Study North/South Branch Raritan River Watershed Area Model

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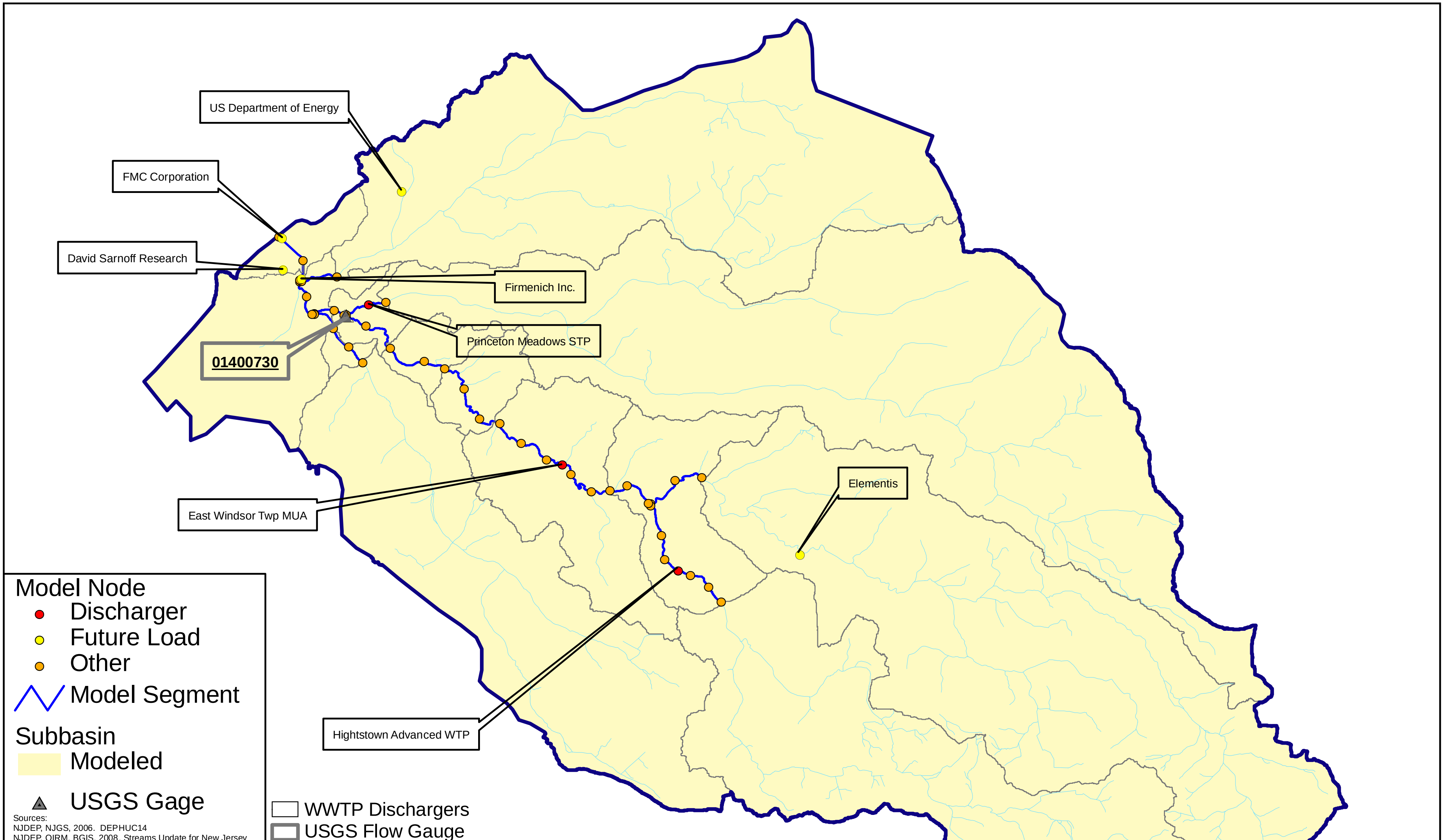

Sources:
NJDEP, NJGS, 2006. DEPHUC14
NJDEP, OIRM, BGIS, 2008. Streams Update for New Jersey

Figure 10

Raritan River Basin Nutrient TMDL Study Upper Millstone River Watershed Area Model

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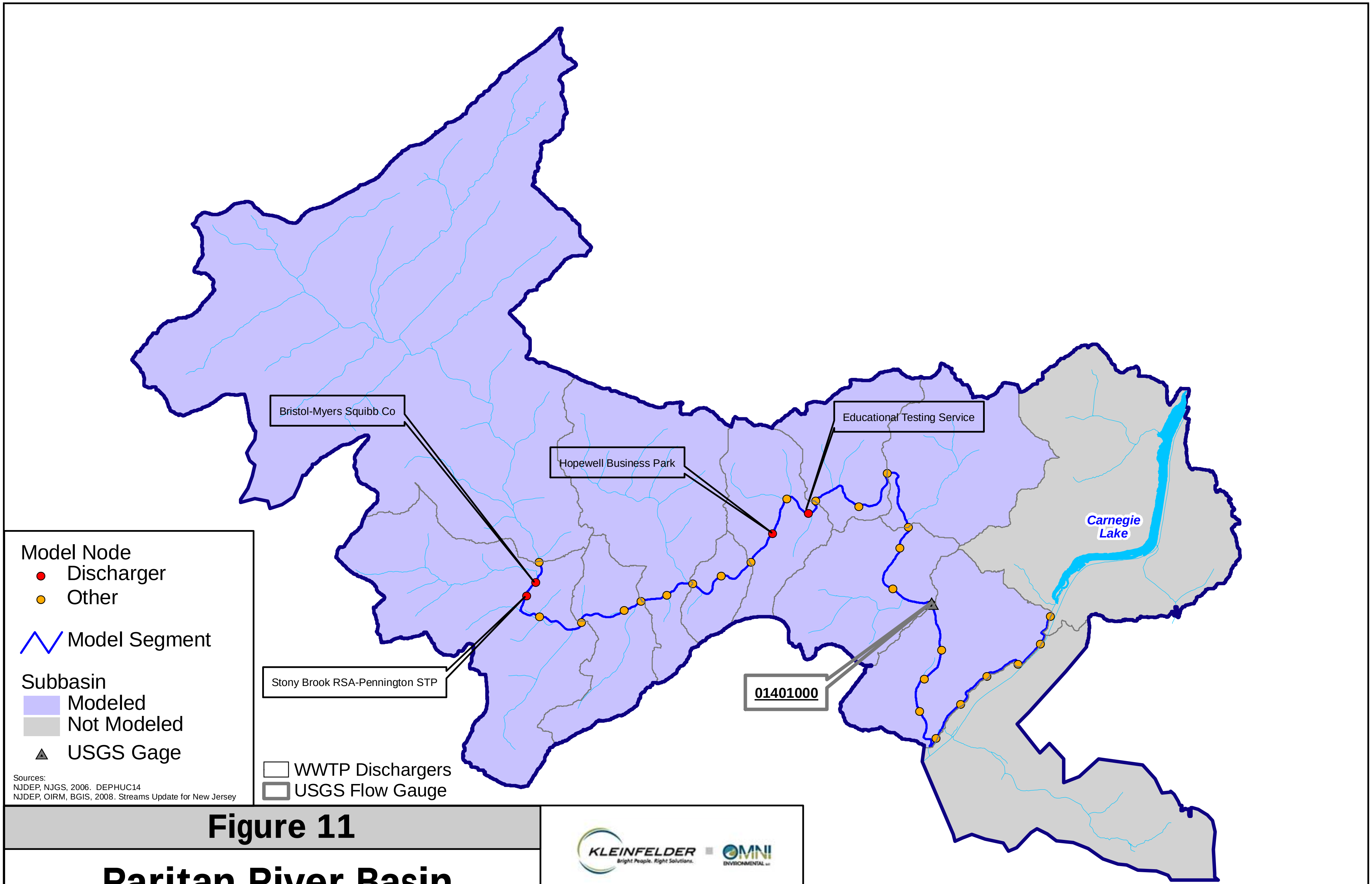

Figure 11

Raritan River Basin Nutrient TMDL Study Stony Brook Watershed Area Model

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4. Beden Brook / Lower Millstone River Watershed Area Model

The Beden Brook and the lower Millstone River watersheds are modeled together as a single watershed area model (BBLowerMills), which consists of a 115 square mile area. Seventeen subwatersheds are defined for the Beden Brook/Lower Millstone watershed area model. The lower Millstone River begins downstream of Carnegie Lake and ends at the confluence with the Raritan River. Beden Brook is a tributary of the lower Millstone River. The Delaware and Raritan Canal runs parallel to the lower Millstone River. The drainage areas of the Canal, which cover approximately 18 square miles, were excluded from the analysis. No wastewater point sources discharge to the canal drainage area, nor was the canal or its tributaries listed an impaired for any of the pollutants of concern. Note that discharge from the canal to the lower Millstone River at Ten Mile Lock was included as a point source. A total of 5 branches are defined for this area. Figure 12 shows the modeled branches, the subwatersheds, and point source inputs to the Beden Brook/Lower Millstone watershed area model.

5. Lower Mainstem Raritan River Watershed Area Model

The last watershed area model (Mainstem) simulates the lower mainstem Raritan River watershed downstream of its confluence with the Millstone River, with a drainage area of 90 square miles. The Mainstem watershed area model extent begins downstream of the USGS gage 01400500 (Raritan River at Manville) and ends at the Raritan River at Fieldville Dam (Kleinfelder/Omni sampling station R4), which is downstream of the confluence with Green Brook. Fieldville Dam was selected as the downstream model boundary because it is the last accessible location that is completely non-tidal. The actual head of tide is about 2.5 miles downstream near Landing Lane Bridge. Seven subwatersheds and five branches were defined for this area. Figure 13 shows the modeled branches, the subwatersheds and point source inputs to the Mainstem watershed area model.

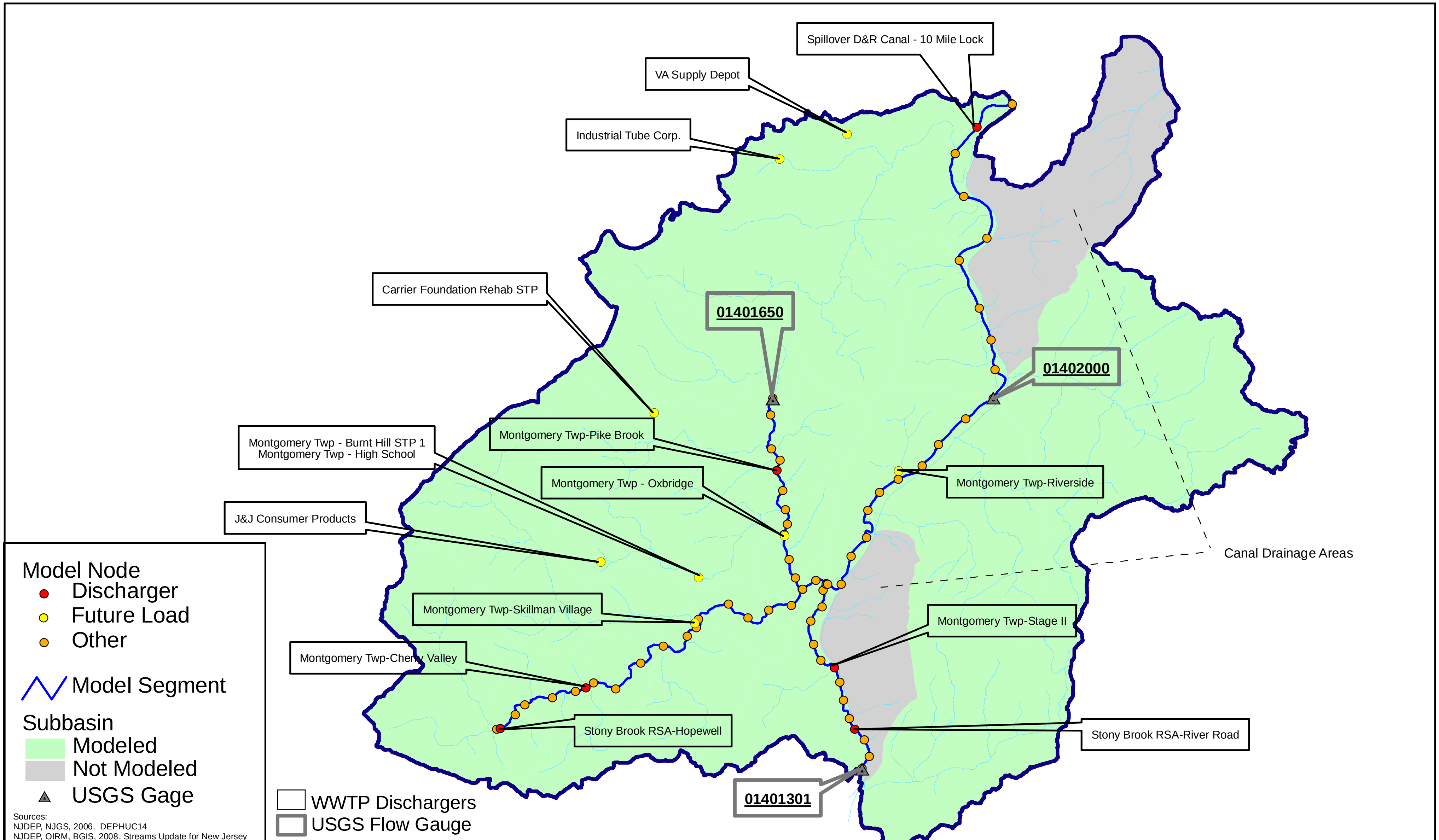

Figure 12

Raritan River Basin Nutrient TMDL Study Beden Brook/Lower Millstone River Watershed Area Model

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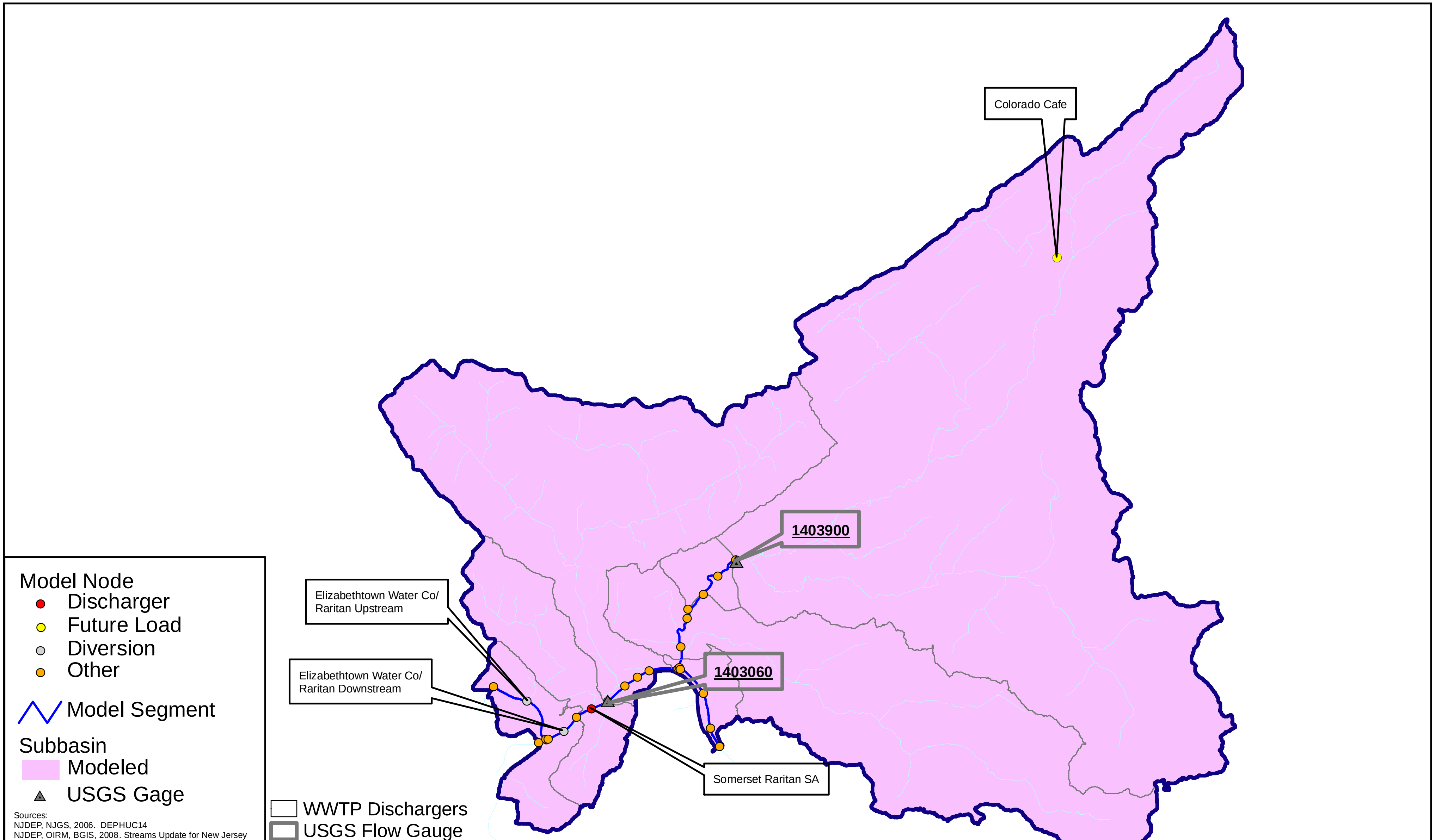

Figure 13

Raritan River Basin Nutrient TMDL Study Lower Mainstem Raritan River Watershed Area Model

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B. Hydrologic Model: HydroWAMIT

The hydrologic model developed by Kleinfelder/Omni for the Raritan River Basin, HydroWAMIT, is a continuous and spatially distributed model. It incorporates some of the features of both GWLF (Haith et al., 1996; Haith and Shoemaker, 1987) and HSPF (Bicknell et al., 1997) to provide a robust modeling structure. It is relatively easy to calibrate without losing significant representation of flows and is linked to an independent flow routing routine. HydroWAMIT was designed to capture the spatial and temporal variability of parameters for multiple subwatersheds and to perform continuous simulations. HydroWAMIT performs simulations on a daily time step for a maximum of a five year period. While intra-day flow peaks may get truncated because the flow model is daily, historic precipitation data are generally available in daily format, and the same is true for historic stream flow data. In addition, there is really no value to simulating intra-day flow peaks for a large-scale watershed model, especially one that is interested in productivity impacts that occur primarily during dry weather periods.

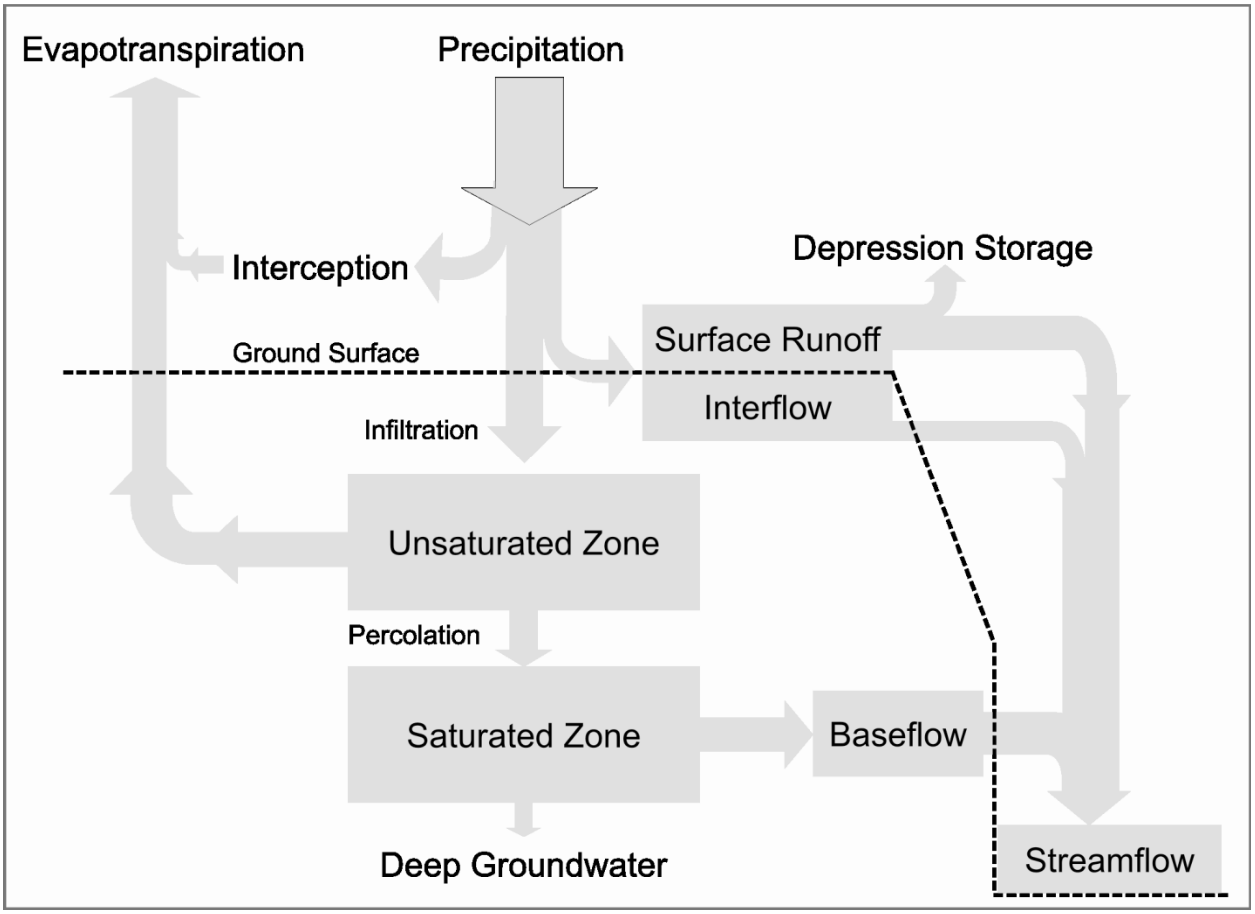
HydroWAMIT consists of two independent routines. The first routine is responsible for the simulation of the land phase of the hydrologic cycle for each land use type defined within the subwatersheds. The second routine is responsible for streamflow routing. The simulation of the hydrologic cycle is entirely coded within the HydroWAMIT interface, and it simulates for all time steps, the surface runoff for each land use and baseflow, based on meteorological inputs and model parameters. The second routine is DAFLOW code (Jobson, H. E., 1989). DAFLOW is a widely used hydraulic model developed by USGS, and it is embedded within HydroWAMIT for the streamflow routing. The stream flows simulated using the hydrologic model are assigned to stream network elements of DAFLOW and routed through the stream network.

HydroWAMIT operates with two levels of spatial resolution for the simulation of the hydrologic cycle. Surface flows and the associated loads are simulated for each land use element of the given subwatershed. Baseflows are simulated for the entire subwatershed. For each land use element defined in the model there is a set of parameters that represent the characteristics of that area. All the subwatersheds are linked by a stream network. The stream network is a conceptual model of the system's connectivity. It represents the water bodies and the path of water using a sequence of interconnected elements. The stream network elements are junctions, branches, nodes and segments. Junctions define headwater boundaries and the confluence of rivers. Branches are defined between two junctions. Each branch contains at least two nodes. A segment is defined as the section of a branch between two nodes. Nodes are model boundaries. Input or output flows from the system can be defined at each node. The baseflow and surface runoff simulated from each subwatershed by HydroWAMIT are assigned to the nodes and then routed downstream as streamflow using the flow model.

HydroWAMIT operates on a daily time step. Similar to the GWLF, the model mimics the hydrologic cycle using two storage layers for water storage. The top layer represents the unsaturated zone, which directly impacts the surface runoff and evapotranspiration. The bottom layer represents the saturated zone, which is the source for baseflows. Water percolates from the unsaturated zone to the saturated zone. A model structure similar to GWLF was preferred because it reduces the number of parameters necessary for calibration and yet provides good results on a daily time step.

Water input to the hydrologic model occurs through precipitation. The precipitation can be in the form of rain or snow depending on the temperature on that respective day. When precipitation occurs, it is subject to infiltration into the unsaturated zone and interception. Interception is the fraction of precipitation that does not reach the ground due to the water trapped in the structures or vegetation. The remaining water becomes surface runoff and interflow. The fraction of water that is intercepted is lost by evaporation. Interflow is a fraction of the surface runoff from pervious areas which occurs in the superficial layer of the soil. The fraction of precipitation that infiltrates into the unsaturated zone is subject to evapotranspiration and percolation to the saturated zone. The fraction of water that reaches the saturated zone becomes baseflow or can be lost as deep groundwater. The sum of baseflow, surface runoff and interflow form the incremental streamflow for each subwatershed at each time step. Figure 14 shows the land phase of the hydrologic cycle as simulated in HydroWAMIT.

Figure 14: Land Phase of Hydrologic Cycle Simulated in HydroWAMIT



HydroWAMIT uses event mean concentrations (EMCs) and baseflow concentrations (BFCs) to calculate the watershed yields. An EMC is an estimate of the total mass of pollutant delivered divided by the total storm flow volume. EMC values incorporate the nutrient cycling, buildup, and washoff processes, thus representing the net contribution from a variety of land uses (Butcher, J. B., 2003). The use of an EMC approach is especially appropriate given that flows are provided on a daily basis. The EMCs are defined for each constituent, and they are associated with each land use type for each watershed. The BFCs are defined for each constituent and vary by subwatershed. The EMCs and BFCs are input parameters and are not meant for calibration. They are estimated from field measurements and should be representative of the areas they are applied to in the model. Constituents simulated in HydroWAMIT are ammonia nitrogen (NH3-N), nitrate nitrogen (NO3-N), organic nitrogen, dissolved orthophosphate (OrthoP), organic phosphorus[7] (OrgP), dissolved oxygen, biochemical oxygen demand (CBOD5) and total suspended solids (TSS). The technical description of the processes in HydroWAMIT is provided in Appendix C (Cerucci and Jaligama, 2008).

C. Water Quality Model: WASP7.1

WASP7.1 (Water Quality Analysis Simulation Program) is a compartment model supported by the U.S. Environmental Protection Agency that uses finite difference methods to simulate the transport and fate of pollutants within a stream network. WASP7.1 simulates conventional pollutant dynamics and toxic pollution (Ambrose, R.B. et al. 1993). The sub-model PERIPHYTON was used for the Raritan TMDL Study models. The PERIPHYTON sub-model is an enhancement of the original EUTRO sub-model, which is used to simulate conventional pollution problems involving dissolved oxygen, biochemical oxygen demand, nutrients and eutrophication. Most significantly, the PERIPHYTON sub-model simulates the phenomenon of nutrient luxury uptake. Nutrient luxury uptake is critical to sustain the growth of algae and aquatic plants when the available nutrients in the water column are scarce (Wetzel, 2001; Effler, 1996; and Sigee, 2005).

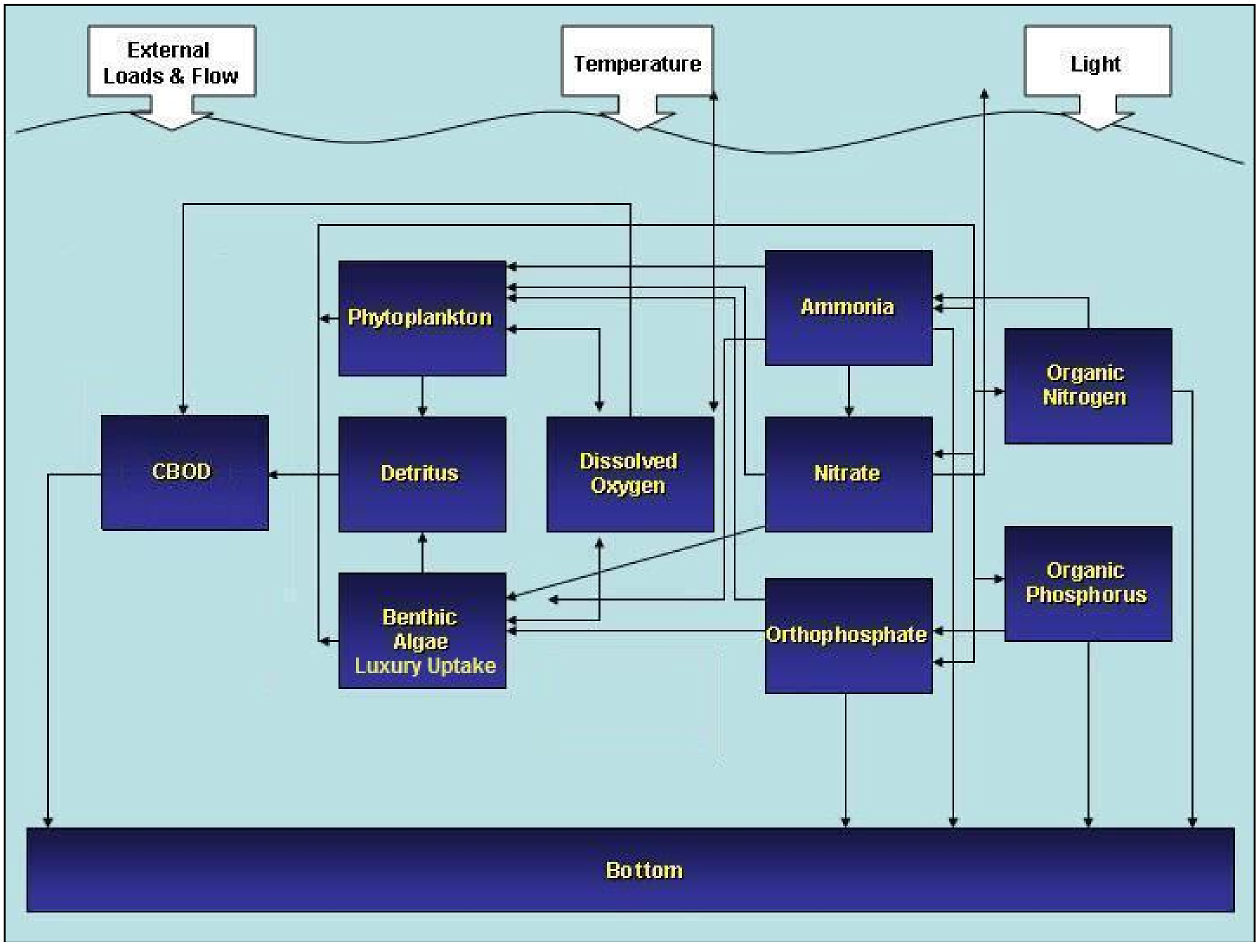
Many locations in the Raritan River Basin present low concentrations of available nutrients in the water column, in particular dissolved inorganic phosphorus, when periphyton productivity is significant. Given the characteristics of the Raritan River basin, the use of an eutrophication algorithm that considers the effect of nutrient luxury uptake is critical. In fact, the PERIPHYTON sub-model was specially developed to attend to the needs of the Raritan Basin Model. This sub-model was implemented by the U.S. Environmental Protection Agency (EPA) and was tested and applied by Kleinfelder/Omni. The PERIPHYTON algorithm is based on a structure suggested by Chapra, S. et al. (2006).

There are several physical-chemical processes that affect the transport and interaction among nutrients, phytoplankton, benthic algae (and/or macrophytes), carbonaceous material, and dissolved oxygen in the aquatic environment (Wool et al. 2003). Figure 15 presents the main kinetic interactions for the nutrient cycle and dissolved oxygen

[7] OrgP is assumed to be equal to TP minus OrthoP.

as modeled within the WASP7.1 PERIPHYTON sub-model. The dark blue boxes represent systems simulated in WASP7.1, and the arrows represent the relationships among them.

Figure 15: Processes Modeled within WASP7.1



As is typical for water quality simulations, the model simulated two phosphorus compartments: orthophosphorus (OrthoP) and organic phosphorus (OrgP). While it is often assumed that inorganic phosphorus is dissolved and organic phosphorus is particulate, inorganic and organic phosphorus exist in both particulate and dissolved fractions. The model accounts for these less important components (suspended inorganic phosphorus and dissolved organic phosphorus) through the use of the particulate fraction parameters, which determine the fractions of OrthoP and OrgP that are subject to settling. However, the particulate fractions are determined solely through calibration. The only data available are total phosphorus (TP) and dissolved reactive phosphorus (OrthoP). For the purpose of establishing model inputs and comparing predicted versus observed results: OrthoP is assumed to be equal to measured dissolved reactive phosphorus; and OrgP is assumed to be equal to TP minus OrthoP.

D. Model Inputs and Assumptions

The hydrologic and water quality model setup consist of several tasks and assumptions. The methods for obtaining the data inputs and the relevant modeling assumptions for the Raritan River Basin Model are discussed in the next sections.

1. Simulation Period

The simulation period for the Raritan Basin hydrologic and water quality model is from January 2002 through August 2005. This time frame provides a wide variety of flow conditions, which is important for calibrating the water quality model and for performing the TMDL analyses. Years 2002 and 2005 are considered dry, 2003 is wet and 2004 is typical. Besides the flow conditions, the availability of data for model inputs and calibration also influences the selection of the simulation period. Calibration and input data were assembled until August of 2005, when the modeling effort was initiated.

2. Node Positioning, Stream Network and Time Steps

The positioning of nodes is important to account for the correct entry of point and non point source flows, and loads to the model. Each branch contains at least two nodes, with one node defined at the beginning and the other at the end of the branch. Nodes defined along the branch can represent point source dischargers, diversions, reservoir releases, major watershed inputs, or sampling stations. Nodes do not necessarily represent a flow boundary. They were also placed to obtain flow outputs at specific locations and to define segments of sizes that would be consistent with the time scale of the water quality model.

The section of the stream between two consecutive nodes represents a segment in WASP7.1. The node positioning affects the time step of WASP7.1. The time scale of the flow and velocity has to be within the spatial scale of the segment. For example, if the velocity is 1m/s and time step is 60 seconds, the length of the segment has to be greater than 60 meters. Thus, small segments may require a very small time step in WASP7.1 to avoid model instability, which results in highly time consuming simulations. On the other hand, large segments can cause unacceptable levels of numerical dispersion to occur. The size of the segments (defined by the position of the nodes) needs to be considered when adding nodes to the model. If nodes are too close, the time step in WASP7.1 will be small, making simulations more cumbersome. If segments are too big, the numerical dispersion can jeopardize the results of water quality simulations.

The stream network for the water quality model is the same as the one used to simulate hydrology. The compatibility of the stream networks of the hydrologic and water quality model is critical to provide stable simulations. The WASP7.1 stream network, segment volumes, depths, flows, and velocities are all created within HydroWAMIT. Although the spatial domains of the hydrologic and water quality model are identical for each watershed group, their time steps are not. WASP7.1 requires a more refined timeframe discretization, which varies according to the watershed area model. A daily time step was adopted for HydroWAMIT for all watershed area models, whereas in WASP7.1 the time steps vary from 3 minutes to 1.2 minutes, depending on the stream network of each watershed area model. HydroWAMIT linearly apportions the hydrologic flows and loads from each daily time step into each time step in the water quality model without losing mass or continuity.

The watershed area models developed for the Raritan River Basin Model contain distinct stream networks that define completely independent models. The segment size was defined as a function of the particular characteristics of each watershed area model. The time step of the water quality model is a function of the size of the segment. The specifics of the stream network and water quality time step of each watershed area model are presented in the following paragraphs.

A total of 148 segments were defined for the North and South Branch Raritan River watershed area model (NSBranch). These segments total approximately 125 miles of stream network. Due to the large size of the drainage area, the stream network could not be very dense in order to avoid small time steps and overly time-consuming simulations in WASP7.1. The spatial distribution of point source features and sampling stations was favorable for defining relatively large segments for this watershed area model. Although large segments are desirable in order to optimize the simulations, their size has to be within the scale of the longitudinal dispersion to avoid numerical dispersion instability. The average segment is 0.85 miles long. This segment size and a time step of 3 minutes was enough to support stable simulations for the North/South

Branch watershed area model. Figure 9 shows the stream network of the North/South Branch watershed area model.

Thirty five segments were defined for the 13 mile stream network that includes the upper Millstone River and its modeled tributaries (UpperMills). The average segment size is 0.4 miles. Stable simulations were obtained for this stream network configuration using a 3 minute time step. Figure 10 shows the stream network of the Upper Millstone watershed area model.

A total of 15 miles of the Stony Brook were modeled within the watershed area model (Stony), ending at the inlet to Carnegie Lake. The Stony Brook was divided into 30 segments with an average segment size of 0.5 miles. A time step of 3 minutes provided stable simulations for the Stony Brook watershed area model. Figure 11 shows the stream network of the Stony Brook watershed area model.

The 30 miles of stream network that includes Beden Brook, Pike Run and the lower Millstone River (BBLowerMills) were divided into 64 segments. The average segment size is 0.47 miles. Some sections of the Beden Brook required a finer segmentation because of the spatial distribution of dischargers and sampling stations. This finer resolution required a smaller time step for the simulation in WASP7.1. For the Beden Brook/Lower Millstone watershed area model, a simulation time step of 1.2 minutes was adopted. Figure 12 shows the stream network of the Beden Brook/Lower Millstone watershed area model.

The Mainstem stream network includes 21 segments covering approximately 8.5 miles of the Raritan River and its tributary, Green Brook. The average segment size is 0.43 miles. A time step of 3 minutes provided stable simulations for this watershed area model. Figure 13 shows the stream network of the Mainstem watershed area model.

3. Slope and Segment Length

The longitudinal distance between nodes, which is an input parameter for HydroWAMIT, was calculated using GIS methods. The slopes were estimated using the elevation and distance between consecutive nodes. A ten meter resolution digital elevation model (DEM), which is a grid layer with constant elevation assigned to a 10x10 meter cell, was used to determine nodes elevations. This method is effective and simple to be applied with the help of GIS. However, negative slopes can occur when the terrain is flat. When negative slopes were calculated, a representative positive slope for the segment was assumed. The representative slope can be the minimum positive slope for a given branch or the average (positive) slope for the entire branch. If the branch was relatively small and the slopes are consistently low, the second approach was utilized.

4. Watershed Delineation

The delineation of subwatersheds was necessary to estimate nonpoint source flows and loads from particular drainage areas. Subwatersheds for the Raritan watershed were delineated automatically using GIS routines and a DEM. There are several GIS routines able to delineate watersheds based on a DEM. They work in conjunction with ArcView spatial analyst extension and differ on functionally. The extension chosen for the delineation of drainage areas was the AVSWAT2000 (http://www.brc.tamus.edu/swat/avswat/). This extension allows digitized streams to be defined as preferential flow paths, leading to more accurate watershed delineation.

Subwatersheds were delineated by AVSWAT2000 using a 10-meter resolution DEM. A layer with the model's stream network was used to define preferential drainage paths. The sub-basins were automatically delineated for "watershed input nodes," which represent tributary inputs, incremental watershed flows, or streams headwaters. The 10-meter resolution DEM was obtained from the NJDEP Bureau of Geographic Information System. DEMs are originally distributed by WMA. Therefore, DEMs from WMAs 8, 9 and 10, which comprises the spatial extent of the Raritan River Basin, were used.

The drainage area for the Delaware and Raritan Canal was not obtained according to the methodology described above. The drainage area to the canal is affected by man-made structures which are not taken into account by the automatic delineation tool. Therefore, the areas draining to the canal were manually delineated based on the USGS Water Resources Investigation Report (USGS, 2001). While the drainage areas to the canal were not simulated, delineating them was important to ensure that they were excluded from modeled drainage areas.

The delineated subwatersheds were also compared against the existing USGS HUC-14 watersheds. The delineated subwatersheds provide a finer and customized drainage network ideal for the model purposes. The main ridges align very well with the main ridges of the USGS HUC-14 watersheds.

5. Land Use Parameters

Land use spatial distribution and parameters are necessary for the calculation of watershed flows and the respective loads. Land use parameters include: area, average curve number, and fraction of impervious area per land use type and per subwatershed. Land use parameters were obtained from land use and soil data. Land use data consists of digital land use layers based on 2002 data, which are published by NJDEP and available for download on NJDEP's website by WMA. Data from the North and South Branch Raritan River Watershed (WMA8), Lower Raritan, South River, Lawrence Watershed (WMA9) and the Millstone River Watershed (WMA10) were used for determining land use parameters.

The land use layers are formed by polygons. Each polygon defines a spatial area and it is associated to multiple attributes. Among the attributes are two levels of the Anderson land use classification (USGS, 1976), and the fraction of impervious area. The first level of land use classification separates land use into main land use categories: urban, forested, agricultural, wetlands and water. Level two is a break up of the level one category into many sub-categories. For the Raritan River Basin Model, the differentiation between residential and commercial (i.e., other urban) areas was deemed important for determining NPS loads. Therefore, the land use types classified as urban were subdivided into residential and other urban according to the level two Anderson's classification. The land use types listed according to the level two classification assumed as other urban areas are: commercial services, extractive mining, industrial/commercial, mixed urban and transportation utilities. The remaining urban areas were considered as residential areas. Therefore, six land use types are considered for deriving areas, curve numbers, and impervious fractions: residential, other urban, forested, agricultural, wetlands and water.

Soil type classification is also necessary to derive land use parameters. Curve numbers are a function of land use and soil hydrologic group, which is given according to the soil type. The NRSC STATSGO layer (NRCS, 1994) was used to obtain the hydrologic soil group for multiples soils present in the Raritan River Basin. STATSGO is the state level soil coverage. It aggregates many county level soils within a single group (state MUID). The use of STATSGO for obtaining hydrologic soil groups is appropriate for the scale of the Raritan River Basin Model. The use of NRCS SSURGO layer, which has a finer resolution, is not justifiable; since curve numbers are averaged by land use and by watershed, the finer resolution of SSURGO would be lost due to the averaging of the curve numbers in such large areas. Soils types B and C are present within the Raritan River Basin study areas.

Curve numbers were assigned to each area defined by a land use and hydrologic soil group combination. Table 3 shows the curve numbers adopted for the Raritan River Basin Model according to land use and hydrological soil group. The Curve Numbers (CNs) for residential and other urban areas are lower than the values suggested on the NRCS tables. This difference in CN values is because the impervious fractions of residential and commercial areas are considered separately in the hydrological model. Therefore, the CN values adopted are assumed to represent the pervious fraction of the residential and commercial areas.

Table 3: Average Moisture Curve Numbers

Land Use	Soil Hydro Group	
	B	C
Residential	65	75
Other Urban	65	75
Forested	60	73
Agricultural	69	79
Wetlands	98	98
Water	100	100

Once the curve numbers were assigned the total area of each land use type within a subwatershed, the respective area-weighted CN and fraction of impervious area are obtained. Appendix D shows tables with the land use distribution and land use parameters derived for subwatersheds delineated for the five watershed area models. Table 4 shows the land use breakdown by watershed area model.

Table 4: Land Use Composition by Watershed Area Model

Watershed Area Model	Residential		Commercial (Other Urban)		Agricultural		Forest		Wetlands		Water		Total
	mi²	%LU	mi²	%LU	mi²	%LU	mi²	%LU	mi²	%LU	mi²	%LU	mi²
NSBranch	91.7	21%	34.3	8%	115.8	27%	149.7	35%	35.7	8%	4.1	1%	431.3
UpperMills	16.7	17%	12.8	13%	35.3	36%	11.0	11%	21.0	21%	1.0	1%	97.8
Stony	9.1	19%	3.2	7%	11.0	23%	17.7	37%	6.1	13%	0.5	1%	47.5
BBLowerMills	25.1	22%	11.7	10%	28.1	24%	32.2	28%	17.2	15%	1.0	1%	115.3
Mainstem	39.1	43%	19.9	22%	2.5	3%	14.8	16%	13.5	15%	0.9	1%	90.6

6. Cross Sectional Parameters

The cross sectional parameters used in the mathematical equations that provide cross sectional area and tributary width as a function of flow need to be derived in order to provide a reasonable representation of the stream geometry. Cross sectional areas are of great importance for the transport of water constituents and to determine velocity in the water bodies. The average depth is calculated by dividing the cross sectional area by the top width. The average depth influences many processes of the water quality simulation, such as reaeration, and light availability in the water column, which influence algae and periphyton growth.

Relationships between flow and cross sectional area, flow and average depth, flow and velocity, and flow and top width are referred to as rating curves. The cross sectional parameters were obtained by deriving rating curves based on the equations used in the hydraulic model (Jobson, 1989) and plotting measured values obtained from two sources: cross section surveys performed at Kleinfelder/Omni's stations and USGS gage data along the modeled water bodies. A total of 90 stations and 9 gages were used for deriving cross sectional inputs for the Raritan River Basin Model. Cross sectional surveys provide values of cross sectional area and average depth for a variable number of flow measurements per station. In some cases, when very few measurements were available for a given station, a methodology that uses a water surface elevation model (HEC-RAS) was applied for estimating the cross section shape (depth vs. width) and theoretical rating curves for fitting cross sectional parameters.

The cross sectional parameters were optimized by visually fitting rating curves based on the hydraulic model to the measured values obtained at survey stations, or to theoretical values derived using HEC-RAS when necessary. Cross sectional areas were adjusted first, followed by the width versus depth parameters using an iterative procedure. Sometimes, either the area or the width needs to be rearranged to improve the depth representation. Appendix E contains the hydraulic input verification plots showing measured values and hydraulic rating curves for flow versus cross sectional area, flow versus average depth, flow versus average velocity, and flow versus top width for all stations. In addition, the cross section shape derived from the hydraulic input parameters is plotted to provide a comparison between the actual and theoretical cross section at each location.

7. Point Source and Flow Gage Inputs

Point source in this context is a model input that consists of a time series of flow and concentrations that are used as model boundary conditions. Gage flows consist of continuous flow records obtained at specific locations in the watershed and measured by the USGS. Gage data are considered point source data when used as a boundary condition to the hydrologic model, and were input directly as daily values. Flow gage data within the model domain were used to calibrate the hydrologic model. USGS stream flow gages are generally relied upon by hydrologists across the country; USGS publishes an estimate of percent accuracy for each gage, which is generally within 10-15%. Although gage flows are continuous flow records, some gages were not active for the entire model simulation period. Thus, regression analyses were performed to estimate the necessary flow boundaries.

In addition to boundary gaged flow, point source data include the inputs of flows from dischargers, releases, and water diversions. Discharger flows can include major municipal, minor municipal, major industrial or thermal dischargers, all of which are regulated under the New Jersey Pollutant Discharge Elimination System (NJPDES). Water releases are reservoir yields and water transfers. Reservoir yields for the Raritan River Basin Model include flows from the Spruce Run Reservoir, Cushetunk Lake, and Carnegie Lake. The flows from Spruce Run Reservoir, Cushetunk Lake, and Carnegie Lake were obtained from USGS gages located near their outlets. Water transfers are flow inputs diverted from a reservoir or canal. There are no USGS gages to measure water transfers, thus the relevant data were obtained directly from New Jersey Water Supply Authority (NJWSA), the agency responsible for the control of these transfers. The final category of point source data are diversions. This category of data is essentially the same as the water transfers, except that they consist of output flows from the system instead of input. These data were also obtained from NJWSA.

All model boundary conditions are provided electronically in Appendix T. All the relevant aspects of point source data and gage data are discussed in the following sections.

a. Point Source Flows

There are many point source discharges located in the Raritan River Basin that could have been included in the Raritan River Basin Model. The list of existing discharges was extensively reviewed in order to include those that could be potentially significant for calibration. Twenty-two (22) wastewater treatment plant (WWTP) discharges were included in the model as significant flow and water quality boundaries. These "major" WWTP discharges contribute significant point source flows directly to the stream. "Major" in this context means that they were simulated directly as a flow and water quality boundary condition, and has nothing to do with the distinction between Major and Minor dischargers in the NJPDES database. The Raritan River Basin Point Source Pollutant Loading and Attenuation Rate Analysis (TRC Omni, 2001) was used to identify all active discharges with the potential to impact flow or stream quality during the calibration period. It is important to recognize that all point sources were included in the TMDL analyses, not just those point sources relevant for calibration. In addition to the WWTP discharges, two releases, two diversions, and one pumping station that can operate as a release or diversion in the Raritan River Basin were included in the model as flow boundary conditions. A complete list of simulated discharges and diversions is provided in Table 5.

Table 5: Point Source Discharges and Diversions Simulated as Boundaries

Watershed Area Model	Branch	Node	Node Type	Description	Discharge/Release Type
NSBranch	2	2	Discharger	Mt Olive Twp – Clover Hill STP	Municipal WWTP
NSBranch	3	4	Discharger	Washington Twp - Schooley's Mt	Municipal WWTP
NSBranch	3	6	Discharger	Washington Twp -Long Valley	Municipal WWTP
NSBranch	4	2	Discharger	NJDC Youth Correct - Mt View	Domestic/Industrial WWTP

Table 5: Point Source Discharges and Diversions Simulated as Boundaries

Watershed Area Model	Branch	Node	Node Type	Description	Discharge/Release Type
NSBranch	5	2	Discharger	Town of Clinton WTP	Municipal WWTP
NSBranch	7	2	Diversion	SB Raritan Diversion at Hamden	Water Supply Diversion/Release
NSBranch	7	11	Discharger	Flemington Boro*	Municipal WWTP
NSBranch	7	14	Discharger	Raritan Twp MUA	Municipal WWTP
NSBranch	12	2	Discharger	Roxbury Twp – Ajax Terrace	Municipal WWTP
NSBranch	14	2	Discharger	Whitehouse Release	Water Supply Release
NSBranch	15	2	Discharger	Readington-Lebanon SA	Municipal WWTP
NSBranch	17	2	Discharger	Mendham Boro	Municipal WWTP
NSBranch	20	2	Discharger	Bernardsville	Municipal WWTP
NSBranch	21	3	Discharger	Environmental Disposal Corporation	Municipal WWTP
UpperMills	2	4	Discharger	Hightstown Advanced WTP	Municipal WWTP
UpperMills	3	6	Discharger	East Windsor Twp MUA	Municipal WWTP
UpperMills	4	2	Discharger	Princeton Meadows STP	Municipal WWTP
Stony	1	2	Discharger	Bristol-Myers Squibb Co.	Domestic/Industrial WWTP
Stony	1	3	Discharger	Stony Brook RSA Pennington	Municipal WWTP
Stony	1	13	Discharger	Hopewell Business Park	Domestic WWTP
Stony	1	14	Discharger	Educational Testing Service	Domestic WWTP
BBLowerMills	1	2	Discharger	Stony Brook RSA-Hopewell	Municipal WWTP
BBLowerMills	1	7	Discharger	Montgomery Twp - Cherry Valley STP	Municipal WWTP
BBLowerMills	2	5	Discharger	Montgomery Twp - Pike Brook	Municipal WWTP
BBLowerMills	4	4	Discharger	Stony Brook RSA - River Road	Municipal WWTP
BBLowerMills	4	8	Discharger	Montgomery Twp - Stage II	Municipal WWTP
BBLowerMills	5	19	Discharger	Spillover D&R Canal - 10 mile lock	Water Supply Release
Mainstem	2	2	Diversion	NJ American Water (Raritan Upstream)	Water Supply Intake
Mainstem	3	2	Diversion	NJ American Water (Raritan Downstream)	Water Supply Intake
Mainstem	3	4	Discharger	Somerset Raritan SA	Municipal WWTP

* Wet-weather discharge only

Daily discharger data were included in the model when available. When daily data were not available for dischargers, the DMR flow values provided by NJDEP were used for every day of the month. Daily data for diversions and releases were obtained from NJWSA.

Three major releases were included in the hydrologic model. At the Hamden pumping station, water is sometimes released from Round Valley Reservoir into the South Branch Raritan River. At Whitehouse, water is released occasionally from the Round Valley Reservoir and enters the South Branch Rockaway Creek directly upstream from the gauging station 01399670 at Whitehouse Station. Finally, at Ten Mile Lock, water is diverted from the Delaware and Raritan Canal into the Millstone River. NJWSA provided daily data for all three of the release locations. In addition to the three releases mentioned above, the water yields from Spruce Run Reservoir, Cushetunk Lake and Carnegie Lake are inputs to the models. The reservoir releases are given by USGS gage data and are discussed in section III.D.7.b below.

Three major diversions are included in the hydrologic model based on daily data provided by NJWSA. At the Hamden pump station, water is diverted to Round Valley Reservoir upstream of the gauging station on the South Branch Raritan River at Stanton. In addition, New Jersey American Water diverts water from the confluence of the Millstone and Raritan Rivers. The intake structure has multiple inlets, allowing water from the Raritan River to be withdrawn preferentially and the Millstone River as needed. Two nodes were used to simulate the New Jersey American Water diversion intake. The data provided by NJWSA from New Jersey American Water included the daily sum of all the water diverted at the confluence; the data were split into two series for the diversion nodes upstream and downstream of the Millstone River confluence. In accordance with the operational procedures in place, namely that water was diverted preferentially from the Raritan River and only as needed from the Millstone, all diversion was assumed to occur at the upstream node as long as flow is available in the Raritan River. When the diverted water exceeded the flow in the Raritan River, it was assumed that the rest of the water was diverted from the Raritan River downstream of the confluence with the Millstone River.

b. USGS Gage Flows

USGS gage data were used as reservoir flow boundary and calibration flow data for the hydrologic model. Table 6 presents the gages used and a summary of the data available for these gages. A few of the gages did not have complete published records from 2002 to 2005 and interpolations were necessary to make a complete time series of flow data. For each of these gages, correlations were made with gages that were considered to have similar discharge measurements and drainage areas. Table 6 lists the missing data records and the gages that were used to interpolate the missing data.

Some gages did not have flow records for the entire period of simulation. This is the case of the Carnegie Lake gage in Princeton. During the time of simulation, the gage at Carnegie Lake was not fully funded and was a Crest Stage gage only. In order to estimate data for this boundary, data were obtained from USGS gage 01401301 Millstone River at Carnegie Lake from 1/1/1973 to 9/30/1974 and 1/1/1988 to 12/31/1989, two periods when the gage was active, and were plotted versus data during the same time for USGS gage 01402000 Millstone River at Blackwells Mills. An r-square value of 0.87 was obtained, and data for Millstone River at Blackwells Mills during the period of simulation were therefore used to estimate flows for Carnegie Lake.

Table 6: USGS Gage Flows

Watershed Area Model	Calibration Gage	Boundary Gage	Model Node	Gage Name	Missing Data	Gage Used for Interpolations
NSBranch		01396800	3-24	Spruce Run at Clinton	6/28/2005-7/18/2005	1398500 NB Raritan River near Far Hills
		01399670	14-1	SB Rockaway Creek at Whitehouse		
	01396190		3-2	SB Raritan River at Four Bridges	12/28/2004-1/14/2005	1396500 SB Raritan River near High Bridge
	01396500		3-19	SB Raritan River near High Bridge		
	01397000		7-7	SB Raritan River at Stanton		
	01398000		8-1	Neshanic River at Reaville	4/13/2005-4/26/2005	1398500 NB Raritan River near Far Hills
	01399500		12-12	Lamington River near Pottersville		
	01398500		19-8	NB Raritan River near Far Hills	1/25/2005-2/14/2005	1399500 Lamington River near Pottersville
	01400000		22-8	NB Raritan River near Raritan		
	01400500		23-8	Raritan River at Manville		
UpperMills	01400730		5-1	Millstone River at Plainsboro	1/1/2002-8/31/2005	Older simulation period selected
Stony	01401000		1-20	Stony Brook at Princeton		
BBLowerMills		01401301	4-1	Carnegie Lake	1/1/2002-8/31/2005	1402000 Millstone River at Blackwells
	01401650		2-1	Pike Run at Belle Mead		
	01402000		5-12	Millstone River at Blackwells		
Mainstem	01403060		3-4	Raritan River below Calco Dam		
	01403900		5-1	Bound Brook at Middlesex	1/1/2000-1/31/2004	None

The water yield from Cushetunk Lake was estimated by subtracting the Whitehouse release data provided by NJWSA from USGS gage 01399670 South Branch Rockaway Creek at Whitehouse Station. In some instances, the gage data was corrected because the release data was greater than the gage. This occurred at very low temperatures when the gage could be frozen and in periods with extremely high flows. For these times, USGS gage 01398500 North Branch Raritan at Far Hills was used to correct the Whitehouse gage; specifically, a percent difference was calculated from the daily flow measurements for the Far Hills gage and applied to the Whitehouse gage when the flow estimated appeared inaccurate and when the stream was most likely frozen. Generally, USGS performs its own gage corrections during their annual review, and the corrected data were relied upon directly with the exception noted above.

8. Meteorological Data

Meteorological data drive the hydrologic simulations in HydroWAMIT. Meteorological data consist of precipitation and temperature data measured at several weather stations within the Raritan River Basin and vicinity. Weather stations are maintained by the National Climatic Data Center (NCDC), airports, or by several WWTPs located in the Raritan basin.

The type, resolution and time frame of meteorological data vary considerably. Some stations measure only precipitation and not temperature. Most of the stations report daily average data. However, hourly data can also be found in a few locations. Table 7 contains a summary of the selected weather stations used for the Raritan River Basin Model. The stations were selected based on location and data availability. Table 8 shows the weather data source (reference weather gage) defined in the hydrologic model for each watershed area model.

Table 7: Meteorological Data and Stations

Station Name	Location	Type	Data Type	Period
Bound Brook	Lower Raritan River	NOAA	Daily Precip; Hourly Precip; RealTime Precip	1/1/00 - 5/31/05
Hightstown	Upper Millstone River	NOAA	Daily Temp (min, mean, max); Daily Precip	1/1/00 - 5/31/05
Succasunna	North Branch Raritan River	Local	Daily Temp (min, mean, max); Daily Precip	2/14/04 - 8/31/05
Trenton Airport	Outside of Watershed	Airport	Daily Temp (min, mean, max); Daily Precip	1/1/01 - 12/31/04

Table 8: Reference Weather Gages Assigned to Watershed Area Models

Watershed Area Model	Reference Weather Gage	
	Precipitation	Temperature
NSBranch	Bound Brook – Succasunna	Hightstown
Beden-LowerMillstone	Bound Brook	Hightstown
Stony Brook	Trenton Airport	Hightstown
Upper Millstone	Hightstown	Hightstown
Mainstem Raritan	Bound Brook	Hightstown

9. Nonpoint Source (NPS) and Stormwater Pollutant Loads

The structure provided by HydroWAMIT to calculate the surface runoff from areas containing multiple land uses and baseflow from multiple subwatersheds was used to calculate the pollutant loads from these areas. The EMCs and BFCs obtained through sampling of different land use types and sub-basins were assigned to land use source areas within the subwatersheds. NPS loads were derived by multiplying the EMCs and BFCs by the surface flow from each respective land use source area and baseflow from each subwatershed. The methodology to derive the EMCs and BFCs is described in this section.

EMCs are flow-weighted average concentrations that provide an estimate of the total mass of pollutant divided by the total storm volume. The use of EMCs is preferred for large-scale watershed modeling because the scale of analysis attenuates any "first flush" impact. In the case of the modeling framework adopted for the Raritan River Basin Model, EMCs and BFCs were selected based on actual stormwater and baseflow data, and were not subject to calibration.

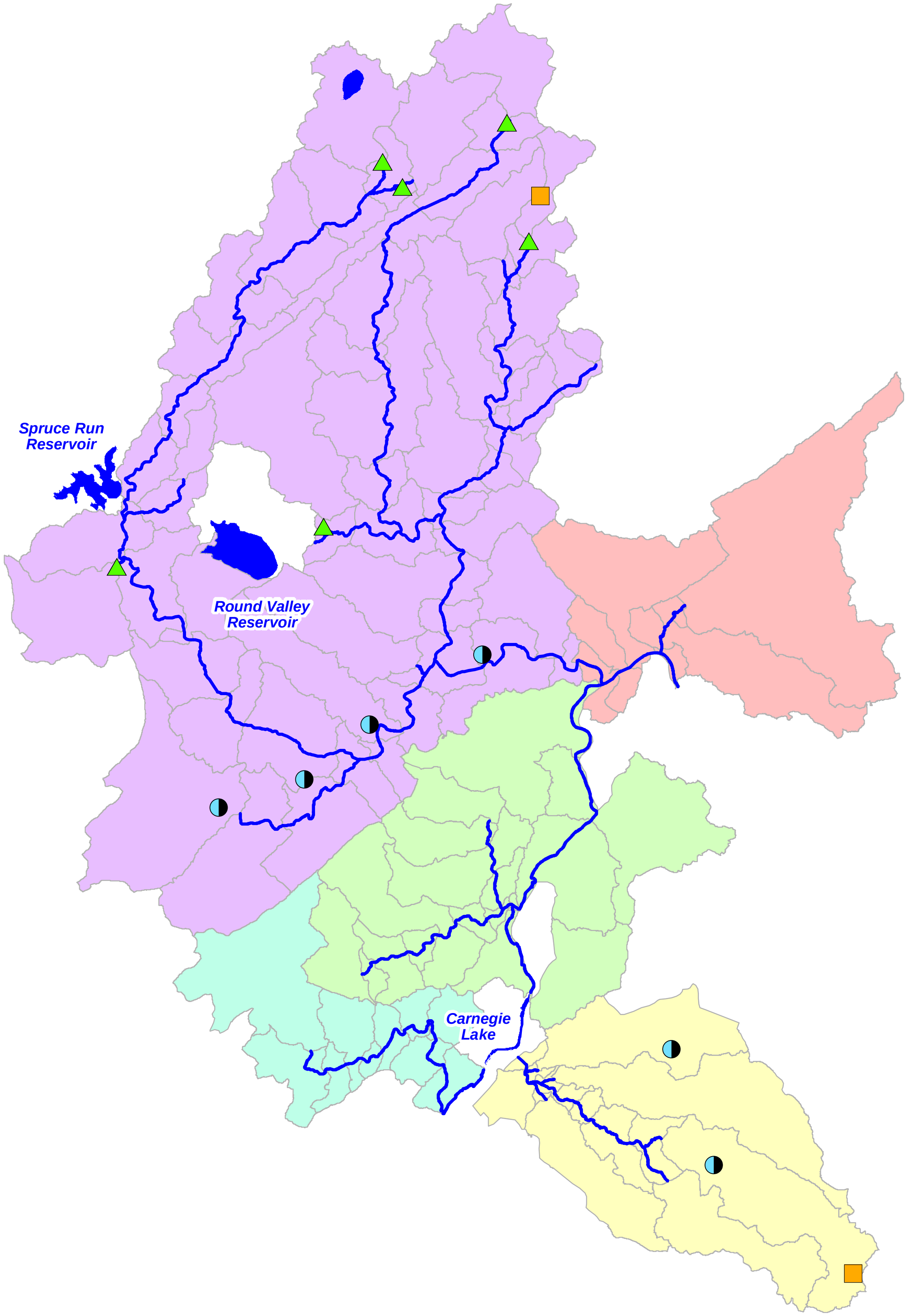
BFCs are average concentrations of stream flow samples collected under low flow conditions. During dry periods, baseflow is the only source of water to the streams when point sources are not present in the basin. Watershed and water quality models generally assign either a constant tributary baseflow concentration or one that varies by major geographic basin. However, baseflow is delivered to modeled streams in small tributaries, and can also be influenced by the land cover. Therefore, it is desirable that the stream sampling sites for BFCs be representative of both the geographic sub-basins as well as the land use types found within the study areas. This approach was adopted for the Raritan River Basin Model.

The Phase 1 Raritan TMDL Study (TRC Omni, December 19, 2005) specifically monitored stormwater and baseflow in different geographic areas and land use areas in order to augment existing stormwater and baseflow data. Three stormwater events were performed at six stormwater stations within the Raritan River Basin, each event consisting of approximately five samples per storm. Three baseflow sampling events were performed at eight baseflow stations, each event consisting of two consecutive days of sampling. Of the eight baseflow sampling locations, six were the same as the stormwater locations, which were carefully selected to represent important land use types within the Raritan River Basin. The other two baseflow sampling locations were selected to characterize baseflow in headwaters of the major geographic sub-basins in the Raritan River Basin. Finally, low-flow data from six relatively pristine headwater stream sampling locations were used to provide a finer representation of baseflow nitrogen concentrations, because nitrate exhibited greater geographic variability than other constituents. Figure 16 shows the stormwater, baseflow, and headwater stream sampling sites for the Phase 1 monitoring study.

a. Runoff NPS Concentrations (EMCs)

EMCs for TSS, ammonia nitrogen (NH3-N), nitrate nitrogen (NO3-N), dissolved orthophosphorus (OrthoP), organic phosphorus (OrgP), carbonaceous biochemical oxygen demand (CBOD5) and total dissolved solids (TDS) were derived for each of the major land types within the Raritan River Basin based on actual stormwater sampling data. The six stormwater stations sampled for the Phase 1 Raritan River TMDL study drained catchment areas of the following uniform land use types: agricultural pasture, agricultural cropland, agricultural wetlands, deciduous wooded wetlands, rural residential, and older high-density residential. Similar stormwater sampling data from other studies in the Raritan River Basin (Omni, 2000) as well as from the adjacent Passaic River Basin (TRC Omni, May 2003 and March 2004) were also utilized as described below.

EMCs were calculated by averaging concentrations first within each storm at each station, then among storms at each station, then among stations for each land use category. The reason for averaging first within each storm and then among storms for each station was to avoid artificially weighting the values according to how many samples happened to be sampled during each storm or how many storm events were sampled at each station. Stormwater exhibits considerable variability in quality both within a storm, between storms, and of course among land uses. EMCs were developed as composite values that adequately represent specific land use categories.



Sources:
NJDEP, NJGS, 2006. DEPHUC14
NJDEP, OIRM, BGIS, 2008. Streams Update for New Jersey

Simulated Watershed
- Beden Brook/Lower Millstone River
- North & South Branch Raritan River
- Main Stem Raritan River
- Stony Brook
- Upper Millstone River

Sampling Station
- Baseflow
- Baseflow / Stormwater
- Headwater Stream
- Simulated Stream

Figure 16

Raritan River Basin Nutrient TMDL Study Stormwater & Baseflow Sampling Stations

5 2.5 0 5
Miles

August 2013

The breakdown of land use categories and the stations used to characterize each land use category were carefully selected based on the representation of land use types within the basin and the distribution of the resultant total phosphorus and nitrate concentrations. For instance, the stormwater results in terms of total phosphorus and nitrate concentrations were similar between agricultural cropland, agricultural pasture, and agricultural wetland; therefore, all agricultural land uses were lumped into a single land use category. On the other hand, residential land uses were separated from other urban land uses because the stormwater data justified a distinction. The stormwater sites used to characterize each land use category are provided in Table 9.

Table 9: Stormwater Sites Used to Characterize Each Land Use Category

Study Year	Basin	Watershed	Station ID	Station Type	Land Use Category
2004	Raritan	Neshanic	AgCrop	Agricultural Cropland	Agricultural
2004	Raritan	SB Raritan	AgPast	Agricultural Pasture	Agricultural
2004	Raritan	Upper Millstone	AgWet	Agricultural Wetland	Agricultural
2001-2002	Raritan	Beden / Pike	A	Agricultural	Agricultural
2001-2002	Raritan	Beden / Pike	F	Forest	Forest
1996-1998	Passaic	Whippany	LS-1	Forest	Forest
2001-2002	Raritan	Beden / Pike	C	Commercial	Other Urban
2003	Passaic	Upper Passaic	SW6	Corporate Center	Other Urban
1996-1998	Passaic	Whippany	LS-2	Mixed Urban	Other Urban
2004	Raritan	Raritan	OldUrb	Old Urban	Residential
2004	Raritan	SB Raritan	Rural	Rural Residential	Residential
2004	Raritan	Upper Millstone	DWW	Wetlands, Deciduous Wooded	Wetlands
2001-2002	Raritan	Beden / Pike	R	Residential	Residential

Averages within storms were flow-weighted according to the data available; for instance, if depth in a culvert was recorded, then samples taken during high depths were weighted more than samples taken with little depth. In cases where neither flow nor depth was measured, precipitation was used as a surrogate for flow to weight the results. Flow-weighting had only a minor impact on the results. Concentration variability among sites from different land use categories is much greater than variability within sites, lending further credence to the approach of tying runoff concentrations to land uses.

Stormwater concentration results were carefully evaluated to detect differences among geographic sub-basins as well as seasons during which stormwater sampling was performed. Land use category proved much more important than geographic sub-basin in influencing stormwater pollutant concentration. While all parameters were evaluated within each land use category for seasonal influences on stormwater concentration, only phosphorus in forest showed a significant seasonal pattern; specifically, phosphorus concentration in stormwater from forest lands increased substantially in the fall, presumably due to the contribution of leaf litter. Since the volume of stormwater from forest land is relatively minor compared to other land use types, the EMCs for phosphorus for forest stormwater were simply seasonally averaged, avoiding the need to vary the EMCs seasonally.

Unlike EMCs for other constituents, EMCs for DO were not based on stormwater sampling data. Dissolved oxygen and other in-situ measurements are not generally analyzed during stormwater sampling events, and in any case may not reflect the impact of stormwater on DO in the stream due to reaeration and other processes that occur prior to reaching the stream. With the exception of wetland runoff, it is reasonable to assume that stormwater runoff would be near saturation when it reaches the stream. Runoff from wetlands includes displacement of stored water that would be expected to be lower in DO. Dissolved oxygen EMC values are not important to model simulations, since the impact of stormwater DO is so transient. The summer DO EMCs were assumed to be 6 mg/l for all land use types except wetlands, which was assigned a value of 5 mg/l. Seasonal variation of DO EMCs is allowed in the model, an exception developed to accommodate the variation of DO concentration in stormwater runoff during summer and winter months due to temperature changes. A constant value of 8 mg/l was assumed for the winter months for all land uses. These assumed DO EMCs result in stream DO impacts that are consistent with the limited post storm data that are available.

The EMCs calculated for each land use category for the Raritan River Basin are provided in Table 10.

Table 10: Stormwater EMCs for Each Land Use Category (mg/l)

Constituent	Residential	Other Urban	Agricultural	Forest	Wetlands
TSS	38.4	51.2	71.1	28.9	8.0
NH3-N	0.23	0.25	0.16	0.06	0.23
NO3-N	1.87	0.76	1.18	0.75	0.22
OrthoP	0.118	0.100	0.191	0.044	0.013
OrgP	0.085	0.089	0.164	0.036	0.059
CBOD5	2.81	5.08	3.27	4.16	1.04
DO summer	6	6	6	6	5
DO winter	8	8	8	8	8

b. Tributary Baseflow NPS Concentrations (BFCs)

BFCs are assigned within HydroWAMIT by subwatershed and not by land use. Sampling data obtained during baseflow conditions at baseflow monitoring locations and relatively pristine headwater stream locations were used to assign BFCs. For most parameters, baseflow concentration varies geographically. However, the degree of geographic variation and the impact of land use on baseflow concentration varied for different baseflow constituents.

CBOD5 was observed to be mostly non-detect in baseflow throughout the system, and was assigned a value of 1.1 mg/l for all subwatersheds. OrthoP was found to vary regionally and was assigned BFC values by each watershed area model. Unmonitored watersheds in the NSBranch, UpperMills, and Mainstem watershed area models were assigned BFCs of 0.006, 0.02, and 0.02 mg/l OrthoP, respectively. Data were insufficient to assign constant BFCs for OrthoP in the Stony and BBLowerMills watershed area models; BFCs for OrthoP were instead characterized as a percentage of the BFC assigned for TP: 57% and 72% in the Stony and BBLowerMills watershed area models, respectively. Similarly, TSS was found to vary regionally and was assigned BFC values by each watershed area model.

Baseflow concentration of nitrate was more difficult to assess. Land use likely influences baseflow nitrate concentrations in some locations, but geographic differences were observed to be more important in the Raritan River Basin. Therefore, BFCs for nitrogen constituents were assigned regionally by watershed area model, and also by major watershed within the North/South Branch model, as follows.

- UpperMills, Stony, and BBLowerMills subwatersheds were assigned BFCs for nitrate of 1.267 mg/L based on data from MRB.
- South Branch Raritan River subwatersheds were assigned BFCs for nitrate of 1.543 mg/L based on data from SBRR1, DkB1, and CC1.
- Lamington River subwatersheds were assigned BFCs for nitrate of 0.778 mg/L based on data from LR1 and NBRC1.
- North Branch Raritan River subwatersheds were assigned BFCs for nitrate of 0.920 mg/L based on data from IB1.

Baseflow concentrations of total phosphorus and TDS were found to vary substantially by land use. Baseflow quality was measured in small tributaries during low-flow sampling events, consistent with the manner in which baseflow was modeled. Tributary baseflow as defined in this study is not primarily the direct discharge of groundwater to modeled streams, but also reflects dry-weather discharge of tributaries within each contributing sub-basin. In other words, baseflow is delivered to modeled streams in small tributaries. As a result, baseflow is influenced by processes within the contributing tributaries, most notably settling/resuspension and stream bank erosion. The land uses within the contributing drainage area substantially influence the tributary baseflow concentration of organic phosphorus. Although baseflow is not assigned by land use in the model, the impact of land use on baseflow concentration was simulated by deriving BFCs individually for each subwatershed as a function of the land use distribution. Three land uses were defined for baseflow OrgP concentrations: agricultural, urban and forest/wetlands. OrgP concentration in baseflow associated with agricultural and urban land uses was based on the baseflow monitoring data from representative land uses in each sub-basin. Values for OrgP concentration in baseflow associated with natural (forest/wetlands) land uses in each sub-basin were determined iteratively to match the measured baseflow concentration in headwaters impacted only by NPS. BFCs for OrgP in unmonitored subwatersheds were obtained by calculating the area-weighted average TP based on the weighting factors associated with agricultural, urban and forest/wetlands land uses, and then subtracting the assigned BFC for OrthoP. The TP weighting factors used to derive BFCs for OrgP are provided in Table 11.

For all constituents, the actual average concentration measured under low-flow conditions was used whenever baseflow monitoring data were available near the outlet of a contributing watershed. For instance, the BFCs for watershed at branch 1 node 1 in the NSBranch watershed area model were based on the average of baseflow monitoring data from station SBRR1. The values of BFCs derived for each subwatershed based on the methodology described above are provided in Appendix F by watershed area model.

Table 11: Baseflow TP Concentration Weighting Factors (mg/l)

Watershed Area Model	Agriculture	Urban	Forest/Wetlands
NSBranch	0.122 ((AgPast, AgCrop), AgWet)	0.070 (Rural×3, OldUrban)	0.010 (Calibrated)
UpperMills	0.090 (AgWet)	0.070 (Rural×3, OldUrban)	0.054 (DWW)
Stony Brook	0.122 ((AgPast, AgCrop), AgWet)	0.064 (Rural)	0.010 (Calibrated)
BBLowerMills	0.122 ((AgPast, AgCrop), AgWet)	0.064 (Rural)	0.010 (Calibrated)
Mainstem	0.133 (AgPast, AgCrop, AgWet)	0.077 (Rural, OldUrban)	0.025 (Calibrated)

BFCs for DO are assumed to vary as a function of daily stream water temperature and the average land use value of percent dissolved oxygen saturation. Equation 5 (APHA, 1992) is used to determine the dissolved oxygen saturation (o_{sf}) based on the stream temperature (T). The final dissolved oxygen concentration is obtained by multiplying the theoretical DO saturation by the land use area weighted average percent DO saturation of a given subwatershed.

$$\ln o_{sf} = -139.34411 + \frac{1.575701 \times 10^5}{T_a} - \frac{6.642308 \times 10^7}{T_a^2} + \frac{1.243800 \times 10^{10}}{T_a^3} - \frac{8.621949 \times 10^{11}}{T_a^4} \quad (5)$$

c. Baseflow and Runoff Adjustment Factors

The EMCs and BFCs derived for all simulated sub-basins as described in the previous sections represent a generalization based on measured stormwater and baseflow concentrations from selected sites and land use distribution of simulated sub-basins. Adjustment factors were adopted to provide a more accurate representation of headwater subwatersheds that are larger than where the stormwater and baseflow sampling were performed, and to take into account effects of settling/resuspension and stream bank erosion that occurs in tributary streams. Three types of adjusting factors are available: “Tributary Baseflow Factor” that multiplies BFCs of OrthoP and OrgP; “Watershed Runoff Factor” that multiplies EMCs of OrthoP and OrgP; and “Sediment Delivery Ratio” that multiplies EMCs of TSS. Generally the adjustment factors were designed to adjust baseflow and runoff values to be equal to measured concentrations, as described below.

The Tributary Baseflow Factors for OrthoP and OrgP are simply ratios of observed average TP baseflow concentrations to the general BFCs for TP derived based on land use weighting factors. Watershed Runoff Factors were developed for the four sub-basins in the upper Millstone River Watershed that drain to lakes that were sampled extensively during Phase I monitoring. Data at the inlet and outlet of each lake were used in conjunction with the hydrologic model to estimate annual phosphorus loading in and out of each lake. The Watershed Runoff Factors were back-calculated based on these simple lake analyses, and incorporate the net effect of both the watershed itself as well as each lake. The use of these ratios as adjustment factors provided a better representation of sites where stormwater and baseflow sampling was performed.

A sediment delivery ratio of 0.5 were adopted only for the Upper Millstone watershed area model, because the headwatersheds are comparatively much larger than other watershed area models, and are also influenced by upstream lakes.

Table 12 shows the sub-basins where Tributary Baseflow Factor, Watershed Runoff Factor and/or Sediment Delivery Ratio were adopted along with their respective values.

Table 12: Baseflow and Runoff Adjustment Factors

Watershed Area Model	Sub-basin	Basis	Tributary Baseflow Factor	Watershed Runoff Factor	Sediment Delivery Ratio
NSBranch	1&1	SBRR1	1.220	1	1
	2&1	DkB1	0.800	1	1
	6&1	CC1	0.305	1	1
	8&1	NR1	0.640	1	1
	10&1	HB1	1.186	1	1
	12&1	LR1	1.246	1	1
	13&1	NBRC1	0.287	1	1
	17&1	IBI	1.068	1	1
	18&1	BuB1	1.067	1	1
	19&11	PeB1	0.661	1	1
UpperMills	1&1	UMR1	0.810	1	0.5
	2&1	Peddie Lake	1.202	0.719	0.5
	3&3		1	1	0.5
	3&9		1	1	0.5
	3&12		1	1	0.5
	3&14		1	1	0.5
	4&1	Plainsboro Pond	0.858	0.522	0.5
	5&2		1	1	0.5
	6&1	Grovers Mill Pond	0.594	0.825	0.5
	6&3		1	1	0.5
	8&1	Gordon Pond	1.022	0.723	0.5
	9&2		1	1	0.5
BBLowerMills	1&1	BB1	0.883	1	1
Stony	1&1	SB1	0.985	1	1

10. WASP7.1 Time Series

Time series comprise a class of input data to WASP7.1. These data are variable in time and can be assigned to one or multiple segments. Three types of time series were used for the Raritan River Basin water quality model: stream water temperature, solar radiation, and ammonia and phosphorus sediment flux. The assumptions and methodologies used to derive the time series for the Raritan River Basin Model are discussed in the ensuing sections.

a. Temperature Time Series

Stream temperature plays an important role in water quality modeling. It influences the kinetics of chemical reactions and the solubility of gases within the aquatic environment. For smaller models of limited spatial and temporal extents, stream temperature can sometimes be obtained from existing temperature gages. More often, as is the case for the Raritan River Basin Model, stream temperatures must be estimated (or simulated separately) and supplied to the model.

None of the active USGS stations in the Raritan River Basin records stream temperature. As a result, linear correlations between measured air and stream temperatures were used to generate stream temperatures for all the streams in the Raritan River Basin Model. A methodology to obtain continuous stream temperature records was developed for the Raritan River Basin Model. The methodology consists of deriving linear regressions using stream temperature records obtained during diurnal monitoring events at various locations and continuous air temperature measurements from weather stations. Continuous stream temperature measurements were collected at various sampling locations with a 5-minute interval during the diurnal monitoring events conducted by Kleinfelder/Omni. Hourly measurements of air temperatures were obtained from weather stations maintained by National Climatic Data Center (NCDC) in the Raritan River Basin. Note that the weather stations used to obtain air temperatures are different than those used to supply precipitation data for the hydrologic model. These data are independent, and no conflict is presented by using separate data sources for precipitation and air temperature.

NCDC has five weather stations either inside or next to the Raritan River Basin in Somerset, Trenton, Newark, Morristown and Sussex. Of these five weather stations, only Somerset and Trenton lie within the Raritan River Basin. Weather data from 2002 through 2005 were obtained for all these stations when available. Only Newark and Morristown weather stations had records for the entire time period. Somerset, Trenton and Sussex weather stations had data only for the years 2004 and 2005. The presence of gaps in the air temperature records are the norm for most of the stations. The only exception is the Newark station, which has continuous hourly records from 2002 through 2005. The gaps in temperature records were filled by correlating the existing records with gaps and the continuous records at Newark's weather station. The correlation was then used to extrapolate the missing data as a function of Newark's records.

The timeframe of existing stream temperature records collected by Kleinfelder/Omni varies according to the watershed area model. For North/South Branch, Upper Millstone and Mainstem, temperature records are available for the diurnal sampling events performed during the summer and fall of 2004, and summer of 2005. For the Stony Brook and Beden Brook/Lower Millstone watersheds model areas, temperature records are available for the diurnal sampling events performed in the summer and fall of 2003. These data were sufficient to characterize stream temperatures throughout the study areas adequately.

The NCDC continuous temperature records for all the five weather stations and the stream temperature collected by Kleinfelder/Omni at various sampling stations within the Raritan River Basin were correlated. As a result of these correlations, five stream temperature time series per sampling station were obtained, one for each weather station. These multiple time series provided a basis for selecting the most representative weather station to be assigned to a particular sampling location. Only one weather station can be assigned to a sampling station. The weather stations were assigned to sampling locations based on the coefficient of determination (R^2) and the geographical proximity of the weather station to the sampling location. For example, the weather station within the Raritan River basin was given preference over the weather station outside the basin if their R^2 values are similar.

Table 13 summarizes the sampling locations in the Raritan basin with assigned weather stations and the corresponding correlation coefficients. The continuous hourly temperatures measured at most of the sampling locations correlate very well with the air temperature data from the assigned weather station.

Although stream temperature regressions were derived for all sampling stations with diurnal data within the Raritan River Basin Model, the number of temperature time series that can be used in WASP7.1 is limited to a maximum of four temperature time series per watershed area model. Therefore, not all the individual time series derived for each sampling station could be used directly in the model. Instead, a few temperature series were selected as index stations, and all other locations were assigned to an index station (also shown in Table 13).

Table 13: Temperature Correlations and Index Assignments

Watershed Area Model	Assigned Weather Data	Temperature Index	Sampling Station	R^2
North & South Branch	Somerset	NSBTS-1 (SBRR2) Somerset $R^2 = 0.77$	BvB1	0.76
	Somerset		CC1	0.81
	Somerset		DkB1	0.75
	Somerset		LR1	0.77
	Somerset		LR2	0.82
	Somerset		LR3	0.78
	Somerset		LR4	0.77
	Somerset		LR4U	0.90
	Somerset		NBRC1	0.75
	Somerset		NBRR1	0.79
	Somerset		SBR4	0.79
	Somerset	NSBTS-2 (NBRR6) Somerset $R^2 = 0.73$	LR5	0.77
	Newark		NBRR3-RL	0.71
	Somerset		NBRR5	0.65
	Somerset		NBRR7	0.60
	Newark		RC1	0.72
	Somerset		SBRR4-SL	0.68
	Somerset		SBRR6	0.72
	Somerset		SBRR7	0.73
	Somerset		SBRR8	0.76
	Somerset	NSBTS-3 (SBRR10) Somerset $R^2 = 0.63$	NR1	0.75
	Somerset		NR2	0.69
	Newark		RR1	0.72
	Somerset		SBRR9	0.65
Upper Millstone	Trenton	UMTS (UMR2) $R^2 = 0.90$	RB4	0.86
	Trenton		UMR1	0.91
	Trenton		UMR3	0.89
Stony Brook	Trenton	SBTS (SB2) $R^2 = 0.86$	SB1	0.57
	Trenton		SB3	0.55
Beden Brook / Lower Millstone	Trenton	BBLM-1 (BB2) $R^2 = 0.90$	BB1	0.69
	Trenton		BB3	0.56
	Trenton	BBLM-2 (M4) $R^2 = 0.79$	M2	0.41
	Trenton		M7	0.26
Mainstem	Somerset	NSBTS-1	GB1	0.61
	Trenton	MSTS-1 (R4) $R^2 = 0.81$	R2	0.35
	Trenton		R3	0.41

Appendix G shows comparisons between assumed temperature inputs and measured temperature at sampling locations with diurnal measurements. For all temperature time series used in the model (i.e. at the index station locations), actual measured temperature was used during periods when diurnal measurements were available.

b. Solar Radiation Time Series

Diurnal solar radiation time series are necessary in order to simulate the diurnal dissolved oxygen variation in the stream. Solar radiation records were obtained from two sources: Rutgers University solar radiation station located at Cook Campus in New Brunswick, New Jersey, and from solar radiation gages deployed by Kleinfelder/Omni during diurnal sampling events at various locations within the Raritan River Basin. Solar radiation records were available for almost the entire simulation period. When records were not available, average values during the same time for other years were used to fill in the missing data.

Hourly solar radiation records are available from Rutgers for most of the modeling simulations period (January 2002 through August 2005). Due to WASP7.1's constraints, most of the hourly solar radiation data had to be averaged within a 3-hour time step. WASP7.1 can handle a maximum of 4,000 records for each time series. If hourly data were used for the entire year, more than 8,000 records would be necessary. The Kleinfelder/Omni solar radiation gages were deployed only during the diurnal sampling events in 2004 and 2005. Kleinfelder/Omni solar radiation data consists of fifteen-minute records of solar radiation. These fifteen-minute records were averaged to hourly records.

The solar radiation data from the Rutgers station forms the core of the solar radiation time series for WASP7.1 due to its continuous record for most of the modeling timeframe. In order to take into account spatial variation of solar radiation and provide the most direct measured values during calibration and validation periods, the Rutgers solar radiation records were substituted during the times of the diurnal sampling events by the hourly averaged Kleinfelder/Omni data. Table 14 shows the time periods and the locations when the Kleinfelder/Omni solar radiation data were used to replace the Rutgers solar radiation series.

Table 14: Localized Solar Radiation Series

Start Date	End Date	Location	NSBranch	Mainstem	BBLowerMills	Stony	UpperMills
6/19/2004	7/2/2004	UWPM			x	x	x
7/2/2004	7/13/2004	UWPM			x	x	x
8/5/2004	8/18/2004	RLSA	x				
9/2/2004	9/9/2004	UWPM			x	x	x
10/28/2004	11/2/2004	WTMUA	x				
11/2/2004	11/9/2004	RLSA	x				
11/9/2004	11/16/2004	UWPM			x	x	x
11/17/2004	11/17/2004	WMUA					x
7/29/2005	8/9/2005	Clinton	x				

c. Phosphorus and Ammonia Sediment Flux

Time series of orthophosphate and ammonia flux were used as needed to represent the effects of processes that occur in the sediment layer that are not explicitly simulated by WASP7.1. Sediment diagenesis (chemical, physical, or biological changes undergone by sediment after its initial deposition) is not currently implemented within WASP7.1. The flux of orthophosphate and ammonia were implemented only for the lower Stony Brook, because the data at SB4 indicated an increase in load that is likely attributable to the sediment. This area is influenced by Carnegie Lake and the inclusion of the sediment nutrient flux was necessary for calibration. Specific details about the times and the values are provided in the model calibration section. The fact that sediment flux was not required to explain observed nutrient concentrations anywhere else demonstrates that explicitly modeling processes within the sediment was not justified.

11. WASP7.1 Kinetic Parameters

The kinetic parameters used in WASP7.1 are a function of the systems that are simulated. In the case of the Raritan River Basin Model, the simulated systems are ammonia, nitrate, organic nitrogen, orthophosphate, organic phosphorus, chlorophyll, dissolved oxygen, CBOD, benthic algae, periphyton cell quotas of nitrogen and phosphorus, detritus, and solids.

Kinetic parameters are global, meaning they affect all compartments of the system and do not change in space and time. Although their value is fixed in space and time, they are often assigned temperature correction coefficients. As each watershed area model has an independent WASP7.1 model setup, the kinetic parameters may change according to the particular characteristics of a watershed area model; in general, most parameters are the same across all watershed area models. However, more sensitive parameters such as nitrification rate, growth rate of phytoplankton and benthic algae, respiration and death rates were assigned different values.

Most kinetic parameters are subject to calibration. A range of values is generally available in the literature. Most of the processes simulated by WASP7.1 and their associated parameters are well-documented. The benthic algae system with luxury uptake is an exception. A limited number of models adopt the Droop method to simulate nutrient limitation and algae growth with a compartment and dynamic framework. In fact, WASP7.1 seems to be the only model available in the public domain that combines all these conditions. A public domain steady-state model that adopts the Droop method is Qual2K 2.04 (Chapra et al., 2006). The application of the Droop method in Qual2K 2.04 is also recent. Literature values are not available for the parameters of the periphyton algorithm.

Although most kinetic parameters are subject to change during calibration, parameters that establish the stoichiometric composition of organic matter were fixed. Stoichiometric composition was calculated using compositions idealized by Redfield et al. (1963), and Stumm and Morgan (1981). The dry-weight composition can be idealized as the following detailed representation of the photosynthesis/respiration process:

$$106CO_2 + 16NH_4^{\ +} + HPO_4^{\ 2-} + 108H_2O \Leftrightarrow \underbrace{C_{106}H_{263}O_{110}N_{16}P_1}_{Algae} + 107O_2 + 14H^+$$

The stoichiometric parameters used for the Raritan TMDL are below:

- mgN/mgC : 0.18
- mgP/mgC: 0.025
- mgO/mgC: 2.69
- mgDry/mgC: 2.5

Global kinetic parameters for each watershed area model are provided in Table 15. All of the kinetic parameters used fall within the normal literature ranges. Nitrification rates were calculated directly using data downstream of WWTP discharges.

Table 15: WASP7.1 Global Kinetic Parameters for each Watershed Area Model

Parameter	NSBranch	UpperMills	Stony	BBLowerMills	Mainstem	Literature Values	
						Minimum	Maximum
Nitrification Rate Constant @20ºC (per day)	5	2.5	1	1	1	1	10
Nitrification Temperature Coefficient	1.07	1.07	1.07	1.07	1.07	1	1.08
Half Saturation Constant for Nitrification Oxygen Limit (mg O/L)	1	1	1	1	1	0	2
Diss. Organic N Mineralization Rate Constant @20ºC (per day)	0.02	0.02	0.02	0.02	0.02	0	1.08
Diss. Organic Nitrogen Mineralization Temperature Coefficient	1.07	1.07	1.07	1.07	1.07	1	1.08
Fraction of Phytoplankton Death Recycled to Organic Nitrogen	0.5	0.5	0.5	0.5	0.5	0	1
Mineralization Rate Constant for Diss. Org. P @20ºC (per day)	0.2	0.2	0.1	0.2	0.2	0	0.22
Diss. Organic P Mineralization Temperature Coefficient	1.07	1.07	1.07	1.07	1.07	0	1.08
Fraction of Phytoplankton Death Recycled to Organic P	0.5	0.5	0.5	0.5	0.5	0	1
Phytoplankton Max. Growth Rate Constant @20ºC (per day)	1.85	1.25	1	0.75	1.85	0	3
Phytoplankton Growth Temperature Coefficient	1.068	1.068	1.068	1.068	1.068	1	1.07
Algal Self Shading Light Extinction in Steele (0=Yes, 1=No)	0	0	0	0	0	-	-
Phytoplankton Carbon to Chlorophyll Ratio	40	40	40	40	40	0	200
Phytoplankton Half-Saturation Constant for N Uptake (mg N/L)	0.025	0.025	0.025	0.025	0.025	0	0.05
Phytoplankton Half-Saturation Constant for P Uptake (mg P/L)	0.0025	0.0025	0.003	0.0025	0.0025	0	0.05
Phyto Endogenous Respiration Rate Constant @20ºC (per day)	0.15	0.15	0.15	0.15	0.15	0	0.5
Phytoplankton Respiration Temperature Coefficient	1.068	1.068	1.068	1.068	1.068	1	1.08
Phytoplankton Death Rate Constant (per day)	0.1	0.1	0.1	0.1	0.1	0	0.25
Nutrient Limitation Option (1= nutrient limitation active)	1	1	1	1	1	-	-
Phytoplankton Phosphorus to Carbon Ratio	0.025	0.025	0.025	0.025	0.025	0	0.24
Phytoplankton Nitrogen to Carbon Ratio	0.18	0.18	0.18	0.18	0.18	0	0.43
Phytoplankton Half-Sat. for Recycle of N and P (mg Phyt C/L)	0.5	0.5	0.5	0.5	0.5	0	1
Phytoplankton Light Formulation Switch (1=Steele, 2=Smith)	1	1	1	1	1	-	-
Phytoplankton Maximum Quantum Yield Constant	720	720	720	720	720	0	720
Phytoplankton Optimal Light Saturation	350	350	350	350	350	0	350
Benthic Algae D:C Ratio (mg Dry Weight/mg C)	2.5	2.5	2.5	2.5	2.5		
Benthic Algae N:C Ratio (mg N/mg C)	0.18	0.18	0.18	0.18	0.18		
Benthic Algae P:C Ratio (mg P/mg C)	0.025	0.025	0.025	0.025	0.025		
Benthic Algae Chl a:C Ratio (mg Chlorophyll a / mg C)	0.025	0.025	0.025	0.025	0.025	0	0.05
Benthic Algae O2:C Production (mg O2/mg C)	2.69	2.69	2.69	2.69	2.69		
Benthic Algae Max Growth Rate (gD/m2/d)	25	25	25	25	25	10	100
Temp Coefficient for Benthic Algal Growth	1.07	1.07	1.07	1.07	1.07	1	1.08
Respiration Rate (1/day)	0.1	0.1	0.1	0.1	0.1	0.05	0.2
Temperature Coefficient for Benthic Algal Respiration	1.07	1.07	1.07	1.07	1.07	1	1.08
Internal Nutrient Excretion Rate for Benthic Algae (1/day)	0.01	0.01	0.01	0.01	0.01	0	10
Temperature Coefficient for Benthic Algal Nutrient Excretion	1.07	1.07	1.07	1.07	1.07	1	1.1
Death Rate (1/day)	0.01	0.01	0.01	0.01	0.01	0.01	0.5
Temperature Coefficient for Benthic Algal Death	1.07	1.07	1.07	1.07	1.07	1	1.08
Half Saturation Uptake Constant for Extracellular N (mg N/L)	0.02	0.02	0.02	0.02	0.02	0.015	0.1
Half Saturation Uptake Constant for Extracellular P (mg P/L)	0.005	0.005	0.005	0.005	0.005	0.0025	0.08
LIGHT OPTION, 1=Half saturation, 2=SMITH, 3= STEELE	2	2	2	2	2	-	-
Light Constant for growth (langleys/day)	100	100	100	100	100	0	350
Benthic Algae ammonia preference (mg N/L)	0.025	0.025	0.025	0.025	0.025	0	0.5
Minimum Cell Quota of Internal Nitrogen for Growth (mgN/gDW)	26.6	26.6	26.6	26.6	26.6	0	1000
Minimum Cell Quota of Internal P for Growth (mgP/gDW)	3.7	3.7	3.7	3.7	3.7	0	1000
Maximum N Uptake Rate for Benthic Algae (mgN/gDW-day)	38.3	38.3	38.3	38.3	38.3	1	100
Maximum P Uptake Rate for Benthic Algae (mgP/gDW-day)	1.86	1.86	1.86	1.86	1.86	1	10
Half Saturation Uptake Constant for Intracellular N (mgN/gDW)	44.4	44.4	44.4	44.4	44.4	0	1000
Half Saturation Uptake Constant for Intracellular P (mgP/gDW)	7.4	7.4	7.4	7.4	7.4	0	1000
Calc Reaeration Option (0=Covar,4=Tsivoglou)	4	4	4	4	0	-	-
Theta -- Reaeration Temperature Correction	1.024	1.024	1.024	1.024	1.024	1	1.03
Oxygen to Carbon Stoichiometric Ratio	2.69	2.69	2.69	2.69	2.69	-	-
BOD (1) Decay Rate Constant @20ºC (per day)	0.5	0.5	0.5	0.5	0.5	0	5.6
BOD (1) Decay Rate Temperature Correction Coefficient	1.04	1.04	1.04	1.04	1.04	1	1.07
BOD (1) Half Saturation Oxygen Limit (mg O/L)	0.5	0.5	0.5	0.5	0.5	0	0.5
Detritus Dissolution Rate (1/day)	0.01	0.01	0.01	0.01	0.01	0	1
Temperature Correction for detritus dissolution	1.07	1.07	1.07	1.07	1.07	1	1.08

12. WASP7.1 Descriptive Parameters

Descriptive parameters in WASP7.1 are assigned for each model segment. They can define a time series function that corresponds to a particular segment, such as temperature, or specify local constants, such as SOD and the fraction of segment bottom covered with benthic algae (or aquatic plants). The descriptive parameters used for the Raritan River Basin Model are discussed below.

a. Temperature Time Series Identifiers

The stream water temperature time functions need to be assigned to a segment of the stream network through an identifier. This identifier is the descriptive local parameter assigned to a model segment. Temperature time series are assigned according to the sampling station and stream category they represent. Table 16 shows the temperature time series indexes and their respective identifiers. Recall that the index station assignments are shown in Table 13.

Table 16: WASP7.1 Stream Temperature Time Series Identifier

Temperature Time Series	Identifier
NSBTS-1	1
NSBTS-2	2
NSBTS-3	3
MSTS-1	1
MSTS-2	2
MSTS-3	3
BBLM-1	1
BBLM-2	2
UMTS	1
SBTS	1

b. Temperature Correction Multipliers

The number of temperature time series that can be assigned to WASP7.1 stream network is limited. Therefore, temperature correction multipliers were defined for each segment to scale their respective temperature time series index. Stream temperature varies spatially according to a number of factors, such as canopy cover, stream depth and width. The temperature correction multipliers adjust the index temperature time series to a particular location of the stream network.

Once the temperature series are assigned to a group of segments, the stream temperature correction multipliers are obtained. The temperature correction multipliers are calculated by dividing the average of the measured stream temperature data at a given location by the average temperature of its respective temperature time series during the same time periods. The list of sampling locations with their respective temperature correction factors is given below in Table 17.

Table 17: Temperature Correction Factors

Watershed Area Model	Station	Temperature Correction Factor
NSBranch	BvB1	1
NSBranch	CC1	0.92
NSBranch	DkB1	1.08
NSBranch	LR1	1.12
NSBranch	LR2	1.1
NSBranch	LR3	1.02
NSBranch	LR4	1.06
NSBranch	NBRC1	1.04
NSBranch	NBRR1	0.97
NSBranch	NR1	1.12
NSBranch	NR2	1.08
NSBranch	SBRR2	1
NSBranch	LR4U	1.18
NSBranch	NBRR5	0.98
NSBranch	NBRR6	1
NSBranch	RC1	1.02
NSBranch	SBRR6	1.02
NSBranch	SBRR7	1.01
NSBranch	SBRR8	1.05
NSBranch	NBRR3 RL	1
NSBranch	SBRR4 SL	1
NSBranch	SBRC2 CL	1.05
NSBranch	NBRR7	1.09
NSBranch	RR1	1.05
NSBranch	SBRR9	1
NSBranch	SBRR10	1.05
UpperMills	BBB2-GMP	1.08

Table 17: Temperature Correction Factors

Watershed Area Model	Station	Temperature Correction Factor
UpperMills	CB2-PP	1.05
UpperMills	DB2-GP	1.1
UpperMills	RB4	1
UpperMills	UMR1	1
UpperMills	UMR2	1
UpperMills	UMR3	1
Stony	SB1	1
Stony	SB2	1
Stony	SB3	1.08
BBLowerMills	BB1	0.96
BBLowerMills	BB2	1
BBLowerMills	BB3	1.02
BBLowerMills	M2	1.02
BBLowerMills	M4	1
BBLowerMills	M7	1
Mainstem	R2	1
Mainstem	R3	1.03
Mainstem	R4	1
Mainstem	GB1	1.05

c. Light Extinction Coefficients

Light extinction coefficients are important parameters for the Raritan River Basin Model. Diurnal DO variations occur mostly due to photosynthesis by periphyton and macrophytes attached to substrate at the stream bottom. Light extinction influences photosynthesis by directly impacting the amount of light reaching the stream bottom thereby influencing the diurnal DO variations. Light extinction coefficients were derived based on light extinction measurements performed at Kleinfelder/Omni sampling stations during the summer of 2003, 2004 and 2005.

Light extinction data collected by Kleinfelder/Omni consists of the available light in the water column at several depths taken at a given location. The light extinction coefficients were derived by calculating the slope of the linear regression between the natural log of the measured light availability (I) at depth (d), and the respective depth in meters. The slope, or the light extinction coefficient, is the rate of change along the regression line. This method is analogous to the Beer-Lambert law, which models light extinction as an exponential decay. The light extinction coefficient (*k*) (m^{-1}) is given by Equation 6.

$$k = \frac{\sum (d - \bar{d})\left(\ln\left(\frac{I_d}{\bar{I}}\right)\right)}{\sum (d - \bar{d})^2} \qquad (6)$$

Light extinction measurements were taken at water quality sampling stations throughout the Raritan River Basin. More than one measurement was usually performed at each station. A total of 103 light extinction measurements were performed for the Raritan River Basin Model. When multiple measurements were available for the same station, an average *k* was calculated. Table 18 shows the values of *k* obtained for all the measurements and relevant sampling stations.

As the *k* values are derived only at sampling stations, they need to be generalized throughout the stream network. The *k* values of the stream network segments are assigned based on their location and proximity to a sampling station. For example, when only one station is available in a branch, all the segments of that branch have the same *k* as their respective sampling station. When multiple stations are available in a branch, the *k* values for the segments between consecutive sampling stations are interpolated.

Table 18: Light Extinction (K) Values Derived from 2003 to 2005 Measurements (m^{-1})

2003 events		2004 events					2005 events		
Station	July	June	July	August	September	October	August	October	Average K
BuB1				11.19					11.19
LR1				10.92		2.45	6.88		6.75
LR2				1.69		1.87	1.72		1.76
LR3				1.76		1.96	1.92		1.88
LR4				1.03		2.44	1.33		1.60
LR5				2.37		1.85	2.33		2.18
NBRC1				3.51		1.11			2.31
NBRR1				3.57			2.20		2.88
NBRR2-RLi				1.75					1.75
NBRR3-RL				1.63		2.06	1.69	1.99	1.84
NBRR4-Rlo				3.26					3.26
NBRR5				1.85		1.80	1.11		1.59
NBRR6				1.30		1.36	1.24		1.30
NBRR7				0.04		3.72	1.31		1.69
RC1				0.98		1.18	1.16		1.11
SBRC2-CL				4.40		2.47	2.97	2.06	2.97
SBRC3-CLo				1.32					1.32
BvB1				1.51		1.85	2.97		2.11
CC1				1.08		0.72			0.90
DkB1				1.41		2.27	1.65		1.78
NR1				3.88		2.28	2.40		2.85
NR2				2.09		1.35	1.38		1.60
SBR4				3.32					3.32
SBRR10				2.27		2.98	1.92		2.39
SBRR2				6.09		1.71			3.90
SBRR4-SL				1.90		1.62	2.01	1.66	1.79
SBRR5-Slo				1.12					1.12
SBRR6				1.95		1.26	1.84		1.68
SBRR7				0.68		1.31	2.08		1.36
SBRR8				0.93		0.66	1.51		1.03
SBRR9				1.48		2.14	1.86		1.83
RR1				0.82		1.67	1.09		1.19
R4				1.32					1.32
GB1				3.02		3.30	4.68		3.67
SMR1			4.27		1.59				2.93
CB2-PP					2.30				2.30
DB2-GP					5.19				5.19
RB2-PL					1.80				1.80
RB4		4.52				5.57			5.04
UMR1			2.45		2.21				2.33
UMR2			1.41		2.08				1.75
UMR3			3.92		2.12				3.02
BB3	2.7								2.70
M5	3.68								3.68
M6	1.7								1.70

Recent light extinction measurements taken in 2003, 2004 and 2005 were available only for the lower Millstone River and the North/South Branch, Upper Millstone, and Mainstem watershed area models. Light extinction data for the Stony Brook, Beden Brook and Pike Run were obtained from historical measurements made by Kleinfelder/Omni in 1994. Table 19 shows the *k* values obtained using historical light extinction data.

Table 19: Light Extinction (K) Values Derived from Historical Measurements

Station	K (m^{-1})
BBu	2.55
BB1	1.75
BB3	0.75
BB2	0.88
SBu	11.28
SB3	4.79
SB2	3.46
SB1	3.20

d. Dissolved fraction of water constituents

The dissolved fraction of a water constituent determines the mass fraction that is not subject to settling. WASP7.1 does not model the phenomena of adsorption and desorption of compounds to or from the particulate material. Thus, the fraction of the substances that is not attached to the particulate material is given by the dissolved fraction. The dissolved fraction is a constant value assigned to a segment of the stream network, and it is obtained exclusively through calibration.

Dissolved fraction varies from zero to one. A dissolved fraction of one implies the constituent is completely present in dissolved form. Only constituents that are subject to settling should have a dissolved fraction value that is less than one. A dissolved fraction of zero means the constituent is found completely in the particulate form. In the case of the Raritan River Basin Model, the constituents that are subject to settling are solids, organic phosphorus and nitrate. In WASP7.1, solids are considered to be 100% particulate by default. The dissolved fractions of organic phosphorus and nitrate were calibrated for each segment.

The dissolved fraction of organic phosphorus plays an important role in the calibration. Organic phosphorus is highly reactive, and can get easily adsorbed into sediment. Dissolved fractions of organic phosphorus had to be calibrated for almost all model segments of the North/South Branch, Upper Millstone, Beden Brook/Lower Millstone and Stony Brook. Unlike organic phosphorus, nitrate is soluble in water and normally does not get adsorbed into the sediment. However, the dissolved fraction of nitrate was used to associate a settling rate with a fraction of the nitrate in order to capture the extra nitrate removal that occurs in the marshy area in the Lamington River (near LR3). Details about how the dissolved fraction of organic phosphorus and nitrate were obtained, and the values used for the model are presented in the calibration section of this report.

e. Settling Velocity

Settling functions define the settling velocity that is assigned to a group of segments. Although settling velocity could assume time varying values, the settling velocity is assumed constant in time for the Raritan River Basin Model. Settling velocity is one of the factors that influences the amount of particulate material that is removed from the water column. The actual settling depends on the settling velocity, stream depth, fraction dissolved and the stream velocity.

The settling velocity was obtained exclusively through calibration of OrgP and TSS; in many cases, zero settling achieved an acceptable calibration. The number of settling functions defined for the stream network varies according to the watershed area model. Settling was defined for the North/South Branch, Upper Millstone, Beden Brook/Lower Millstone, and Stony Brook watershed area models. The Mainstem model area did not require settling. Appendix H shows the spatial distribution of settling velocities within the stream network of each watershed area model.

f. Sediment Oxygen Demand

Sediment oxygen demand (SOD) is not explicitly simulated by WASP7.1. In order to account for the effect of SOD, WASP7.1 utilizes a constant SOD value assigned to each segment. This SOD value represents the typical SOD when stream temperature is 20°C. A temperature correction coefficient is provided and the actual SOD used in the calculations is a function of the stream temperature and the temperature correction factor.

SOD is generally determined through calibration, although SOD measurements were performed by Kleinfelder/Omni at some locations in the Raritan River Basin in 2004. SOD data also exists for multiple historical studies performed by Kleinfelder/Omni. Recent SOD measurements, where available, were used as a basis to assign initial SOD values to each segment of the stream network. However, because SOD can vary significantly, the initial values are adjusted and final SOD values are defined through calibration.

In general, SOD values throughout the Raritan River Basin are very low. There are exceptions, mostly in the upper Millstone and lower Millstone Rivers. SOD is an important calibration parameter since it can directly affect DO levels in the stream. The measured SOD and final values adopted for the Raritan Basin are discussed in the DO calibration section of this report. Appendix H shows the spatial distribution of SOD within the stream network of each watershed area model.

g. *Benthic Algae Fraction*

Benthic algae fraction, or "percent of bottom segment covered by benthic algae," is a representation of the amount of periphyton and plants that are attached to the stream bottom. The benthic algae fraction varies spatially and is determined only through calibration. Measurements of this parameter are not available. As the model uses this parameter as indication of both the total amount of periphyton and other attached aquatic plants, it would be difficult to obtain a meaningful measured value. More about this important calibration parameter is discussed in the DO calibration section of this report. Appendix H shows the spatial distribution of benthic algae fraction within the stream network of each watershed area model.

h. *Reaeration coefficients*

Stream reaeration can significantly impact the levels of dissolved oxygen in the stream. Factors that can influence stream reaeration are temperature, slope, stream depth and velocity. Many formulas have been developed for predicting reaeration in natural waters. Their applicability generally varies according to the type of the stream and the normal range of velocities and depths. WASP7.1 can calculate reaeration according to four main methods: O'Connor-Dobbins, Owen-Gibbs, Tsivoglou and the Covar method.

Reaeration for the Raritan River Basin Model was calculated using the Tsivoglou formula and the Covar method. The Covar method (Covar, 1976) uses the O'Connor-Dobbins and Owen-Gibbs formulas jointly. It selects the best formula to better represent stream reaeration according to stream depth and stream velocity. WASP7.1 automatically retrieves the stream velocity and the stream depth from the HYD file for each time step to calculate the instantaneous reaeration. The Tsivoglou formula (Tsivoglou and Neal, 1976) uses the slope (*S*), stream velocity (*U*) and the escape coefficient (*C*) to estimate stream reaeration (K_a) (Equation 7).

$$K_a = C \times U \times S \quad (7)$$

The escape coefficient can be measured through tracer method techniques. Historical studies performed by Kleinfelder/Omni using tracer methods techniques to identify the escape coefficient were available for the Beden Brook and Stony Brook (Omni, September 1995a; Omni, September 1995b). Kleinfelder/Omni used a widely accepted technique for determining the reaeration rates that involved introducing Rhodamine dye and a gas tracer (i.e., ethylene) into the streams and measuring the rate at which the gas escapes. Table 20 lists the range of Tsivoglou-Neal escape coefficients calculated by Kleinfelder/Omni for Stony Brook and Beden Brook using the tracer studies conducted in the respective rivers.

Table 20: Tsivoglou-Neal Escape Coefficients for Stony and Beden Brooks

Stream	Tsivoglou-Neal Escape Coefficient
Stony Brook	0.26
Beden Brook	0.18-0.24

The values obtained from these studies were generalized for the Raritan River Basin, meaning values were selected by calibration within this range. The slope of the segment, which is another input for the Tsivoglou method, is entered directly in WASP7.1. The slope is necessary only if the Tsivoglou method is adopted. The same slopes derived for the determination of flows using

HydroWAMIT were entered in WASP7.1. Figures with the values of the escape coefficient and the slope for each segment are provided in Appendix H.

The Covar method and its associated formulas are commonly used. They are applicable to most of conditions encountered in streams. However, it is not necessarily the best predictor for all the flow regimes. In the case of steep streams and rivers, the Tsivoglou method generally provides a better representation of the reaeration. When the Covar method is applied to small and steep streams, such as the ones present in the Raritan River Basin, the reaeration is overestimated during some critical time periods.

The use of the Covar method or the Tsivoglou method for a given watershed area model depends on the predominant characteristics of the streams. The Tsivoglou method was adopted for the North/South Branch, Beden Brook/Lower Millstone, Stony Brook, and Upper Millstone watershed area models. The Covar method was adopted only for the Mainstem watershed area model. More details about the selection of these two approaches to calculate stream reaeration is presented in the calibration section of this report.

i. Dam reaeration coefficients

Dams and waterfalls can have a significant localized impact on dissolved oxygen transfer in streams. The amount of DO reaeration downstream of the falls depends on the height through which water falls, DO deficit upstream of the dam, temperature, type of the dams and water quality conditions. WASP7.1 simulates the effect of dams and waterfall reaeration according to the formulation proposed by Chapra (1997). The most sensitive parameters in this formulation are the DO deficit upstream of the dam, and the height of the waterfall. The remaining parameters have little or no impact in the DO reaeration.

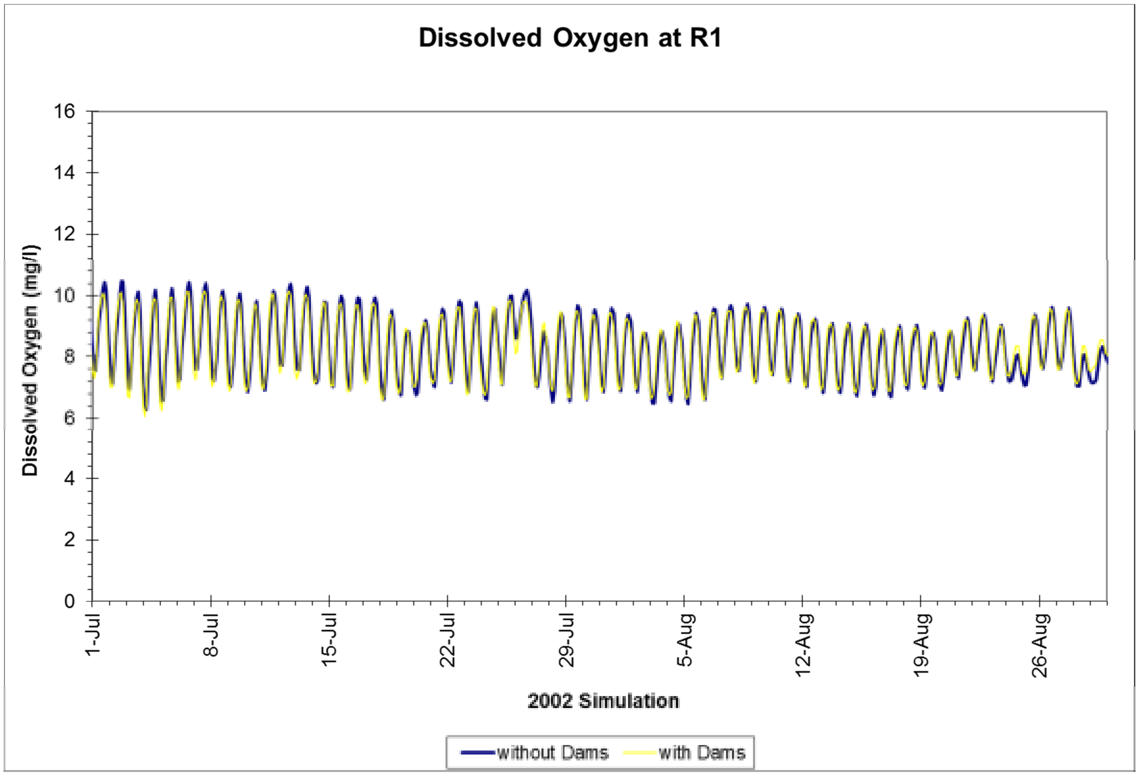
The dams present in the Raritan River Basin were first identified using NJDEP Statewide Dam Coverage shape files. The identified dams on the modeled streams were later verified using the aerial photographs, USGS quad maps and/or field surveys conducted by Kleinfelder/Omni. The NJDEP coverage also provides the dam elevation for most of the dams. Table 21 lists the dams modeled in each of the watershed area models and their corresponding elevations, dam type and water quality coefficients. The streams in the Raritan River Basin are considered to be clean or moderately polluted (water quality coefficient = 1). The dams are assumed to be flat broad-crested regular step (dam type coefficient =0.7).

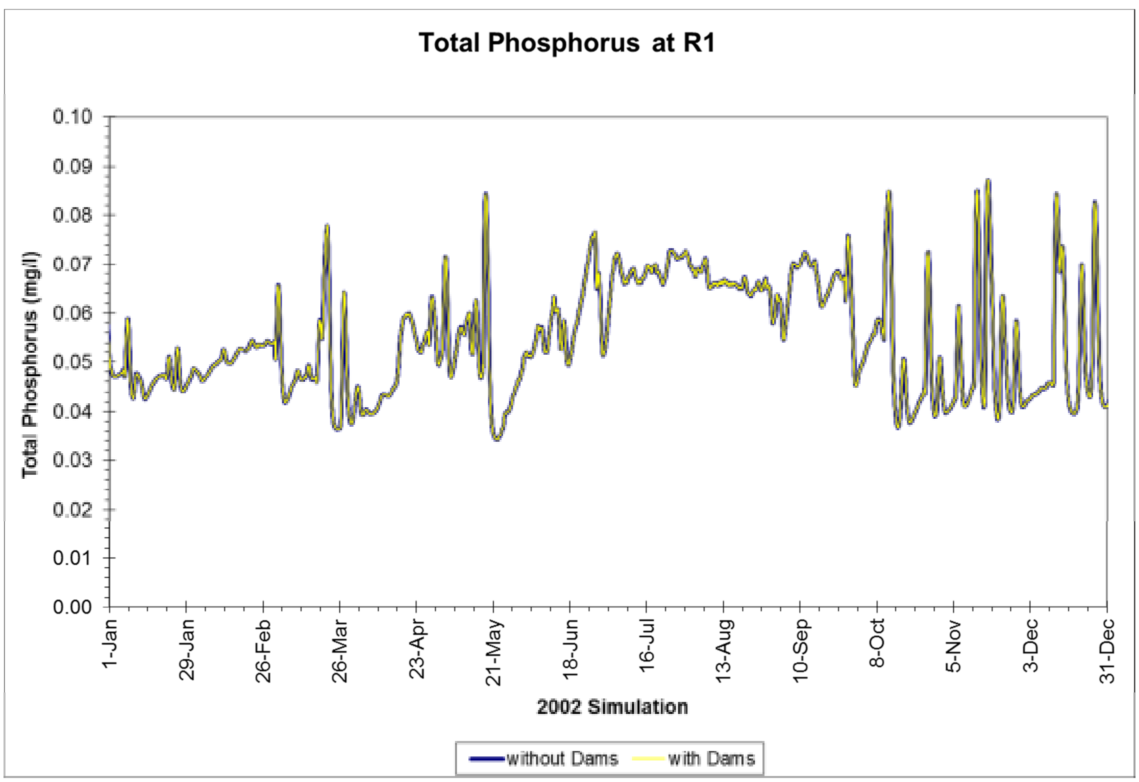
Table 21: Modeled Dam Coefficients

Watershed	Dam Name	Branch Node	Dam Elevation (meters)	Dam Pool Water Quality coefficient	Dam Type coefficient
NSBranch	Nunns Mill Dam	3-1	1.83	1	0.7
	Coles Mill Dam	3-14	3.05	1	0.7
	Lake Solitude Dam	3-19	12.80	1	0.7
	Clinton Mills Dam	3-24	4.21	1	0.7
	Darts Mills Dam	7-9	1.22	1	0.7
	Holcomb Mills Dam	7-10	0.91	1	0.7
	Rockafellow's Mills Dam	7-12	2.50	1	0.7
	Higgins Mills Dam	7-16	1.83	1	0.7
	Amerman Mills Dam	9-2	1.83	1	0.7
	Chester Lake Dam	12-7	7.32	1	0.7
	Milltown Bridge Dam	12-8	3.51	1	0.7
	Pottersville Mill Dam	12-12	1.83	1	0.7
	Vliettown Dam	12-15	2.90	1	0.7
	Ravine Lake Dam	19-7	13.84	1	0.7
	Headgates Dam	23-1	3.05	1	0.7
	Robert Street Dam	23-3	3.51	1	0.7
	Duke Farms Dam	23-4	2.13	1	0.7
Stony	Stony Brook at Princeton	1-21	0.61	1	0.7
BBLowerMills	Bridge Point Mill Dam	2-8	1.77	1	0.7
	Blackwells Mills	5-12	6.58	1	0.7
	Weston Mills Dam	5-18	3.28	1	0.7
Mainstem	NJWSA Water Supply Dam	3-1	1	1	0.7
	Calco Dam	3-4	0.98	1	0.7

Since the TMDL model and analyses were completed, three of these dams have been removed: Robert Street Dam, Duke Farms Dam (a.k.a Nevius Street Dam), and Calco Dam. Kleinfelder/Omni performed additional simulations, which demonstrate that the impact of the dam removals on phosphorus and dissolved oxygen is localized, and is negligible with respect to TMDL analyses (Figure 17).

Figure 17: DO and TP at R1 With and Without Upstream Dams





E. Model Tests

Model tests are important to guarantee stable simulations, to check assumptions made for stream network, and to verify aspects of the modeling framework. The primary tests performed for the Raritan River Basin Model include hydraulic stability and pollutant dilution and transport.

The hydraulic stability tests consisted of performing WASP7.1 simulations for each watershed group using their respective hydrodynamic files and constant boundary concentrations of a conservative substance. This test is critical to show possible instabilities due to time step and potential problems with the stream network configuration. In order to perform this test, the HYD files for each watershed group were input to WASP7.1, and a constant concentration of 1 mg/l is assigned to all boundaries, including NPS inputs. No kinetic parameters are used, so that only the transport and dilution are simulated.

A successful test results in concentrations that converge to 1 mg/l and remain constant with very small fluctuations for all model segments. Fluctuations in the concentrations occur unless an extremely small time step is used. Fluctuations are in the order of 0.001 mg/l and they do not represent instabilities. The hydraulic tests were performed for all the watershed area models defined for the Raritan River Basin Model. None of them presented instabilities or significant levels of fluctuation that would lead to inaccurate simulations.

In addition to the hydraulic stability test, total dissolved solids (TDS), a conservative substance, was simulated and compared to sampled data in the stream. The purpose of this test is to verify if the stream network is compatible with the scale of the longitudinal dispersion and dilution within the segments. The effect of longitudinal dispersion and dilution are more critical when the stream network presents long segments. Thus, TDS was simulated for the North/South Branch watershed group, which presents the highest average segment length.

As TDS is a conservative substance, the results of the simulations were not subject to calibration. TDS EMCs and BFCs derived for the subwatersheds as described previously were used. Point source concentrations of TDS were linearly interpolated when there was not enough data for the simulated year, and average values were assumed for the years without measured data from the dischargers. TDS simulation graphs are presented in Appendix I. The TDS simulations demonstrate that the stream network segmentation, selected time step, and the volume of the segments provide meaningful simulations. Predicted concentrations of TDS indicate that the scale of the segment volumes is valid, and that numerical dispersion is not affecting the simulations. In addition, the TDS simulations show that HydroWAMIT provides reasonable inputs of nonpoint source pollutants to the model.

F. Calibration of the Hydrologic Model

Calibration was performed for the hydrologic model. Calibration consists of changing model parameters to optimize the fitness of model outputs with observed data. Observed flow data was available at USGS streamflow gages. Output from the model nodes located near the gages was compared with the respective gage's flows, and statistics were derived to provide a quantitative measure of the model's fitness.

Model calibration is not only based on quantitative criteria. A "weight-of-evidence" approach is becoming the preferred practice for model calibration and validation (USEPA, 2001). According to this approach, there is no single criterion that determines whether a model is calibrated or not. Rather, a set of graphs and statistics should be used to assess the quality of the model results. In addition, models are not expected to be more accurate than observed data. Uncertainty is present in many levels of the modeling process and observed data is certainly one of them.

In order to assess the quality of the simulations, the predicted and observed mean streamflow are compared first. This is a measure of the total volume of water passing through the gage over the entire period of calibration. The mean percent error ([mean observed values – mean predicted values]/mean observed values) is a good statistic for verifying if the overall predicted volume is compatible with the observed. A small percent mean error implies that the predicted volume is very close to the observed. Mean percent errors below 15% are within the gage precision and are acceptable.

Plots of flow over time are an important tool for calibration and validation. They consist of plotting observed and predicted flow over time in the same graph. Flow plots can be prepared on an annual, monthly, daily or hourly time scale. In the case of the Raritan River Basin Model, the time scale of the calibration data was daily and monthly. Monthly plots reveal the seasonal pattern of the flows. It is easier to verify if the model is capturing the overall water budget on monthly plots. Seasonal discrepancies in dry and wet seasons can be captured in the monthly plots. Daily plots provide a finer level of resolution for calibration. By comparing daily observed and predicted flows, the peaks and recessions can be calibrated more accurately.

Correlation between observed and predicted time series is also derived on a monthly and daily time scale. Monthly time scales generally provide better values due to the monthly averaging of the data. The statistics used to compare time series are described below. The relevant formulae and detailed descriptions about the statistics can be found in Reckhow and Chapra (1983) and Stow C.A. et al. (2003).

- AP: average predicted: It measures the average of predicted values.
- AObs: average observed: It measures the average of observed values.
- AE: average error. It measures the size and discrepancy between predicted and observed values.
- R^2: squared correlation coefficient (coefficient of determination) of model predictions and observations. It measures the tendency of the predicted and observed values as they vary together linearly. An r^2 of 1 indicates that the data vary proportionally.
- R: correlation coefficient. It measures the discrepancy of measured and predicted data departing from a 45 degree straight line. An R of 1 indicates that predicted and observed values are identical.
- E_{NS}: Nash-Sutcliffe coefficient. An efficiency of 1 (E_{NS}=1) corresponds to a perfect match of modeled discharge to the observed data. An efficiency of (E_{NS} =0) indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero ($-\infty<E_{NS}<0$) occurs when the observed mean is a better predictor than the model.

In addition to time series plots, flow frequency plots are also valuable for calibration. Frequency plots show the frequency distribution of predicted and observed flows. The comparison of predicted and observed frequency distributions demonstrates how well the overall peaks and recessions are being simulated. If the frequency distributions overlap, the frequency of flows magnitudes is the same.

The combination of the graphs and statistics were used to optimize model calibration. The hydrologic model calibration was performed for a period of almost four years from January 2002 through August 2005 for most gages. This time period was selected because it includes years with wet, dry and average weather conditions. Also, the representation of the flows during these years is critical for the water quality calibration, since most of water quality samples were taken in 2004. An exception to this calibration time frame was the upper Millstone River watershed. Continuous gage measurements were available for this basin only from March 1987 through October 1989. Therefore, March 1987 through October 1989 was selected as the calibration period for the upper Millstone River watershed. Land Use data from NJDEP's 1986 GIS coverage were used for the Upper Millstone hydrologic calibration.

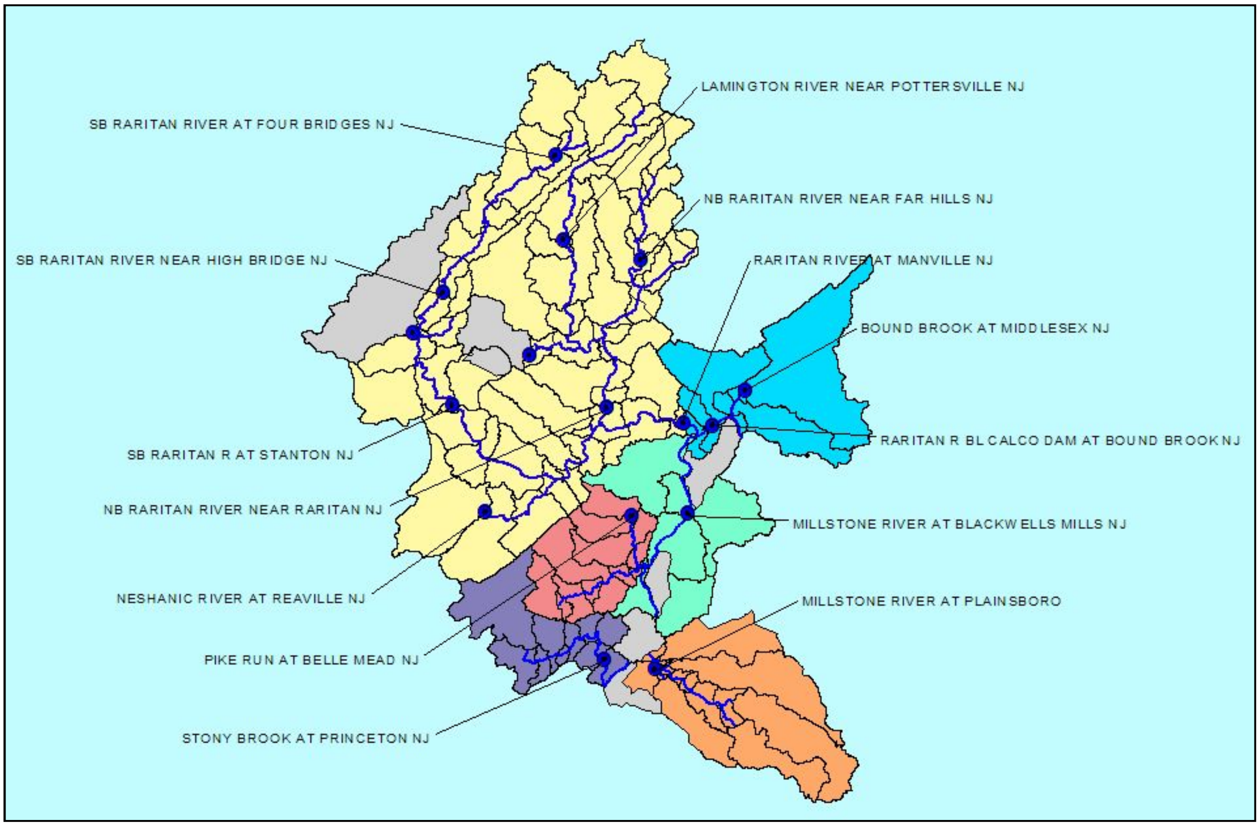
Table 22 shows a summary table containing the time period, weather station, calibration gages, and associated model nodes per watershed area model. Figure 18 shows the flow calibration gage locations.

Table 22: Hydrologic Calibration Stations

Watershed Area Model	Calibration Period	Weather station	Calibration gage	Model Node	Gage name
NSBranch	1/1/2002-08/31/2005	Bound Brook-Sucassuna	01396190	3-2	SB Raritan at Four Bridges
			01396500	3-19	SB Raritan near High Bridge
			01397000	7-7	SB Raritan at Stanton
			01398000	8-1	Neshanic River at Reaville
			01399500	12-12	Lamington R. nr Pottersville
			01398500	19-8	NB Raritan near Far Hills
			01400000	22-8	NB Raritan near Raritan
			01400500	23-8	Raritan at Manville
UpperMills	03/26/1987 - 10/10/1989	Hightstown	01400730	5-1	Millstone River at Plainsboro
Stony	1/1/2002-08/31/2005	Trenton Airport	01401000	1-20	Stony Brook at Princeton
BBLowerMills	1/1/2002-08/31/2005	Bound Brook	01401650	2-1	Pike Run at Belle Mead
			01402000	5-12	Millstone River at Blackwells

Watershed Area Model	Calibration Period	Weather station	Calibration gage	Model Node	Gage name
Mainstem	1/1/2002-08/31/2005	Bound Brook	01403060	3-4	Raritan below Calco Dam
			01403900	5-1	Bound Brook at Middlesex

Figure 18: Flow Calibration Gage Locations



Calibration began by selecting precipitation from a weather station that provides the best model output when compared with streamflow gage data. The weather stations closest to the simulated watershed were selected first and generally provide the best representation for precipitation. The spatial variation of precipitation significantly impacts the model outputs. Streamflow gages for small drainage areas generally provide a worse fit due to the higher dependency on the precipitation records. Streamflow of smaller watersheds are more responsive to localized precipitation. Thus, the representation of precipitation becomes even more critical for smaller watersheds. Air temperature is another weather input, but its spatial variability is not as significant as precipitation. In the case of the Raritan

River Basin Model, the daily air temperature records for the Hightstown NOAA station were used for all areas.

Calibration proceeded by adjusting the fixed sub-watersheds hydrology parameters. The most sensitive fixed sub-watersheds hydrology parameters include unsaturated recession and saturated recession. These two parameters were adjusted first to capture the peaks and recessions. The next calibration process involved adjusting impervious recession, interflow recession, interflow fraction, detention storage, maximum percolation, and deep groundwater loss.

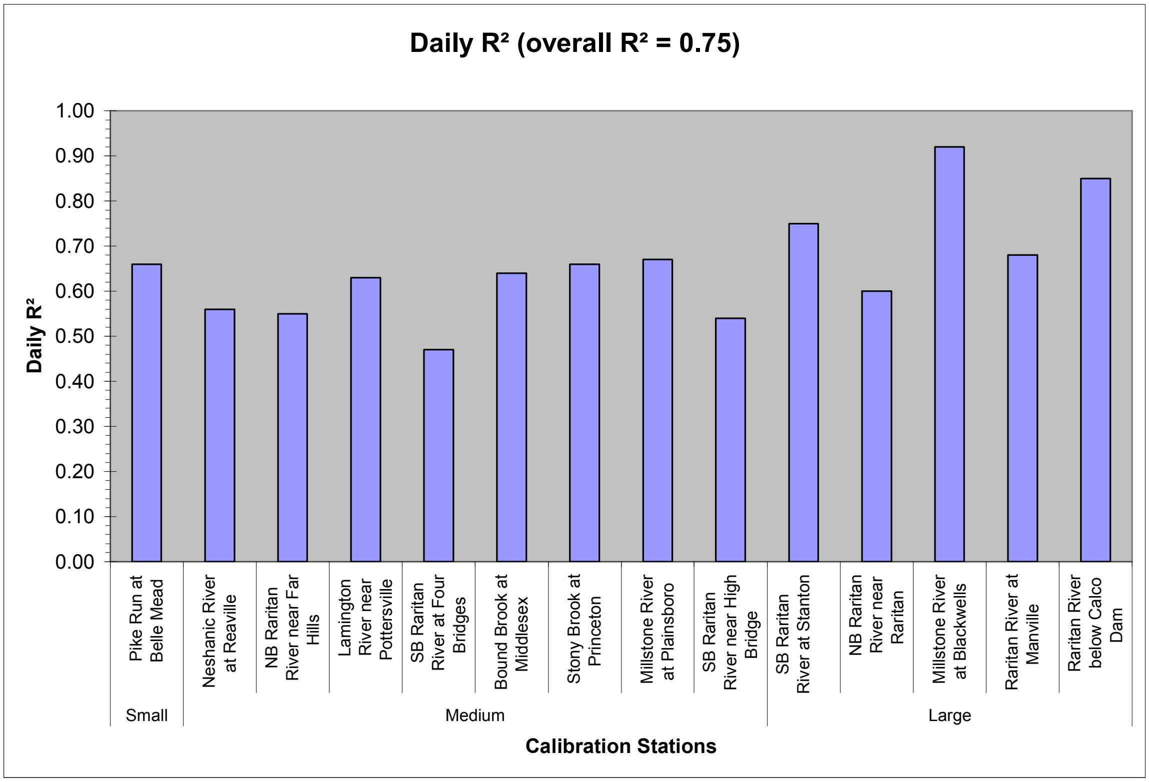
Monthly sub-watershed hydrology parameters were calibrated next. The baseflow recession, field capacity, and potential infiltration are the most sensitive within the class of parameters. Seasonal differences can be captured by adjusting these monthly values. Monthly plots are useful at the early stage of calibration because they provide a good estimate of whether the seasonal and annual patterns are being captured. Once the first round of calibration is performed, all parameters were revisited until the model fitness converged to an acceptable level.

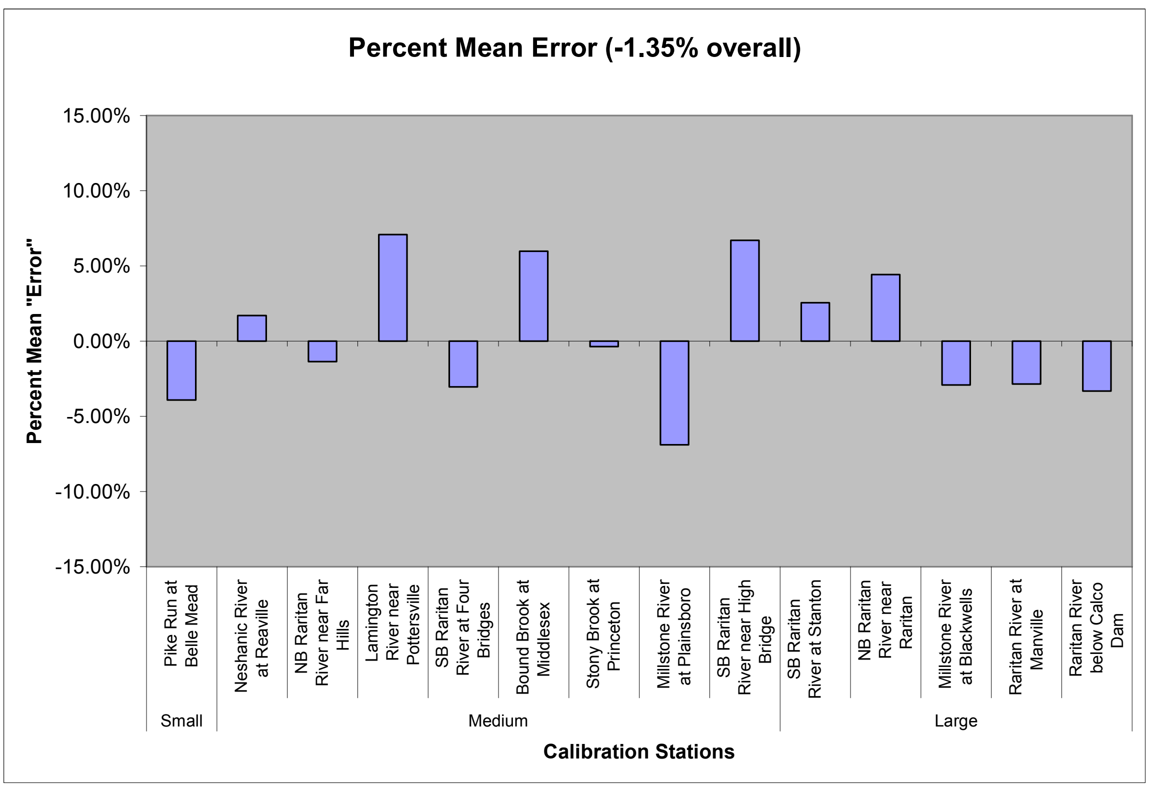
The acceptable calibration level depends on the gage drainage area. According to the numerical criteria provided by BASINS, 2001 to guide calibration, the average mean error should be below 15%, correlation coefficient R above 0.75, and coefficient of determination R^2 above 0.65 to obtain a fair calibration on a daily time scale. However, due to the dependency on precipitation records, simulated flow at gages with smaller drainage areas are not expected to have high values for the coefficient of determination (R^2). It is more important to capture the general pattern of recessions and the peaks in the daily time series plots. The hydrologic model calibration statistics at each calibration gage are provided in Table 23. The daily R^2 and percent mean errors are plotted in Figure 19. The overall R^2 value (mean flow-weighted) is 0.75, well within the acceptable range. All of the percent mean errors are below 15%, and the overall percent mean error (mean flow-weighted) is 1.35%. While the R^2 values for a few of the gages are below 0.65, this is common and expected for large scale hydrologic models. The time series plots and frequency distribution plots (provided in Appendix J) demonstrate that the calibration at all locations captures the general pattern of recessions and the magnitude of the peaks. All calibration graphs are shown in Appendix J. Calibration of individual watershed area models is discussed below.

Table 23: Hydrologic Calibration Statistics

Gage Size	Calibration Gage	USGS Gage#	Daily R	Daily R^2	Nash-Sutcliffe	Simulated Mean	Gage Mean	Mean Error	% Mean Error	Monthly R	Monthly R^2
Small	Pike Run at Belle Mead	01401650	0.81	0.66	0.65	9.34	9.72	-0.38	-3.91%	0.91	0.83
Medium	Neshanic River at Reaville	01398000	0.75	0.56	0.53	44.94	44.19	0.75	1.70%	0.91	0.83
	NB Raritan River near Far Hills	01398500	0.74	0.55	0.51	48.21	48.88	-0.67	-1.37%	0.85	0.72
	Lamington River near Pottersville	01399500	0.80	0.63	0.36	61.45	57.39	4.06	7.07%	0.86	0.74
	SB Raritan River at Four Bridges	01396190	0.68	0.47	0.43	56.53	58.30	-1.77	-3.04%	0.78	0.61
	Bound Brook at Middlesex	01403900	0.80	0.64	0.73	78.7	74.26	4.44	5.98%	0.87	0.75
	Stony Brook at Princeton	01401000	0.81	0.66	0.66	77.24	77.53	-0.29	-0.37%	0.85	0.73
	Millstone River at Plainsboro	01400730	0.82	0.67	0.63	103.82	111.51	-7.69	-6.90%	0.94	0.89
	SB Raritan River near High Bridge	01396500	0.73	0.54	0.46	138.47	129.76	8.71	6.71%	0.80	0.63
Large	SB Raritan River at Stanton	01397000	0.87	0.75	0.75	289.01	281.82	7.19	2.55%	0.93	0.86
	NB Raritan River near Raritan	01400000	0.77	0.60	0.58	368.17	352.57	15.60	4.42%	0.84	0.71
	Millstone River at Blackwells	01402000	0.96	0.92	0.92	428.45	441.32	-12.87	-2.92%	0.99	0.98
	Raritan River at Manville	01400500	0.82	0.68	0.68	920.81	947.83	-27.02	-2.85%	0.86	0.73
	Raritan River below Calco Dam	01403060	0.92	0.85	0.85	1258.42	1301.81	-43.39	-3.33%	0.96	0.92

Figure 19: Global Water Balance





The calibration of the upstream gages at the North and South Branch watershed were the most difficult. Many gages at the North and South Branch are influenced by dams and backwater effects of reservoirs, which are not explicitly modeled by the hydrologic model. Therefore, the influence of precipitation in headwaters and the presence of dams throughout the stream network are considered the major cause of the poorer representation of flows in some gages (SB Raritan at Four Bridges, SB Raritan at High Bridge, NB Raritan near Far Hills and Neshanic River). These streams are very flashy, accounting for the lower Daily-R values; the monthly flow representation is excellent, as is the overall water balance. Furthermore, results in downstream gages present a considerable improvement.

The Stony Brook watershed has only one calibration gage. The coefficient of determination and the frequency plots suggest the precipitation is well represented in this area. The upper Millstone watershed presents calibration results with quality similar to the Stony Brook watershed. However, this area has a different and shorter time period for calibration due lack of existing gage records for the standard calibration period chosen for other areas. The results are also influenced by the existence of numerous dams upstream and in the immediate vicinity of the Millstone gage in Plainsboro.

The Beden Brook and the lower Millstone watershed have two calibration gages. The upstream gage represents flows from a very small drainage area and could not be used for the overall calibration of this watershed group. Even though the drainage area is small, the precipitation records seem to be well represented, which is reflected by a relatively good coefficient of determination and frequency plots. The USGS gage at Blackwells Mills is the downstream gage. The calibration statistics at this gage are particularly good due to the influence of the boundary flows from Carnegie Lake.

The Mainstem Raritan watershed model has two gages which were used for a partial calibration. This area could not be entirely calibrated because there are no gages near the outlet of the watershed, and there are very limited records from the headwater gage in Bound Brook. The simulation of flows at Calco Dam gage is very good. Flows in this watershed area model are strongly influenced by the boundary flows from the North/South Branch and Beden Brook/Lower Millstone models. Note that the flows used as boundary conditions for this watershed group are not gage flows, but actual model outputs, which gives further credence to model results for the upstream watershed area models. The Bound Brook gage provided records for a period smaller than one year, which cannot be considered appropriate for a formal calibration. However, the results obtained for the existing time period are good, which could be explained by the proximity of the weather station. The parameters for the downstream areas were assumed to be the same as the areas calibrated for the Bound Brook gage.

Long term validation was performed from 1990 through 2001 at all gages with long term data available: South Branch Raritan River near High Bridge (USGS #01396500), South Branch Raritan River at Stanton (USGS #01397000), Neshanic River at Reaville (USGS #01398000), Lamington River near Pottersville (USGS #01399500), North Branch Raritan River near Far Hills (USGS #01398500), Stony Brook at Princeton (USGS #01401000), Pike Run at Belle Mead (USGS #01401650), Millstone River at Blackwells Mills (USGS #01402000), and Raritan River at Manville (USGS #01400500). Validation graphs (30-day average time series plots and frequency distribution plots) are provided in Appendix J.

Overall, the hydrologic calibration and validation of each watershed area model represents a major technical achievement and provides an excellent basis to support water quality simulations.

G. Calibration and Validation of Water Quality Model

Calibration of the water quality model is performed for 75 stations throughout the Raritan River Basin Model domain. The majority of stations were sampled by Kleinfelder/Omni for the Phase I Raritan TMDL Study and from previous phosphorus evaluation studies performed in the Raritan River Basin. Data from other sources such as the NJDEP and USGS were also used when available.

The calibration was performed separately for each watershed area model. The calibration timeframe includes the years 2003, 2004 and 2005. The period of calibration depends on the watershed area model and the sampling location. Because the calibration data were gathered from different studies, not all sampling stations contain water quality samples for all the years. Whenever possible, water quality model calibration was performed during critical periods, namely consistent low flow conditions in the stream that maximizes nutrient impacts (productivity). Years 2003, 2004 and 2005 are considered wet, typical and dry years, respectively, based on the precipitation data available. During all three years, however, critical low flow periods occurred that were suitable for calibration.

Dissolved oxygen is an important aspect of the Raritan River Basin Model. The availability of substantial periods of diurnal dissolved oxygen measurements was critical for capturing primary productivity in the stream and dissolved oxygen levels. Continuous measurements of diurnal DO require special equipment. The diurnal DO sampling was performed by Kleinfelder/Omni at many stations defined for different studies, including the Phase I Raritan TMDL Study. Therefore, the calibration period for each watershed group was defined not only according to the low flow conditions, but also based on the presence of continuous diurnal DO data.

The calibration periods selected for each of the watershed area models are listed in Table 24 below.

Table 24: Calibration Periods

Watershed Area Model	Calibration Period
North South Branch Raritan River	May-August 2004
Upper Millstone	May-August 2004
Stony Brook	Jan-August 2003
Beden Brook / Lower Millstone	Jan-August 2003
Mainstem Raritan	Jan-August 2003

All other data were used for validation. In order to organize the data for calibration and link it to the model's spatial structure, a digital database was assembled. The data collected from the water quality stations in the Raritan Basin were entered in this digital database that is linked to the GIS. Each sampling station is associated to a watershed area model and a model segment. The model output from the segments that correspond to calibration stations is retrieved from WASP7.1 output files, and was compared with the observed data from the respective stations. The comparison of the predicted and observed data was performed using graphs and statistics to evaluate the performance of the simulations.

Model calibration and validation focused on seven parameters: Dissolved oxygen (DO), ammonia nitrogen (NH3-N), nitrate nitrogen (NO3-N), total phosphorus (TP), orthophosphate (OrthoP), chlorophyll-a (Chla) and total suspended solids (TSS). The calibration process is manual and iterative. Each parameter is calibrated individually by station, starting from the most upstream stations. Generally, DO and Chla were calibrated first, followed by NH3-N, NO3-N, TP and OrthoP, and TSS. A total of 75 Kleinfelder/Omni sampling stations were used for model calibration. When Kleinfelder/Omni stations coincide with stations from other sources (e.g., NJDEP or USGS stations), data collected during the calibration period from sources other than Kleinfelder/Omni were also used for calibration. A list of all water quality calibration stations is provided in Table 25.

Comparison of the results from calibration was performed by plotting the discrete observed data and the continuous simulated data together. The first cut of calibration was obtained by visual inspection of the plot. When results converged, statistics were calculated to provide a quantitative measure of calibration fitness. The statistics used for model calibration are described below. The relevant formulae and detailed descriptions about the several statistics can be found in Reckhow and Chapra, 1983 and Stow C.A. et al., 2003.

- AE: Average error, measures the size and discrepancy between predicted and observed values.
- AP: Average predicted, measures the average of predicted values.
- AObs: Average observed, measures the average of observed values.
- RMSE: Root mean square error, measures the differences between values predicted by the model and the observed values.
- E_{NS}: Nash-Sutcliffe coefficient (NSE). An efficiency of 1 (E_{NS}=1) corresponds to a perfect match of modeled discharge to the observed data. An efficiency of (E_{NS} =0) indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero ($-\infty < E_{NS} < 0$) occurs when the observed mean is a better predictor than the model. Nash-Sutcliffe coefficient was used to assess global model performance for phosphorus.

Table 25: Water Quality Calibration Stations

Watershed	Segment	Branch-Node	Station	Description
North and South Branch Raritan River Watershed Model Area (NSBranch)	1	1-1	SBRR1	South Branch Raritan River in Mount Olive
	3	2-1	DkB1	Drakes Brook upstream of Mt. Olive STP
	7	3-2	SBRR2	South Branch Raritan River near Four Bridges
	8	3-3	SBR1	South Branch Raritan River Upstream Washington Township
	9	3-4	SBR2	South Branch Raritan River Downstream Schooley's Mt. STP
	11	3-6	SBR3	South Branch Raritan River Downstream Long Valley STP
	17	3-12	SBR4	South Branch Raritan River at Middle Valley
	24	3-19	Solitude Lake	South Branch Raritan River at Solitude Lake
	25	3-20	SBRR5	South Branch Raritan River at High Bridge
	32	4-3	BB1-BB2	Beaver Brook at Allertown Road
	34	4-5	BvB1	Beaver Brook @ Hamden Road in Town of Clinton
	35	5-1	SBRR6	South Branch Raritan River Upstream Clinton STP
	38	6-1	CC1	Cakepoulin Creek at Lower Lansdown Rd.
	39	7-1	SBRR7	South Branch Raritan River at Hamden Rd
	45	7-7	SBRR8	South Branch Raritan River at Stanton Rd.
	52	7-14	SBRR9	South Branch Raritan River at Three Bridges
	57	8-1	NR1	Neshanic River near Reaville
	61	8-5	NR2	Neshanic River at Hillsborough
	68	9-7	SBRR10	South Branch Raritan River at Studdiford Rd.
	69	10-1	HB1	Holland Brook at South Branch Road
	71	12-1	LR1	Lamington River Upstream Roxbury STP
	73	12-3	LR2	Lamington River Downstream Roxbury STP
	82	12-12	LR3	Lamington River in Pottersville
	86	12-16	LR4u	Lamington River in Lamington
	89	12-19	LR4	Lamington River at River Road near Whitehouse
	90	13-1	NBRC1	North Branch Rockaway Creek at Route 523
	91	14-1	SBRC3	South Branch Rockaway Creek Downstream Cushetunk Lake
	95	15-3	RC1	Rockaway Creek at Lamington Road near Whitehouse
	101	16-4	LR5	Lamington River at Confluence with North Branch Raritan River
	102	17-1	IB1	India Brook at Mountainside Road in Mendham
	106	18-1	BuB1	Burnett Brook at Chester
	108	19-1	NBRR1	North Branch Raritan River in Mendham Township
	113	19-6	NBRR2	North Branch Raritan River Upstream of Ravine Lake
	114	19-7	Ravine Lake	North Branch Raritan River in Ravine Lake
	115	19-8	NBRR4	North Branch Raritan River Downstream Ravine Lake
	124	20-6	MiB1	Mine Brook at Route 512
	126	21-2	NBRR5	North Branch Raritan River at Route 202/206
	132	21-8	NBRR6	North Branch Raritan River at Burnt Mills
	140	22-8	NBRR7	North Branch Raritan River Downstream Route 202
	147	23-7	RR1	Raritan River at Main Street in Manville
Upper Millstone River Watershed Model Area (UpperMills)	1	1-1	UMR1	Upper Millstone River at Old Cranbury Rd.
	3	2-1	RB3	Rocky Brook Downstream Peddie Lake
	6	2-4	RB4	Rocky Brook at Route 130
	20	3-12	UMR2	Upper Millstone River at Cranbury Neck Rd.
	26	5-1	UMR3	Upper Millstone River Downstream Railroad Crossing in Plainsboro
	28	6-1	BBB3	Big Bear Brook Downstream Grovers Mill Pond
	29	6-2	T4	Big Bear Brook at Cranbury Rd.
	32	8-1	DB3	Devils Brook Downstream Gordon Pond
	34	9-2	M1	Millstone River at US Route 1
Stony Brook Watershed Model Area (Stony)	2	1-2	SB1	Stony Brook Upstream SBRSA - Pennington STP
	3	1-3	Pennington	Stony Brook at SBRSA - Pennington STP Discharge
	4	1-4	SB2	Stony Brook Downstream SBRSA - Pennington STP
	5	1-5	SB_Down2	Stony Brook at Old Mill Rd.
	6	1-6	SB_Down3	Stony Brook at Rosedale Park
	21/20	1-21	SB3	Stony Brook at Princeton Rd.
	29	1-29	SB4	Stony Brook at Alexander Road
Beden Brook / Lower Millstone River Watershed Model Area (BedenLowerMills)	1	1-1	BB1	Beden Brook Upstream SBRSA-Hopewell STP
	2	1-2	SBD1	Beden Brook 250' downstream of STP
	4	1-4	BB2	Beden Brook Downstream SBRSA-Hopewell STP
	9	1-9	SBD3	Beden Brook at Great Rd.
	17	1-17	1401600	Beden Brook at State Rd.
	29	2-11	1401700	Pike Run at River Rd.
	30	3-1	BB3	Beden Brook Downstream Pike Brook Confluence
	32	4-1	M2	Lower Millstone River Downstream Carnegie Lake
	35	4-4	River Road	Lower Millstone River at SBRSA - River Road STP Discharge
	38	4-7	M3	Lower Millstone River Downstream SBRSA - River Road STP
	39	4-8	M4	Lower Millstone River Downstream Montgomery - Stage II STP
	49	5-5	M5	Lower Millstone River at Griggstown
	56	5-12	M6	Lower Millstone River at Blackwells Mills
	62	5-18	M7	Lower Millstone River at Manville
Lower Mainstem Raritan River Watershed Model Area (Mainstem)	5	3-2	R2	Raritan River Downstream Millstone River Confluence
	8	3-5	R3	Raritan River @ I-287 bridge
	11	3-8	1403900	Raritan River at Queens Bridge
	12	4-1	GB1	Green Brook (Bound Brook) at Greenbrook Rd.
	20	5-3	R4	Raritan River Upstream Fieldville Dam

The model calibration procedure was started by using average or literature values of most parameters. Parameters can be classified as global or local parameters. Global parameters do not vary spatially, whereas local parameters may vary for each segment defined in the model. Global parameters can be difficult to calibrate because they affect the entire system. Local parameters only influence their particular segment and segments in the downstream vicinity. However, they have to be estimated for every segment in the stream network. The calibration of local and global parameters proceeds simultaneously because they are interdependent. Therefore, a systematic approach for calibrating a large and diverse system such as the Raritan River Basin Model was adopted.

According to the calibration approach adopted, parameters at tributary stations were adjusted first followed by parameters at stations in the main branches. After an acceptable calibration was obtained at the stations in main branches, the tributary stations were revisited to check if the calibration was still valid there. The calibration in the tributaries and the main branches was performed according to the flow direction. The stations near the headwaters were calibrated, first followed by the downstream locations. The global and local parameters used for calibrating the Raritan River Basin Model are listed below.

Global parameters:

- Nitrification rate;
- Mineralization rate constant for dissolved organic P
- Benthic algae maximum growth rate;
- Benthic algae respiration rate;
- Benthic algae death rate;
- Internal nutrient excretion rate constant for benthic algae
- Minimum cell quota of internal nitrogen for growth
- Minimum cell quota of internal phosphorus for growth
- Maximum nitrogen uptake rate for benthic algae
- Maximum phosphorus uptake rate for benthic algae
- Half-saturation uptake constant for intracellular nitrogen

- Half-saturation uptake constant for intracellular phosphorus
- Phytoplankton maximum growth rate;
- Phytoplankton death rate;
- Phytoplankton respiration rate;
- Half-saturation constant for external nitrogen
- Half-saturation constant for external phosphorus
- Light constant for growth; and
- Detritus dissolution rate.

Local parameters:

- Percent of bottom segment covered by benthic algae;
- SOD;
- Benthic ammonia flux;
- Phosphate flux
- Fraction dissolved or organic phosphorus and nitrate; and
- Settling rates for particulate material.

Finding global and local parameters that result in a good overall fit can be difficult to obtain due to the number of calibration stations. In addition, the interdependency between parameters further complicates calibration. In heavily parameterized models like WASP7.1, it is not difficult to obtain a good calibration by focusing on the wrong processes or parameters. The diurnal variation of DO is a good example. Both phytoplankton and benthic algae can influence diurnal variation of DO; therefore, it is important to first calibrate the parameters that influence variables that have more reliable calibration data, and that have a global impact.

Water Quality calibration graphs (predicted and observed over the calibration period) are provided in Appendix K, while water quality validation graphs (predicted and observed validation data over time) are provided in Appendix L. Goodness-of-fit statistics for all modeled constituents are provided in Appendix M, along with the following goodness-of-fit graphs for the TMDL constituents TP and TSS: predicted versus observed, residuals versus flow, and residuals versus concentration.

Given the importance of TP for the TMDL analysis, global model performance for TP was further assessed by evaluating calibration statistics for groups of calibration stations, as shown in Table 26 below.

Table 26: Global Water Quality Model Evaluation for Total Phosphorus

Station Type	# of Samples	Mean Predicted	Mean Observed	Mean Error	RMSE	NSE
Headwater NPS	283	0.068	0.062	-0.006	0.036	0.055
Downstream WWTP	271	0.250	0.250	-0.001	0.157	0.584
Calibration	665	0.113	0.111	-0.002	0.058	0.680
All Stations	1219	0.133	0.131	-0.003	0.087	0.678

"Headwater NPS" refers to those stations at model watershed boundaries, which are impacted only by nonpoint sources. These stations were not subjected to calibration for nutrients. They reflect the hydrologic and pollutant loading model performance. Recall the hydrologic model generates baseflow and runoff, and the pollutant loading model assigns constant concentrations based on a land use and other factors. This is essentially an EMC approach. It is not surprising that actual concentrations are much more variable than simulated. However, the fact that the mean error is very low means the model has captured the overall magnitude of the nonpoint source impact.

"Downstream WWTP" refers to stations located just downstream of WWTP discharges; they are highly impacted by the individual discharge. These stations were also not subject to calibration for nutrients, since the residual error is much more likely to be due to the WWTP concentration. Even when daily effluent data were available, a 24-hour composite does not necessarily indicate the concentration of treated effluent passing the stream when the sample is taken.

All the other calibration stations were lumped into "Calibration". These stations best represent the overall model performance.

The calibration procedures adopted for all watershed area models and for parameters affecting each individual water quality variable are discussed in the ensuing sections.

1. Phosphorus

Phosphorus is one of the important components of the Raritan River Basin Model, and special attention was given to its calibration. The simulation of phosphorus in WASP7.1 can explicitly account for the phosphorus uptake by plants and algae, the settling of particulate organic phosphorus, and the decomposition of organic matter. The use of the PERIPHYTON sub model allows the luxury uptake of phosphorus to be taken into account. The luxury uptake of phosphorus by rooted plants and periphyton plays an important role at many locations of the Raritan River Basin. There are times when primary productivity is substantial while the concentration of dissolved orthophosphate in the water column is undetectable. This would not be able to be simulated if the nutrient luxury uptake were not implemented.

There are five global parameters that directly affect the phosphorus cycle. The first parameter is the mineralization rate of organic phosphorus. This parameter defines how the dissolved organic phosphorus that results from organic compound decomposition is transformed into OrthoP. In general, the watershed area models were not very responsive to this parameter. Only Stony Brook presented some response for the mineralization rate of organic phosphorus. The global value of the mineralization rate of organic phosphorus was assumed as 0.2 day^{-1} for the North/South Branch, Beden Brook/Lower Millstone, Upper Millstone and Mainstem. A value of 0.1 day^{-1} was assumed for Stony Brook.

The other four parameters that directly impact the nutrient uptake of bottom plants are: minimum cell quota of internal phosphorus, maximum phosphorus uptake rate for benthic algae, the half-saturation uptake constant for intracellular phosphorus and half-saturation of external phosphorus. These parameters affect the overall phosphorus uptake and they are significant for the model calibration.

Cell quotas represent the ratios of intracellular nutrient to the bottom plant's dry weight. The minimum cell quota of internal phosphorus (q_{0P}) determines the minimum level of intracellular phosphorus necessary for plants to grow. When the specified value is reached, growth ceases. Maximum phosphorus uptake rate for benthic algae (ρ_{mP})

defines the maximum uptake rate that can occur. The actual phosphorus uptake (*BotAlgUptakeP*) is bound by the available dissolved phosphorus in the water column (p_i), half-saturation constant of external phosphorus (K_{sPb}), ratio of intracellular phosphorus (q_p), bottom algae dry weight and half-saturation uptake constant for intracellular phosphorus (K_{qP}). Equation 8 (Chapra et al., 2006) defines phosphorus uptake as simulated in WASP7.1.

$$BotA\lg UptakeP = \rho_{mP} \frac{p_i}{K_{sPb} + p_i} \frac{K_{qP}}{K_{qP} + (q_P - q_{0P})} a_b \quad (8)$$

The calibrated values of the minimum cell quota of internal phosphorus (3.7 mgP/gDW), maximum phosphorus uptake rate for benthic algae (1.86 mgP/gDW), half-saturation uptake constant for intracellular phosphorus (7.4 mgP/gDW) and half-saturation constant of external phosphorus (0.005 mgP/L) were adopted for all five watershed area models. The fact that changes are not necessary among the watershed area models for this set of parameters indicates the algorithm is robust and the parameters are meaningful.

A parameter used in the phosphorus calibration that is not exclusive for phosphorus cycle is the internal nutrient excretion rate constant for benthic algae. This parameter affects the phosphorus and nitrogen intracellular ratio simultaneously. The calibrated value of this parameter is 0.01 day^{-1} and it did not change among the watershed area models. Half-saturation of phosphorus concentration in the water column for phytoplankton is also a calibration parameter. However, it did not play an important role in the calibration of the Raritan River Basin Model. A constant value of 0.0025 mgP/L was assumed for all watershed area models.

Besides the global parameters directly affecting the phosphorus cycle, total phosphorus concentrations are also sensitive to boundary condition loads, benthic loads, plant productivity, stoichiometry, settling and fraction dissolved. Boundary conditions are defined according to data availability and are described in the previous sections of this report. Plant productivity is calibrated to capture diurnal DO concentrations. Stoichiometry is considered fixed and is obtained using detailed equations for photosynthesis and respiration by algae as suggested by Redfield et al. (1963) and Stumm and Morgan (1981). The settling velocity and the dissolved fraction of organic phosphorus are the parameters used to calibrate total phosphorus at most locations in the Raritan River Basin Model.

According to Wetzel (2001), the exchange of phosphorus between sediments and the water column is a major component of the phosphorus cycle in natural waters. The adsorption and precipitation of phosphorus with inorganic compounds is one of the components of this exchange process. WASP7.1 doesn't simulate the adsorption or desorption of organic or orthophosphate into particulate inorganic material. Instead, it adopts fixed ratios of dissolved and particulate compounds in the water column, which are determined through calibration. All dissolved and particulate compounds are initially available in the water column. However, the particulate fraction is removed from the water column according to a settling function. Assigning the ratio of dissolved and particulate phases provides a mechanism to make a portion of the pool subject to removal through settling. This calibration tool provides a first-order mechanism for simulating the net removal of phosphorus from the water column due to sediment interactions; being first-order, it is in fact responsive to changes in loading scenarios and can accommodate future loading scenarios. The existing conditions in the Raritan River basin exhibit a wide range of nutrient conditions, all of which exhibit a net loss of phosphorus from the water column.

Organic phosphorus is considered very reactive and can be easily adsorbed in the suspended or bottom sediments. Although orthophosphate can also get adsorbed, normally it does not present very strong bonds to the particulate material, unless other substances such as iron or some microbial processes are also involved. Therefore, only organic phosphorus was assumed to have particulate fractions. The dissolved fraction of organic phosphorus and the settling functions were calibrated to provide meaningful simulations of total phosphorus. Note that the dissolved fraction is a modeling tool to make a portion of the OrgP subject to settling; it is not meant to be compared to actual data, and in any case data do not measure OrgP directly. Generally TP and OrthoP are measured.

The fraction of dissolved phosphorus and the settling velocity for various segments were calibrated simultaneously. Higher fractions of dissolved organic phosphorus required higher settling velocities. Therefore, there is a tradeoff between these two parameters. Settling functions specify a group of segments that are subject to a unique value of settling velocity. The settling velocity is generally assumed constant for all the segments of a given branch, whereas the fraction dissolved changes for each segment.

Individual settling functions were generally defined for each branch of the stream network. However, long branches were assigned more than one settling function. Settling was only utilized when necessary to capture observed concentrations. Calibration of organic phosphorus began by determining the settling functions and their respective settling velocities. The dissolved fraction and the settling velocities were then adjusted as necessary. Settling velocities and the dissolved fraction of organic phosphorus vary considerably.

The settling velocity affects all particulate material. This parameter serves as a link between organic phosphorus and TSS. Since TSS is considered to be 100% particulate, settling velocity is the only parameter that can be adjusted for its calibration. Therefore, settling velocity was calibrated primarily for TSS. After TSS was calibrated, minor adjustments are made when necessary for organic phosphorus. Appendix H shows the settling velocities and the fraction of dissolved organic phosphorus calibrated for each segment and for each watershed area model.

The last parameter that was calibrated is the benthic orthophosphate flux. As WASP7.1 does not simulate the transformations in the bottom sediment, some processes that affect the concentration of constituents at some locations could be missed. In order to overcome this limitation of WASP7.1, benthic fluxes of orthophosphate were added only when necessary. Only one location in the entire Raritan River Basin Model required benthic loads; this provides great assurance that nutrient loads from the sediment to the water column are not generally important in the system. This is especially remarkable given the wide range of nutrient concentrations exhibited throughout the basin. The lower section of the Stony Brook, which is essentially part of Carnegie Lake where it was sampled on Alexander Road, is the only area where benthic fluxes of orthophosphate were needed to explain observed phosphorus levels.

The need of such fluxes is determined by the calibration data. Many combinations of parameters were tested before resorting to the addition of benthic fluxes. However, the level of orthophosphate measured in the water column at SB4 was not achieved through calibration of the parameters that affect the phosphorus cycle; benthic fluxes were therefore added. Only the last two segments of the Stony Brook are subject to orthophosphate benthic fluxes. Given the fact that the Stony Brook at this location deepens to over 10 feet deep with a mucky bottom, it is not unreasonable at all to suspect benthic loads. The benthic flux is set to occur only from June through September, and it can reach a maximum of 20 $mg/m^2/day$.

2. Nitrogen

Nitrogen is present in the water column in different forms. The nitrogen compounds are: ammonia-ammonium nitrogen, nitrate-nitrite nitrogen, and organic nitrogen. The concentrations of these substances are interconnected and they are controlled by mineralization rates, temperature, pH, algal respiration and photosynthesis. Concentrations of ammonium and nitrite are generally small, since they are quickly transformed to its more stable forms, which are ammonia and nitrate, respectively. Therefore, the calibration of the nitrogen series consists of adjusting the parameters that affect ammonia, nitrate and organic nitrogen. Since the fate of the nitrogen series is interconnected, the nitrogen cycle is divided into four main compartments in order to better describe the nitrogen calibration: nitrification, organic nitrogen mineralization, nitrogen uptake and excretion, and independent processes.

a. Nitrification

Calibration of ammonia, nitrate and organic nitrogen is interdependent. Parameters affecting their concentrations are nitrification rate, dissolved organic nitrogen mineralization rate, ammonia preference, and nitrogen uptake parameters. The nitrification rate determines how fast ammonia is converted to nitrite and nitrate. Nitrification is caused by autotrophic bacteria, which assimilates ammonia and creates nitrite and nitrate. Nitrification rates can vary considerably. The characteristics of the water body, such as depth, temperature and substrate influence the presence of the nitrifying bacteria.

The value of the nitrification parameter is calibrated separately for each watershed area model. The values of nitrification rate reflect the differences of the areas defined for the Raritan River Basin Model. The calibrated nitrification rate for the North/South Branch was 5 day^{-1}. Although the value calibrated for the North/South Branch is within the range presented in the literature, which varies from

0 to 10 day^{-1} in rivers, the calibrated value is higher than the average. In order to field-verify the nitrification rate adopted for the North/South Branch, the ammonia mineralization was quantified in some locations using water quality samples in the proximity of treatment plants discharges. Three locations were selected for this analysis: the section of the South Branch Raritan River downstream Washington Township WWTP; the section of the Lamington River downstream Roxbury WWTP, and the section of Beden Brook downstream Hopewell WWTP. The first two locations belong to the North/South Branch watershed group, and they are characterized by high discharge flows associated with periods of high ammonia concentrations that can reach 18 and 4.6 mg/l, respectively, and average ammonia concentrations of 2.5 and 0.49 mg/l, respectively. The SBRSA-Hopewell WWTP is located in the Beden Brook/Lower Millstone watershed group. Since the average ammonia concentration is 0.07 mg/l and the maximum is 0.43 mg/l, its ammonia load is considerably lower than Washington Township and Roxbury.

Periods of high ammonia loads and low flows are selected for determining the ammonia mineralization rate. The mineralization rate is determined according to first order kinetics (Equation 9). Steady state conditions are assumed to hold for this analysis.

$$\frac{dc}{dt} = -kC \quad (9)$$

The analytical form of Equation 10 is:

$$C = C_0 * e^{-kt} \quad (10)$$

Where:

C = Final concentration

C_0 = Initial concentration

k = Mineralization rate

t = Travel time in days

Equation 11 can be written as:

$$k = -\ln\left(\frac{C}{C_0}\right)/t \quad (11)$$

The values of C_0 and C are the ammonia concentrations immediately downstream the treatment plant and further downstream, respectively. The value of the travel time t is obtained by dividing the distance between the two sampling stations and the stream velocity. The field-calculated nitrification rates are shown in Table 27.

Table 27: Nitrification Rates Calculated Based on Field Data

River Section	Nitrification rate (1/day)
South Branch Raritan downstream WTMUA WWTP	1.86
Lamington River downstream Roxbury WWTP	7.11
Beden Brook downstream Hopewell WWTP	0.68

The values of nitrification rates calculated for the North/South Branch are representative of locations downstream of the treatment plants, where ammonia mineralization has a greater impact. Because ammonia nitrification is far more important near the dischargers (due to first-order kinetics), it is justified to apply the values of nitrification rates derived near treatment plants to each watershed area model. Nitrification rate is not important outside areas with high ammonia loadings, namely wastewater treatment plant discharges. The value of the nitrification rate calibrated for the North/South Branch (5 day^{-1}) was the highest defined for the Raritan River Basin Model. The values assigned for the other watershed groups are 2.5 day^{-1} for the Upper Millstone, and 1 day^{-1} for Stony Brook, Beden Brook/Lower Millstone and Mainstem watershed area models.

b. Organic Nitrogen Mineralization

The fate of organic nitrogen is also a component of the nitrogen cycle. Organic nitrogen results from the excretion and decomposition of organic material. Organic nitrogen is subject to microbiological processes and it can be transformed to inorganic nitrogen compounds (ammonia and nitrate-nitrite). The levels of organic nitrogen are relatively constant in the water bodies and they are not a focus of calibration of the Raritan Basin Model. Thus, dissolved organic nitrogen mineralization rate did not play an important role in the Raritan River Basin Model calibration. A value of 0.02 day^{-1}, which is the average presented by the literature, was adopted for all the watershed groups.

c. Nitrogen Uptake and Excretion

The ammonia preference is one of the parameters that impacts the nitrogen uptake from the water column, and it is directly associated with algae and plant growth. This parameter determines the proportion of ammonia used in the photosynthesis and respiration processes compared to nitrate. As phytoplankton and macrophytes grow, dissolved inorganic nitrogen is taken up and incorporated into biomass. Both ammonia and nitrate are available for uptake. The value of the ammonia preference was set to 0.025 mg/L and it did not change for the different watershed area models. There are no measurements of ammonia preference. Chapra, 2006, provides a default value of 0.025 mg/L for the QUAL2K 2.04 application, which uses the same formulation as WASP7.1 for the benthic algae simulation.

Parameters of the benthic algae system that impact the uptake of ammonia and nitrate include: minimum cell quota of internal nitrogen, maximum nitrogen uptake rate for benthic algae, half-saturation uptake constant for intracellular nitrogen, and half-saturation constant of external nitrogen. The role of nitrogen is analogous to the phosphorus role for plant uptake. Equation 12 (Chapra et al., 2006) shows the nitrogen uptake as simulated in WASP7.1.

$$BotA\lg UptakeN = \rho_{mN} \frac{N_i}{K_{sNb} + N_i} \frac{K_{qN}}{K_{qN} + (q_N - q_{0N})} a_b \quad (12)$$

According to Equation 12 the actual nitrogen uptake (*BotAlgUptakeN*) is bound by the maximum nitrogen uptake rate for benthic algae (ρ_{mN}), available ammonia or nitrate in the water column (N_i), half-saturation constant of external nitrogen (K_{sNb}), ratio of intracellular nitrogen (q_N), half-saturation uptake constant for intracellular nitrogen (K_{qN}), minimum cell quota of internal nitrogen (q_{0N}), and the bottom plants dry weight (a_b).

The calibrated value of the minimum cell quota of internal nitrogen is 26.6mgN/gDW; maximum nitrogen uptake rate for benthic algae is 38.3 mgN/gDW; half-saturation uptake constant for intracellular nitrogen is 44.4 mgN/gDW, and half-saturation constant of external nitrogen is 0.02 mgN/L. These values were adopted for the North/South Branch, Beden Brook/Lower Millstone, Mainstem, Stony Brook and Upper Millstone watershed area models. Similar to orthophosphate, the nitrogen parameters also demonstrate the robustness of the luxury uptake algorithm by their broad applicability across watershed area models.

Ammonia is a byproduct of organic matter decomposition. External sources of organic matter are wastewater treatment facilities and, to a lesser extent, nonpoint source loads. External sources are accounted for by boundary condition inputs. However, there are also sources of organic matter that are not explicitly simulated by the model. The river bed can contain a considerable amount of organic matter, which is a result of years of continuous accumulation. Therefore, in certain areas and under certain conditions, some of the ammonia load is not automatically taken into account by the model. In order to consider the ammonia generated in the stream bottom, benthic ammonia fluxes are added where appropriate. These loads are local, and are applied only at the specified segments as necessary to simulate the calibration data. As stated previously, only one location in the entire Raritan River Basin Model required benthic loads, indicating that nutrient loads from the sediment to the water column are not generally important in the system. Since this is true across a wide range of nutrient conditions in the Raritan River basin, it is reasonable to assume it will remain true under future loading conditions.

Similar to orthophosphate, only the last two segments of the Stony Brook were assigned benthic fluxes of ammonia. The levels of ammonia and nitrate detected at the last Stony Brook segments, near the confluence with Carnegie Lake, could not be achieved by changing the parameters affecting the nitrogen cycle. Therefore, the benthic ammonia flux was set to occur from June through September, and it can reach a maximum of 300 $mg/m^2/day$. This value was calibrated to capture the observed data available in 2003, and it provides meaningful results for the remaining years. Only 2002, due to the extremely dry conditions, present higher ammonia concentrations than the average observed for the other years where the ammonia flux is added.

d. Independent Processes

Most processes influencing ammonia and nitrate discussed so far are interdependent. Thus, their calibration is performed simultaneously. There are other processes such as denitrification, settling, and loads of nitrate and ammonia that can be considered as independent. The process of denitrification converts nitrate to the gaseous forms of nitrous oxide (N_2O) and elemental nitrogen (N_2). This process removes nitrogen from wet or anaerobic soils or the sediment bed as these gases volatilize. This process does not affect the ammonia balance in the water column directly. Since anaerobic conditions are rare in the simulated streams, denitrification was not simulated in the Raritan River Basin Model.

Although nitrate is water soluble and not normally adsorbed into soil particles, the settling of nitrate is another process that was utilized for the calibration of special areas of the North/South Branch watershed area model. The Lamington River presents a wetland complex near its mid section that impacts the levels of nitrate. Average nitrate levels observed downstream the WWTP discharge near the headwaters are 3 mg/l. This average is considerably higher than the nitrate average observed downstream of the wetlands, 0.7 mg/l. It is possible that macrophytes present in the wetlands complex are absorbing the nitrate from the water column.

In order to address the effect of the Lamington River wetlands on the nitrate concentrations, dissolved fractions of nitrate were adopted for the Lamington River. Nitrate settling is subject to the same settling velocities that were calibrated for TSS and TP. However, the fraction of dissolved nitrate was calibrated to capture nitrate levels in the river. Nitrate settling was adopted exclusively in the Lamington River to address the observed reduction in nitrate concentration as a result of the Black River wetland areas. A fraction of dissolved nitrate of 0.3 (70% particulate) was adopted for the model segments located between sampling stations LR2 and LR3, where most of the wetlands are present in the Lamington River. A fraction dissolved of 0.95 (5% particulate) was adopted for the model segments between LR3 and LR4. The fraction of dissolved nitrate for all other areas is equal to one (100% dissolved).

3. Dissolved Oxygen

The simulation of DO is very complex; phytoplankton growth, attached algae and plant growth, nitrification, CBOD, SOD, and transport related parameters such as velocities and stream geometry that affect reaeration, are the main processes affecting DO concentrations in the water column. Besides the processes mentioned above, environmental factors, such as water temperature, solar radiation, and light extinction, can influence DO concentrations directly or indirectly.

Phytoplankton and benthic algae or macrophytes affect the diurnal concentration of DO. Photosynthesis increases DO concentrations during the day, when the net productivity of oxygen is higher than the demand of oxygen by respiration. At night, when photosynthetic processes are inactive, DO consumption is higher than production and DO levels drop.

Decomposition of carbonaceous material also affects oxygen concentrations in the water column. The decomposition process results in a biochemical oxygen demand caused by decomposing bacteria. This process is not significant in terms of the oxygen budget for the Raritan River Basin Model. Measured CBOD levels are very low throughout the basin, usually below the detection limit. Therefore, CBOD was not relevant for DO calibration.

Nitrogen compounds also have an impact on a river's oxygen resources. Nitrogenous biological oxygen demand (NBOD) is a result of the nitrification of ammonia. The nitrification rate can cause a noticeable impact in the DO concentrations at some stations, generally at lower order streams. However, nitrification rates were determined based on ammonia calibration.

Reaeration is one of the major processes affecting DO. Reaeration can be calculated according to two methods for the Raritan River Basin Model: the Covar and the Tsivoglou-Neal methods. These methods are described in the reaeration parameter section of this report. The utilization of the Covar method and the Tsivoglou-Neal method is a function of the characteristics of the stream network and the response of the DO simulations to the methods. Both methods were tested for all five watershed area models. The quality of DO simulations varies within each watershed area model according to the characteristics of the streams and the reaeration method. The method that provided the best overall result for each watershed area model was selected. The Tsivoglou-Neal method provides better results for the North/South Branch, Beden Brook/Lower Millstone River, Upper Millstone and Stony Brook. The Covar method presents better overall results for the Mainstem. The parameters necessary for the application of the reaeration methods relies exclusively on slopes and model hydrodynamic simulations of depth and velocity.

The escape coefficient of the Tsivoglou-Neal method could be subject to calibration. However, the DO concentrations were not very sensitive to this parameter in the case of the Raritan River Basin Model. The escape coefficients obtained from historic studies performed by Kleinfelder/Omni were extrapolated to all the watershed area models and they were not subjected to calibration. The values of the escape coefficients adopted for segments of all watershed area models are shown on the last page of Appendix H.

Besides reaeration, there are two main processes that have a great impact on DO and are extensively used for calibration: SOD and the growth of rooted algae and plants. SOD is a natural process in lakes and rivers due to oxidation of organic matter in the bottom sediments. These benthic deposits are a result of the accumulation of particulates, such as leaf litter and eroded soils. Regardless of the source, oxidation of the accumulated organic matter will result in a sediment oxygen demand. SOD varies considerably spatially and is difficult to measure and consequently to simulate. SOD is introduced in the model as a fixed local parameter expressing the SOD value in $mg/m^2/day$ at 20^oC. Although the SOD assigned for each segment is fixed, the value used by the model varies according to water temperature. SOD is used during calibration to lower the average DO concentration of a given segment as needed to match observed data.

Each segment can assume a different SOD value, which is obtained through calibration. The SOD calibration is performed only at stations where DO observations are available. Thus, SOD values for segments in between sampling stations are estimated according to its proximity to a calibrated station. In order to perform a reality check on SOD values obtained through calibration, Kleinfelder/Omni conducted SOD measurements at sampling stations in the Raritan River Basin. Measurements of SOD were limited to a few locations and are not available for all the watershed area models. The comparison between the SOD obtained through calibration and the observed values is shown in Table 28.

The calibrated results are close to the measurements made by Kleinfelder/Omni at four stations. At two stations, the measured SOD was low, and the calibrated SOD values were even lower (0.01 g/d/m²). While the relative difference between measured and calibrated values appears high for these two stations, as a practical matter both the measured and calibrated values are low. SOD is a calibration parameter, and it is added only as necessary to lower the predicted DO in order to match observations. At three stations, the calibrated SOD was very different than the measured SOD: LR2, RB4, and UMR2. LR2, near the headwater of the Lamington River, is influenced by wetlands, possibly in ways that are not captured by WASP7.1. Also, the stream is very slow-moving, and wetlands may slow reaeration. In this context, SOD is used as a general term to capture processes that are not explicitly modeled, but that have the effect of lowering water column DO. Calibrated SOD values at RB4 and UMR2 in the upper Millstone River watershed differ from the measured values in exactly the opposite manner: RB4 was calibrated with a high SOD but measured with a low SOD; UMR2 was calibrated with a low SOD but measured with a high SOD. This indicates that SOD exhibits great spatial variability in the upper Millstone River watershed, and may be more or less important in localized areas than appreciated by the model. SOD calibration was determined by conditions at the location of the diurnal measurements. DO did not drive the TMDL evaluations in either the upper Lamington River or the upper Millstone River watershed. The calibrated values of SOD for all the watershed area models are shown in Appendix H.

Table 28: Comparison of Observed versus Calibrated SOD Values

Watershed Group	Segment	Site Name	Observed SOD grams/day/m2	Calibrated SOD grams/day/m2
NSBranch	17	SBR4	0.21	0.01
	61	NR2	0.17	0.15
	73	LR2	0.16	2.1
	90	NBRC1	0.16	0.15
	95	RC1	0.12	0.15
	108	NBRR1	0.16	0.15
	147	RR1	0.25	0.01
UpperMills	6	RB4	0.11	4.5
	20	UMR2	1.97	0.2

SOD influences the average DO and causes only minor impact on the diurnal variation. Diurnal DO swing is caused by the presence of algae and aquatic plants in the system. Photosynthetic and respiration processes from phytoplankton, benthic algae, and rooted aquatic plants are the major causes of diurnal DO variations.

Phytoplankton has a global implication in the model. Once the phytoplankton growth, respiration, and death rates are calibrated, they are effective for the entire system (within each watershed area model). Concentration of phytoplankton can only be affected locally by the presence of enough nutrients to support growth, or hydraulic properties. Chlorophyll measurements in the Raritan River Basin generally do not show concentrations that would cause a significant impact of diurnal DO. In fact, the calibration of phytoplankton has a marginal effect for most of the watershed area models. The calibration of chlorophyll and phytoplankton is discussed in the next section.

The levels of chlorophyll observed in the Raritan Basin are not enough to cause the strong diurnal DO variation that is present throughout the basin. The observed average is approximately 3 μg/l, and maximum values are around 15 to 20 μg/l for many stations. Phytoplankton is not the only photosynthetic organism that impacts the DO budget. Periphyton and aquatic plants, which are known to exist in abundance in the Raritan River Basin, were the most important aspect of the diurnal DO simulation.

The local parameter in WASP7.1 used to account for the presence of benthic algae and aquatic plants is the "percent of bottom segment covered by benthic algae" or simply fraction of benthic algae. This is a local parameter that varies from 0 to 1. The values of fraction of benthic algae were obtained through calibration. Although this is an important local parameter, benthic algae growth, respiration and death rates are global parameters and are also calibrated.

The calibration process, which involves global and local parameters, was performed iteratively. First, the values of global parameters were assumed based on existing applications of WASP and QUAL2K. The initial simulation was performed using average values of fraction of benthic algae, which demonstrates the direction the global parameters needed to be changed. Different growth rates, respiration, and death rates were tested. After the first round of global parameters calibration was performed, the local parameters were changed until meaningful simulations for the entire basin were obtained. This process was repeated for all the watershed area models. After many simulations, a unique set of global parameters affecting the growth of attached plants and diurnal DO was adopted for all the watershed area models. The calibrated value of the maximum growth rate of benthic algae and aquatic plants is 25 $gD/m^2/day$ and the calibrated values for respiration and death rates are 0.1 and 0.01 day^{-1}, respectively.

The values of the fraction of benthic algae were calibrated at all stations that have observed DO. When diurnal measurements were available, the local parameter was adjusted to capture the level of the observed diurnal swing. The fraction of benthic algae was interpolated for segments located in between calibration stations. The occurrence of benthic algae and macrophytes in the streams is highly variable and difficult to measure. Kleinfelder/Omni conducted measurements of periphyton for selected stations. However, because periphyton and aquatic plants are simulated as a single state variable, the observed periphyton data and the simulated values are not comparable. The calibrated values of the percent of bottom segment covered by benthic algae are shown in Appendix H.

The DO calibration focused on the low flow events, which tend to offer critical conditions in the stream. However, the continuous diurnal DO data collected under different flow conditions during the calibration period were also evaluated. Although the overall DO calibration is considered excellent, the representation of the diurnal DO is not ideal for all the events and locations in the Raritan River Basin Model. The sampling event performed in August of 2004 at the stations of the North/South Branch and Mainstem is one example. The observed diurnal DO obtained in August of 2004 show intense diurnal swing for a few consecutive days that cannot be replicated by the model at some locations. The intense DO variation occurs during periods of low flow and average values of temperature and solar radiation for the season. Data collected during periods when conditions were similar, or even more critical than the conditions observed in August of 2004, are very well captured by the model. The calibration parameters were not adjusted to capture the intense DO variability that is observed in August 2004 because this appears to be an isolated phenomenon. This phenomenon is illustrated in Figure 20 and Figure 21, which contrast two diurnal events at the same location in the South Branch Raritan River (SBRR7). Environmental conditions (flow, temperature) are similar in as far as they have been characterized; hence the simulation results are similar as well. However, the peaks in the 2004 event were much higher than can be explained by the environmental conditions that have been characterized. Note also that the issue of capturing the extent of the August 2004 peak is not related to the unexplained water quality observations in the mainstem discussed in Section II.D.5. As stated previously, this single event at a few locations should not detract from the overall assessment of DO calibration, which is excellent considering the scale and complexity of the Raritan River Basin Model.

Figure 20: Diurnal DO Peaks Not Captured by Model

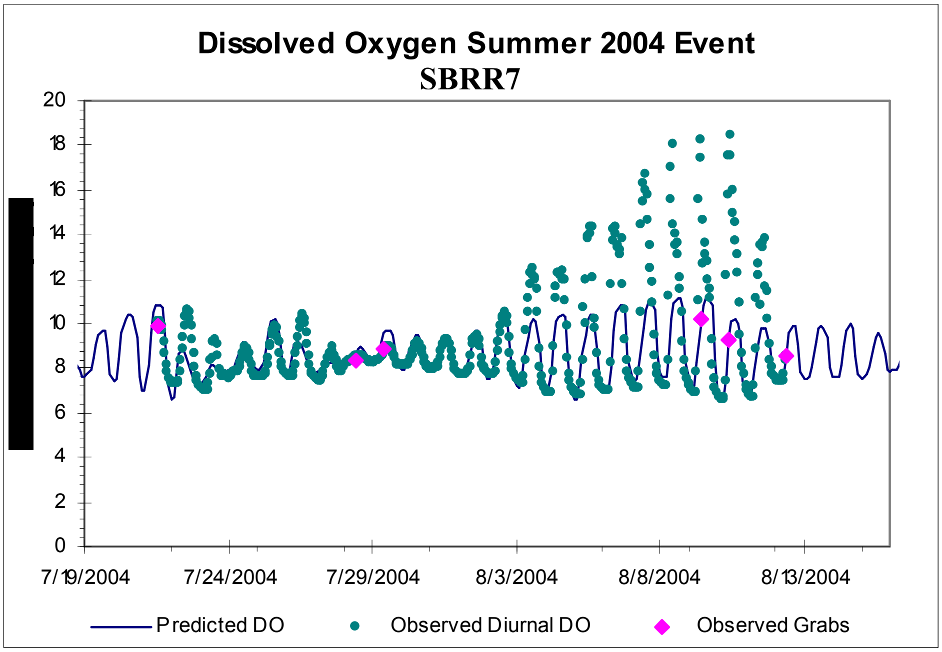
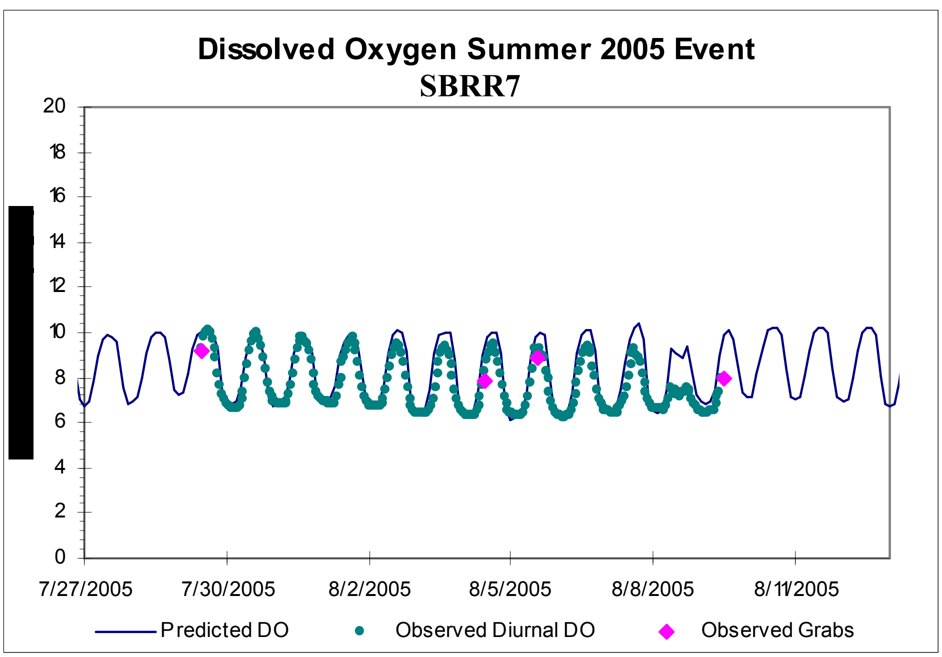


Figure 21: Diurnal DO Variation Captured (Conditions Similar to Aug 2004)



Minor weight is given to the calibration of diurnal DO at headwater segments. The DO at headwaters could be strongly influenced by the input headwater DO loads, which were not characterized as diurnally varying. When the local calibration parameters adjusted at the headwaters were considerably different from those calibrated at downstream stations, an average value for the branch was adopted for the headwater segments. The goal of this strategy is to preserve the meaning of the calibration parameter values, and not to “force” the model to replicate the observed data at the headwater segments.

The diurnal DO calibration indicates the strategy adopted for deriving DO loads was also appropriate for the Raritan River Basin Model. Input loads of DO for baseflow, releases and input boundaries vary daily according to stream water temperature and the percent of DO saturation. The process to obtain DO loads for baseflow is described in the nonpoint source input section of this report. Similar to the BFCs and EMCs, the percent DO saturation defined for each subwatershed was not subject to calibration. However, the headwater of the Lamington River and its downstream subwatershed in the North/South Branch watershed model area needed to be adjusted in order to capture the unusually low average DO concentrations observed in the fall at these stations. The original percent DO saturation calculated for LR1 (segment 71) and LR3 (segment 73) were 100% and 89%, respectively. The percent of DO saturation was adjusted to 75% in order to better capture the observed DO at these locations. This is a fairly modest adjustment within a reasonable range and is justified by the observed data.

The DO loads from lakes and reservoir releases were not subject to calibration and they were obtained similarly as the baseflow DO loads. Instead of obtaining the percent of DO saturation based on the land use distribution, the value of percent DO saturation for releases and boundaries was calculated or estimated based only on the sampling. The releases and boundaries where this methodology was adopted include Spruce Run Reservoir, Cushetunk Lake, and Carnegie Lake. Their input loads, including DO were added as boundary conditions directly in WASP7.1.

The EMCs adopted to estimate the input load of DO during storm events were not subject to calibration. The DO levels during the storm events are well captured for most of the events and locations. Dam reaeration coefficients were also not subject to calibration.

4. Chlorophyll

Chlorophyll provides a measure of the amount of phytoplankton in the water column. Chlorophyll was one of the first water quality variables to be calibrated. Phytoplankton growth is influenced by global kinetic parameters, stream water temperatures, solar radiation transport-related inputs and boundary inputs. Only the global kinetic parameters were subject to calibration. In addition, some boundary inputs were estimated based on observed data to provide a better representation of chlorophyll.

The phytoplankton maximum growth rate is the global parameter adjusted for chlorophyll calibration. The phytoplankton death rate and phytoplankton respiration rate were adjusted during the DO calibration. Observed chlorophyll levels were not significant for most watershed area models. The average observed concentration is approximately 3 μg/l. The maximum observed concentration was 47 μg/l, at the outlet of Carnegie Lake in the Beden Brook/Lower Millstone watershed area model.

The phytoplankton growth was calibrated individually for each watershed group. The value obtained for the North/South Branch and Mainstem are the same, 1.85 day^{-1}. The calibrated values for Beden Brook/Lower Millstone, Stony Brook and Upper Millstone are 0.75, 1 and 1.25 day^{-1}, respectively. These values are within the range suggested by the literature for phytoplankton growth (Chapra, 1997).

Boundary inputs of chlorophyll may be important at some locations. As the model's headwaters do not necessarily coincide with the actual headwater of the stream, the chlorophyll inputs were added in WASP7.1 as boundary concentrations. In general, the use of average concentrations for the boundaries provided good results. However, two of the headwaters required time series of chlorophyll to be derived: Beaver Brook in the North/South Branch and the outlet of Carnegie Lake in the Beden Brook/Lower Millstone. All boundary conditions are provided electronically in Appendix T.

5. Total Suspended Solids

Total suspended solids are mostly inorganic particles that are suspended in the water column. Although these particles are not dissolved in the water, they can react with substances such as organic phosphorus. TSS originates mostly during storm events. Soil erosion caused by rain and stream bank erosion that occurs under high flow conditions are the main processes responsible for TSS. Once the TSS reaches the stream, the natural processes affecting its concentration include settling and resuspension. WASP7.1 simulates the advective transport of TSS and settling. TSS is simulated independently. Even though fractions of dissolved compounds can be assigned in WASP7.1, they are not associated with TSS concentrations. The adsorption and desorption of substances to particulate material is also not simulated in WASP7.1.

TSS is generally a parameter difficult to simulate, due to the levels of uncertainty involved in the processes. The majority of TSS present in the streams is from nonpoint sources. However, point source discharges also provide TSS inputs to the stream. Soil erosion is a process that depends on weather conditions, soil type, land use and geomorphologic parameters. Many models have been developed to simulate the contribution of TSS in streams. The most common approach is the Universal Soil Loss Equation (USLE), which has being widely applied. TSS for the Raritan River Basin Model was estimated using the same methodology adopted for other water quality constituents. TSS EMCs were derived based on storm water samples and were assigned to each land use type. BFC concentrations were derived for the Raritan River Basin Model to account for TSS input from the tributaries within modeled subwatersheds.

The calibration of TSS was made in two phases: the watershed phase and the stream phase. The watershed phase consists of calibrating the sediment delivery ratio (SDR) parameter. This parameter is introduced in watershed models such as GWLF in order to take into account the trapping of particulate material within the watershed. The SDR was also adopted in HydroWAMIT in the same way. The stream calibration of TSS consisted of adjusting the settling rate at several segments. Note that in the case of TSS, there is no dissolved fraction, thus all the TSS is subject to settling.

There are a few empirical formulas and physical models developed to estimate the initial SDR values (Novotny and Olen 1994). SDR values are generally inversely proportional to the size of the drainage area. The bigger the drainage area, the bigger is the likelihood sediment particles will be trapped. However, the estimation of the SDR with empirical or physical methods is subject to much uncertainty, and the SDR was approached solely as a calibration parameter in the Raritan River Basin Model.

The SDR was derived as a ratio of measured TSS concentrations at the headwater stations and simulated TSS obtained without SDR at the headwaters. The concentrations of TSS at the headwaters are influenced only by nonpoint source inputs.

Therefore, the value of SDR was adjusted in order to capture the observed TSS at the headwater stations. Most of the watershed groups do not require the SDR, which reaffirms the technical basis for selecting EMCs. EMCs tend to lump many processes occurring at the watershed level. Only the Upper Millstone required a SDR value of 0.5 for all subwatersheds. The Upper Millstone headwaters drain to impounded ponds, which would be expected to cause a greater impact on SDR.

Settling of TSS in the stream was calibrated based on observed TSS data. Note that the settling functions and settling velocities adopted for TSS also affect calibration of organic phosphorus. Therefore, even though TSS and organic phosphorus are modeled separately in WASP7.1, the calibration of these variables is interconnected by the settling functions. This fact provides an additional challenge for calibration. Sediment settling was therefore calibrated prior to organic phosphorus or other constituent with particulate fractions. Since 100% of the TSS is particulate, only the settling velocity will impact the TSS concentrations in the stream. After the settling velocity was calibrated using the TSS data, the fraction dissolved of other constituents was adjusted.

WASP7.1 does not simulate sediment resuspension and stream bank erosion. These two processes are therefore not captured in the calibration. The effects of stream bank erosion are noticeable especially in the most downstream stations of the North/South Branch. Stream bank erosion occurs due to friction between the water and the banks. It is a function of soil properties and shear velocity. High TSS concentrations are observed at the downstream stations of the North/South Branch during high flow events. These events cannot be captured by the model, and they are consistent with stream bank erosion patterns. The headwaters and upstream stations, which are mostly influenced by runoff sources, compare favorably with observed TSS during high flow events; the downstream stations do not capture the peak TSS concentrations due to stream bank erosion and sediment resuspension.

The calibration of TSS is consistent with the calibration of organic phosphorus in the Raritan Basin, providing additional evidence of the quality of the simulations. Both TSS and organic phosphorus, which are independent variables, utilize a unique settling rate. This indicates the processes affecting these two variables, including settling itself, are well captured.

6. Calibration Considerations for Individual Watershed Groups

The same methodology for calibration was applied for all the watershed area models. Even though the methodology utilized was the same, the characteristics of each watershed area model presented different challenges for calibration.

The calibration of the North/South Branch provides good representation of all parameters and locations. The existence of many calibration stations was a challenge for this area. The use of settling rates for nitrate in the Lamington River is the only aspect that differentiates the calibration of the North/South Branch. The main difficulty for the North/South Branch calibration was the diurnal DO events of August 2004. The model is not able to predict the high diurnal variation observed for several consecutive days during that period for several stations.

Unlike the North/South Branch, which has a broad area covered by sampling stations, the Beden Brook/Lower Millstone does not have calibration stations on all the branches. Specifically, Pike Run does not have water quality measurements during the modeling simulation period. In order to overcome this problem, average values of existing stations in the Pike Run from 2001 were compared with average model outputs during similar flow conditions to confirm that model results are consistent with observed data.

Simulations of phosphorus, ammonia, nitrate, chlorophyll and TSS are generally good for most stations in the Beden Brook and very good for the lower Millstone River. The concentrations in the initial segments of the lower Millstone River branch are influenced by the boundary inputs from Carnegie Lake. Linear regressions were derived to simulate the input of water constituents from Carnegie Lake as a function of flow. This method provides very effective boundary conditions from Carnegie Lake. However, if changes occur in the contributing watersheds of Carnegie Lake, Stony Brook, and upper Millstone River, the effects of the changes are not automatically translated to the Beden Brook/Lower Millstone watershed area model. Carnegie Lake is an element of discontinuity in the Raritan River Basin Model. This was overcome by developing a separate boundary condition for the future simulations based on the TMDL condition being achieved in the Carnegie Lake basin (upper Millstone River and Stony Brook).

DO is the water quality constituent presenting the greatest challenge for the Beden Brook/Lower Millstone watershed area model. Although the representation of diurnal DO is satisfactory for most stations, some events are not well captured, and the calibration is based on the average of grab DO samples. In addition, SOD values in the lower Millstone River are the highest for the entire basin. The lower quality of the DO simulations at the Beden Brook/Lower Millstone model when compared to the North/South Branch model can be attributed to the quality and quantity of observed data and the uncertainty due to flow simulations. It is worth noting that the simulation of both TP and TSS, on which the TMDL evaluations were based, was excellent in the Beden Brook/Lower Millstone watershed area model.

The simulation of all parameters in the Stony Brook watershed area model was considered either good or satisfactory. The Stony Brook watershed area model is unique in ways that required special assumptions to be made for its calibration. The Stony Brook is highly influenced by discharge flows from Stony Brook RSA Pennington wastewater treatment plant. However, the Stony Brook is known to be intermittent for several miles downstream the discharge under extremely dry conditions. The section of the Stony Brook that dries up is located between a few miles downstream the discharge and upstream of the USGS Stony Brook at Princeton gage (01401000). This defines the Stony Brook's intermediate section. Because the flow of Stony Brook is interrupted during very low flow periods at the intermediate section, assumptions were made to account for this reality while avoiding model instabilities and the reporting of inconsistent data.

DAFLOW, which is the flow routing model, would crash if flows in the intermediate section were set to zero. In order to overcome this problem, a simulation strategy was developed to accurately represent the effects of the drought in the Stony Brook. The practical effect of the drought from the model's perspective is that loads from the Stony Brook RSA Pennington WWTP would not reach the downstream segments, and baseflow loads from the smaller tributaries would be the main contributors to the loads at the gage during periods when the intermediate section is dry. The solution therefore consists of eliminating the discharger loads during the drought periods and accounting for the baseflow loads which are in fact contributing to the stream's concentrations at the gage. Thus, when the gage flow was lower than the 90th percentile of flows (D90, 2 cfs), the loads from the treatment plant were not assumed to reach downstream segments. That is equivalent to assuming the intermediate section of Stony Brook is dry, and that the treatment plant loads are infiltrated through the stream bed and not returned to the system. This is a reasonable assumption given the fact that the stream loses flow during dry periods.

The discharger boundary conditions for nutrient inputs at the Stony Brook RSA Pennington WWTP were modified to incorporate this assumption. When flows at the Stony Brook gage are smaller than 2 cfs for the period of simulation, the WWTP boundary concentrations were replaced by baseflow concentrations. This happens for 59 days over the four year simulation period: 44 days in 2002, six days in 2004, and nine days in 2005. No flow less than 2 cfs was recorded in 2003 at the Stony Brook gage.

The substitution of the discharger loads by the baseflow loads addresses the intermittent load issue. However, because the flow is never zero in the model, plant and phytoplankton growth that occurred at periods prior to the drought would lead to inaccurate simulations. The output at the segments in the intermediate section should be ignored when the gage flows are less than 2 cfs. But in order to avoid those inaccuracies reaching the gage location during the drought, a parallel model was also developed. The parallel model is identical to the Stony Brook model with one exception: the boundaries concentrations at the discharger are equal to the baseflow concentrations for the entire simulation period. This provides a scenario without the inaccuracies of phytoplankton that would be propagated to the gage. The output from the parallel model is used during the drought time for the segments downstream of the intermediate section of the Stony watershed group.

The calibration of the Upper Millstone watershed area model provides good results at the internal calibration stations for all parameters including DO. The calibration at some of the headwaters is only satisfactory. The year adopted for calibration is 2004 for most stations. The most downstream station was calibrated for 2003 since it does not have data for 2004. The hydrologic model calibration was the biggest challenge for this watershed area model. There are limited gage data for the hydrology simulation. In addition, the data that are available are from the late 1980's that is not the same period as the water quality calibration. Some discrete flow measurements performed within the calibration period were used to validate the flow simulations and to calibrate the headwaters of the upper Millstone River. Even though the flow simulation could be considered a source of uncertainty for this watershed area model, the DO simulations are very good.

The Mainstem watershed area model defines the smallest stream network and it is a continuation of the North/South Branch and Beden Brook/Lower Millstone watershed area models. The calibration of the Mainstem was influenced by the boundary inputs from its contributing watershed area models. The outputs of the North/South Branch and Beden Brook/Lower Millstone were directly used as inputs for the Mainstem. One of the characteristics of the Mainstem is the confluence of two water bodies with very distinct characteristics: the Raritan River, which is the main focus of the model, and the Green Brook. The difference between the Raritan River and Green Brook presented a challenge to simulate them together within the same watershed area model. An example of the difficulty in simulating the Raritan River and the Green Brook in the same watershed area model is the choice of the reaeration method. The Raritan River required the Covar method, whereas the Green Brook would be better represented with the Tsivoglou-Neal method.

Low concentrations of phosphorus and nitrate were observed in the segment of the Raritan River immediately downstream of Somerset – Raritan Valley Sewerage Authority (SRVSA) WWTP. This problem is attributed to varied locations where the samples were taken within this model segment. During the sampling period, SRVSA effluent traveled through Cuckels Brook to the Raritan River via two paths according to different flow conditions. Samples were taken in between the Cuckels Brook discharge locations. Therefore, under certain flow conditions, the effluent discharge from the WWTP was not captured in some sample events (see Appendix M, pages 189-190). This is not a model issue, but it does render comparisons between observed and predicted concentrations at R3 less meaningful. As discussed in Section II.D.5, the diurnal productivity dynamics are not fully understood in this segment of the Raritan River. Extensive follow-up monitoring is currently underway at this location to better understand the system.

The subdivision of the Raritan River Basin into five watershed area models was beneficial for the model calibration. Because of this subdivision, the particular challenges of each watershed group could be addressed individually. In addition, parameters that vary significantly according to the stream, such as nitrification rates, could be changed among the different areas. On the other hand, parameters that do not vary among the areas, such as those involved in the luxury nutrient uptake routines, demonstrate the robustness of the model and the calibrated parameters. By looking at the five areas separately, the input and output files are not prohibitively large to perform the multiple simulations and the calibration effort is minimized.

IV. WATERSHED MODELING RESULTS

The Raritan River Basin Model, as described above, represents a system-wide water quality model that is calibrated and validated for nutrients, dissolved oxygen, and TSS. Watershed modeling analyses were performed to assess the impact of point and nonpoint source reductions on dissolved oxygen, phosphorus concentrations, and TSS in streams throughout the system.

A. Seasonal Variation and Critical Conditions

The TMDL analysis must account for seasonal variations and demonstrate compliance with water quality standards under critical conditions. These objectives were accomplished through continuous simulation over 44 months, from January 2002 through August 2005. These 3.7 years include a range of hydrologic conditions, both seasonal and year-to-year. The impact of typical spring rains, summer thunderstorms, summer dry periods, and low flows are all represented during continuous simulation over several seasons. Critical conditions are ensured through the inclusion of water years with both typical and extreme hydrologic conditions. 2002 and 2005 represent years with unusually hot, dry summers and extreme low flows. Both 2002 and 2005 included time periods when stream flows declined to 7Q10 levels (the few days below 7Q10 levels were excluded from TMDL analyses as explained in Section V.A). 2004 represents a typical year with a broad range of hydrologic conditions from very dry low flow periods to flood conditions. Finally, 2003 represents a wetter than normal spring and summer period.

B. Phosphorus and TSS Source Assessment

In order to characterize phosphorus and TSS loads in the Raritan River Basin, source assessments were performed using the Raritan River Basin Model described previously. Source assessment identifies the types of sources and their relative contributions. Six categories of phosphorus and TSS sources were evaluated for each watershed area model: WWTP point sources, stormwater point sources, agricultural runoff, NPS background, tributary baseflow, and boundary inputs. Phosphorus and TSS were selected because these pollutant sources are related to TP, TSS, pH, and DO impairments in the Raritan River Basin.

For the purpose of TMDL development, point sources include domestic and industrial wastewater treatment plants that discharge to surface water, as well as surface water discharges of stormwater subject to regulation under the National Pollutant Discharge Elimination System (NPDES). For this source assessment, load from WWTP discharges was characterized as the long-term average concentration associated with each discharger's effective effluent limitation multiplied by their permitted flow. This is consistent with NJDEP's definition of existing water quality, which takes into account the impact of permitted effluent flows. For dischargers with no effective effluent limit, the 90th percentile of actual effluent concentrations was used based on the effluent data that were assembled for this study (generally 5 years ending in July 2005). Stormwater point sources are modeled as NPS runoff in the Raritan River Basin Model; stormwater point sources are the portion of NPS runoff that originates from residential and commercial land use areas. Like nonpoint sources, stormwater point sources derive their pollutant load from runoff from land surfaces and load reduction is accomplished through Best Management Practices (BMPs). The distinction is that stormwater point sources are regulated under the Clean Water Act. Agricultural runoff is simply the portion of NPS runoff that originates from agricultural land use areas. NPS background includes NPS runoff that originates from forest (and barren land), wetland, and water land use areas. Tributary baseflow includes the NPS load each subwatershed delivered in small unmodeled tributaries during dry weather conditions.

Table 29 shows the areal stormwater and NPS loads (i.e., runoff yield) for TP, TSS, nitrate, and ammonia based on model output. Yields are provided approximately by watershed area model, except that the Beden Brook watershed is broken out from Beden Brook/Lower Millstone, and the remaining Beden Brook/Lower Millstone area is combined with the Mainstem. This breakdown is similar to what was applied for the TMDL evaluations. In addition, the total (area-weighted) yields for the entire Raritan River Basin Model extent are provided, as are the area-weighted composite runoff yields from all land use areas. All values represent the annual yields (lbs/acre/yr) over the entire simulation period.

Table 29: Areal Stormwater and NPS Pollutant Yields

Watershed Area Model	Residential	Other Urban	Agricultural	Forest / Barren	Wetland / Water	Composite NPS Runoff	Baseflow
Total Phosphorus (lb/acre/yr)							
NSBranch	0.77	0.77	0.70	0.08	0.41	0.47	0.11
UpperMills	0.56	0.57	0.15	0.03	0.28	0.28	0.16
Stony	1.14	1.09	0.90	0.11	0.54	0.60	0.07
Beden	1.10	1.07	0.96	0.14	0.60	0.63	0.06
LowerMills/Mainstem	0.73	0.89	0.57	0.06	0.36	0.55	0.07
Area-Weighted Average	0.77	0.81	0.61	0.08	0.39	0.48	0.10
Total Suspended Solids (lb/acre/yr)							
NSBranch	129	185	125	18	40	85	4
UpperMills	128	187	33	7	36	67	13
Stony	213	290	178	38	53	122	7
Beden	201	280	187	46	61	127	4
LowerMills/Mainstem	132	221	109	18	36	108	3
Area-Weighted Average	137	206	114	21	40	92	5
Nitrate-Nitrogen (lb/acre/yr)							
NSBranch	8.2	4.4	3.4	1.0	1.1	3.4	2.3
UpperMills	7.0	3.6	0.9	0.4	1.0	2.3	2.1
Stony	10.8	4.8	3.3	1.2	1.5	3.8	1.7
Beden	10.8	5.3	3.9	1.7	1.7	4.0	1.4
LowerMills/Mainstem	7.0	3.7	2.3	0.7	1.0	3.7	1.2
Area-Weighted Average	8.0	4.1	2.9	1.0	1.1	3.4	2.0
Ammonia-Nitrogen (lb/acre/yr)							
NSBranch	0.82	0.95	0.33	0.06	1.15	0.45	0.08
UpperMills	0.81	0.95	0.10	0.03	1.04	0.52	0.15
Stony	1.30	1.45	0.43	0.09	1.53	0.68	0.13
Beden	1.26	1.42	0.47	0.12	1.75	0.70	0.09
LowerMills/Mainstem	0.82	1.10	0.27	0.05	1.03	0.69	0.07
Area-Weighted Average	0.86	1.04	0.30	0.06	1.16	0.54	0.09

Boundary inputs are simply the boundary loads from unmodeled or linked contributing areas. Since almost all watersheds are modeled, there are not many boundary inputs. Upper Millstone, Stony Brook, and Beden Brook do not have any boundary inputs. Boundary inputs to North/South Branch include the load from Spruce Run watersheds, and water supply releases from Hamden and Whitehouse. The boundary inputs to Lower Millstone/Mainstem are the loads from Carnegie Lake to the Lower Millstone, the load from the Raritan River to Mainstem, and the load from the D&R Canal spillover at Ten Mile Lock into Mainstem. Boundary inputs from Carnegie Lake and Raritan River are excluded, since these boundaries link together watershed area models but do not represent additional loads to the overall system (in other words they are already counted). Average annual phosphorus and TSS loads to the Raritan River Basin are shown in Figure 22 and Figure 23, respectively.

Figure 22: Phosphorus Source Characterization

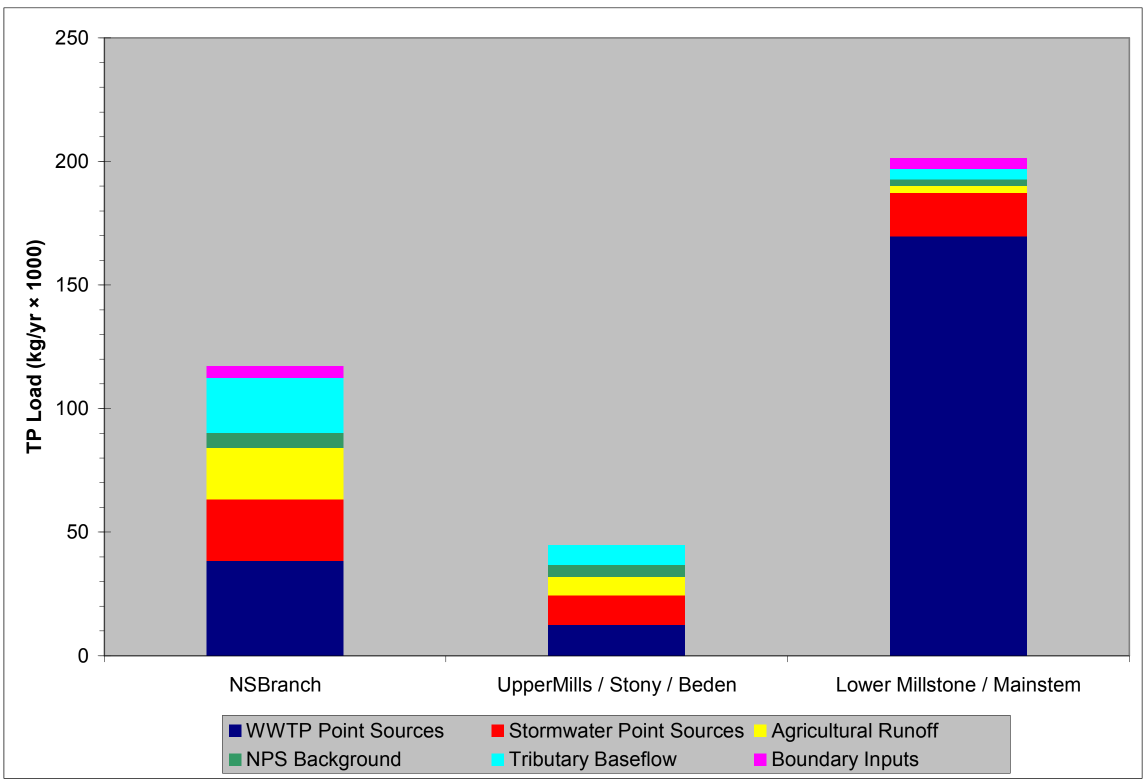
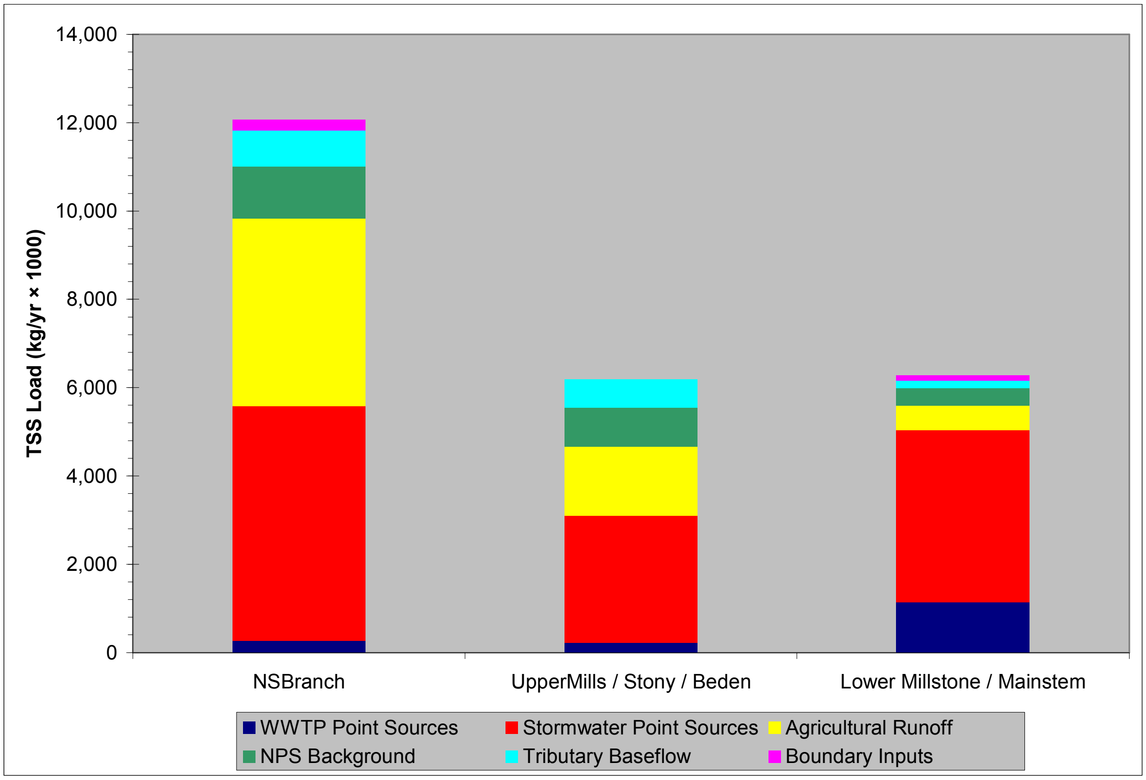


Figure 23: TSS Source Characterization



C. Model Scenarios

Many scenarios were simulated in order to understand the impacts of increases and decreases in phosphorus loads on water quality parameters, namely phosphorus and dissolved oxygen concentrations. A few of the more significant diagnostic scenarios are described below. Boundary conditions assumed for all these scenarios are provided electronically in Appendix T.

1. Existing Condition

The Raritan River Basin Model was run over the entire simulation period in order to define the Existing Condition. The calibrated and validated model essentially defines the Existing Condition for the Raritan River Basin. Boundary loads coming into the model domain represent the best estimate of actual loads that occurred during the simulation period. Similarly, point sources loads were based on the actual effluent flows and concentrations discharged during the simulation period, estimated based on actual records. Nonpoint sources, including runoff and tributary baseflow, were estimated based on actual conditions. The characterization of Existing Condition over such diverse hydrologic conditions throughout the Raritan River Basin represents a major achievement of this study. The WASP7.1 output for the Existing Condition simulation is provided electronically in Appendix T.

2. PermittedMax Condition

A PermittedMax simulation was developed in order to determine how water quality would change in the Raritan River Basin if point sources were discharging their maximum permitted flows at their maximum permitted concentrations. Not all dischargers have permit limits for all modeled constituents; in these cases, the 90th percentile of existing effluent data was used as the boundary condition for the PermittedMax Condition. This scenario represents a high upper boundary in terms of the impact of phosphorus sources on water quality in the Raritan River Basin. The PermittedMax Condition is not intended to be a realistic scenario, but rather a diagnostically useful upper bound on sources of phosphorus and other modeled constituents to the Raritan River Basin.

3. PermittedFlow Condition

The PermittedFlow Condition simulation was developed as a more realistic baseline future condition in order to determine how water quality would change in the Raritan River Basin if point sources were discharging their maximum permitted flows at their average existing effluent concentrations over the time period based on the effluent data that were assembled for this study (generally 5 years ending in July 2005). This scenario represents a more realistic future condition in terms of the impact of phosphorus sources on water quality in the Raritan River Basin. The PermittedFlow Condition is similar to the PermittedMax Condition, except that effluent concentrations for all modeled constituents are set to a constant value equal to the actual average concentration during the simulation period for each discharger.

4. Most Reduced Phosphorus Condition

Whereas the PermittedMax Condition represents an unrealistic upper bound of the load of phosphorus that could ever be expected to occur in the Raritan River Basin, the Most Reduced Condition (MRC) was developed to represent a lower bound to the load of phosphorus that could ever be expected to occur in the Raritan River Basin. The MRC was developed by making the following changes to the PermittedFlow Condition:

- All modeled point sources were set to 0.05 mg/l effluent TP concentrations (0.025 mg/l OrthoP and 0.025 mg/l OrgP);
- Phosphorus runoff loads from urban and agricultural land uses were reduced by 80%;
- Tributary baseflow phosphorus concentrations were reduced in order to be consistent with an 80% reduction of runoff loads using the methodology described in Section IV.D.1.

The purpose of the MRC was to define the water quality condition that would exist if all point sources were discharging at 0.05 mg/l total phosphorus, and all nonpoint runoff sources were reduced dramatically throughout the basin. The value of 0.05 mg/l for point source effluent concentration was selected because a long-term average concentration of 0.05 mg/l coincides with monthly effluent limitations near the phosphorus stream criterion (0.1 mg/l), and is generally considered an extremely stringent effluent limitation for phosphorus below which it would be very difficult to achieve consistent compliance. It is important to note that 0.05 mg/l total phosphorus is lower than the tributary baseflow concentrations in many of the contributing watersheds of the Raritan River Basin study areas, particularly in the upper Millstone River Basin. MRC was not designed as a realistic or achievable scenario; like PermittedMax and PermittedFlow, MRC was designed to be diagnostic in nature in order understand the potential benefits of phosphorus reductions.

5. Natural Condition

A Natural Condition simulation was prepared in order to estimate the pre-developed water quality condition for the Raritan River Basin. A new hydrologic and pollutant loading simulation was prepared using HydroWAMIT by converting all developed land (urban and agricultural) to forest, leaving only wetland, water, and forest land use cover. In addition, all point sources were removed. Finally, the phosphorus BFCs were set to the concentrations associated with forest and wetlands for each watershed area model (Table 30). The Natural Condition simulation provides a strong technical basis to characterize natural water quality; in accordance with the SWQS at N.J.A.C. 7:9B-1.5(c)1, “the natural water quality shall be used in place of the promulgated water quality criteria … for all water quality characteristics that do not meet the promulgated criteria as a result of natural conditions." The WASP7.1 output for the Natural Condition simulation is provided electronically in Appendix T.

Table 30: Phosphorus BFCs for Natural Condition Simulation (mg/l)

Watershed Area Model	OrgP	OrthoP	TP
NSBranch	0.004	0.006	0.010
UpperMills	0.034	0.020	0.054
Stony	0.004	0.006	0.010
BBLowerMills	0.003	0.007	0.010
Mainstem	0.005	0.020	0.025

D. Impact of Phosphorus Reductions

The Raritan River Basin Model was applied primarily to relate point and nonpoint sources of phosphorus to simulated water quality targets, namely TP and DO concentrations. Generally, the PermittedMax Condition increased the frequency of exceedance of the phosphorus criteria, and also increased the diurnal DO swing in many areas, thereby increasing the degree of exceedance of the maximum pH criterion as well. As expected, the Most Reduced Condition resulted in much lower phosphorus concentrations than necessary to satisfy the phosphorus criteria, and also more reduction in DO swing than necessary to bring the peaks below the pH thresholds. Therefore, phosphorus reduction scenarios were developed based on unique and customized combinations of point and nonpoint source reductions in order to satisfy water quality targets throughout the basin.

1. Approach to Developing Phosphorus Reduction Scenarios

Phosphorus reduction scenarios were all based on boundary condition modifications to the PermittedFlow Condition (Section IV.C.3). PermittedFlow was selected as the baseline future condition for several reasons. The flow model simulated treatment plants discharging at a constant rate equal to their maximum permitted flows. This represents the most critical condition in terms of point source impact, since it maximizes the phosphorus load delivered to modeled streams under any particular effluent concentration assumption. The difference between the Existing Condition and the PermittedFlow Condition was minimal in terms of productivity indicators; therefore, the additional treatment plant flow was not enough to attenuate DO swing significantly.

This makes sense because treatment plant flow is small compared to natural baseflow in the Raritan River basin, even in areas with more point sources.

The other important flow assumption built into PermittedFlow, and all the model scenarios, is that water supply diversions and releases throughout the system were simulated at the rates they actually occurred during the simulation period. In other words, the same time series of diversions and releases from all water supply boundaries that were used for the Existing Condition were also used for the future conditions. According to NJWSA, the current demand for the Raritan Basin Water Supply System is 124 mgd, while the current safe yield of the system is 176 mgd. NJWSA supplied a set of time series developed using their Riverware operations model that represents the diversions and releases that would be associated with the Raritan Basin Water Supply System operating at its safe yield of 176 mgd under the hydrologic conditions that occurred during the simulation period. However, as a result of the manner in which water is stored in the reservoirs and made available for water supply by being released into the river systems during low flow period, the water supply system has the effect of mitigating critical productivity. Water released from Spruce Run and Round Valley reservoirs increases flows in the North and South Branch systems during critical summer periods, thereby decreasing nutrient impacts. A future water supply scenario that captures a higher demand would release more water into the river for longer periods of time during, further mitigating critical low flow conditions. Therefore, the current safe yield condition for water supply was selected as the baseline condition for phosphorus reduction scenarios.

Scenarios to simulate phosphorus reductions from WWTP discharges were developed by making two types of changes to the baseline (PermittedFlow) simulation. First, the effluent concentrations for OrthoP and OrgP were changed to the desired level for all WWTP point sources explicitly modeled as both flow and water quality (Table 5). Second, the OrthoP and OrgP loads for all remaining WWTP point sources (Table 31) were set equal to the desired concentration multiplied by the permitted flow for each discharger. Since most of these additional WWTP point sources were simulated as loads, these changes was made within the HydroWAMIT pollutant loading model. Two of the additional dischargers, Exxon Research and Clinton West, were simulated together with NJDC – Mountainview, since all three dischargers are located along the same segment of Beaver Brook.

Table 31: Additional Dischargers Simulated for Future Conditions

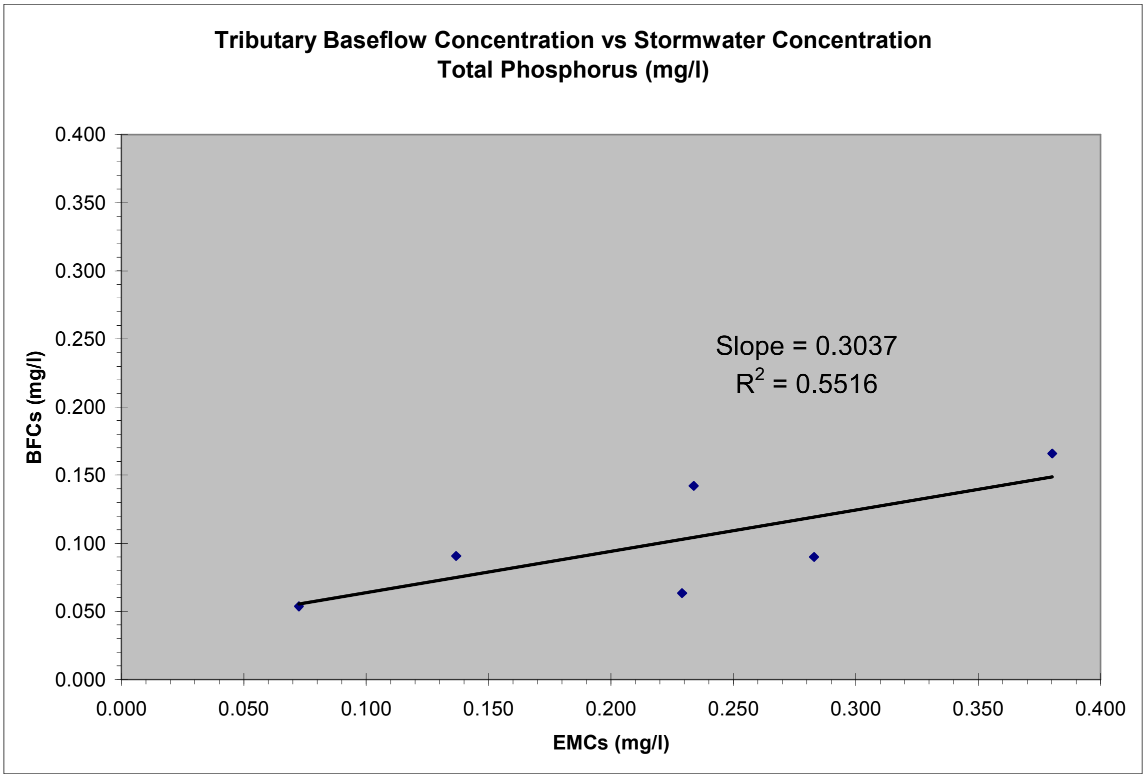
Watershed Area Model	Branch	Node	Description	Discharge/Release Type
NSBranch	2	1	Day's Inn - Roxbury – Ledgewood	Domestic WWTP
NSBranch	4	2	Exxon Research	Industrial WWTP
NSBranch	4	2	Clinton West	Municipal WWTP
NSBranch	7	7	Glen Meadows/Twin Oaks	Domestic WWTP
NSBranch	12	1	Hercules Kenvil Works Facility	Industrial WWTP
NSBranch	12	12	Chester Shopping Center	Domestic WWTP
NSBranch	12	16	Valley Rd Sewer Co - Pottersville STP	Municipal WWTP
NSBranch	12	19	Fiddler's Elbow CC - Reynwood Inc	Domestic WWTP
NSBranch	13	1	Route 78 Office Area – Tewksbury	Domestic WWTP
NSBranch	14	1	Clinton Twp BOE - Round Valley	Domestic WWTP
UpperMills	1	1	Elementis	Industrial WWTP
UpperMills	8	1	USDOE PPPL	Industrial WWTP
UpperMills	9	2	David Sarnoff Research	Industrial WWTP
UpperMills	9	2	Firmenich Inc	Industrial WWTP
BBLowerMills	1	14	Montgomery Twp - Skillman Village	Municipal WWTP
BBLowerMills	2	3	Carrier Foundation Rehab STP	Domestic WWTP
BBLowerMills	2	7	J & J Consumer Products	Industrial WWTP
BBLowerMills	2	11	Montgomery Twp - Oxbridge	Municipal WWTP
BBLowerMills	5	11	Montgomery Twp - Riverside	Municipal WWTP
BBLowerMills	5	19	Industrial Tube Corp	Industrial WWTP
BBLowerMills	5	19	VA Supply Depot	Industrial WWTP
Mainstem	4	1	Colorado Cafe WTP	Domestic WWTP

Scenarios to simulate NPS phosphorus reductions were developed by making changes to the EMCs and BFCs within HydroWAMIT. The OrthoP and OrgP EMCs for runoff from urban and agricultural land areas were reduced by the specified NPS percent reduction. For example, the EMCs for runoff from agricultural land area are 0.191 mg/l OrthoP and 0.164 mg/l OrgP (0.355 mg/l TP). In order to implement a 60% NPS reduction scenario, the agricultural runoff EMCs would be reduced by 60%, or multiplied by (1 – 0.6), or 0.4. This would result in agricultural runoff EMCs of 0.076 mg/l OrthoP and 0.066 mg/l OrgP (0.142 mg/l TP). A 60% NPS reduction would therefore simulate the agricultural runoff load at 40% of its current estimated load.

Changes to BFCs are simple to implement within HydroWAMIT, but the derivation of their assigned values is more complicated. As discussed previously, measured tributary baseflow concentrations for TP were found to vary according to land uses. As a result, BFCs were estimated according to the composition of urban, agricultural, and forest/wetland area in each subwatershed. It is important to reiterate that tributary baseflow quality is not the same as groundwater quality. Tributary baseflow originates from groundwater, but is delivered to modeled streams in small unmodeled tributaries. This conceptual model of how baseflow enters the modeled streams is consistent with the manner in which baseflow quality was measured in the field: small tributaries were sampled under baseflow conditions. The fact that baseflow TP concentration varies with land use reflects the interactions of the baseflow with the stream bank and bed, and indicates that baseflow TP concentration is influenced indirectly by NPS runoff. This argument is bolstered by the fact that the same relationship of baseflow quality and land use is not evident for soluble pollutants such as nitrate or even OrthoP, which could conceivably be expected from NPS other than runoff (such as failing septic systems or infiltration of fertilizer into groundwater). In accordance with feedback and direction from NJDEP, Kleinfelder/Omni assumed, for the development of phosphorus reduction scenarios, that runoff load reductions will also result in a reduction of phosphorus in tributary baseflow. It certainly makes sense that if baseflow quality is affected by NPS runoff, and improvements are made to NPS runoff, that these improvements would eventually be reflected in tributary baseflow quality. However, it must be noted that to the extent that tributary baseflow is affected by nutrient accumulation in stream beds, it is not possible to determine how long it would take after NPS runoff improvements are made before baseflow quality might be expected to improve.

Six monitoring locations in small subwatersheds representative of individual land uses were sampled for both stormwater and baseflow during the Phase I monitoring program (TRC Omni, December 19, 2005). Figure 24 shows the linear slope of the average baseflow phosphorus concentration at each sampling site versus average stormwater concentration at each sampling site where both stormwater and baseflow quality were measured. The graph shows that areas with higher phosphorus concentration in stormwater also have higher phosphorus concentration in tributary baseflow.

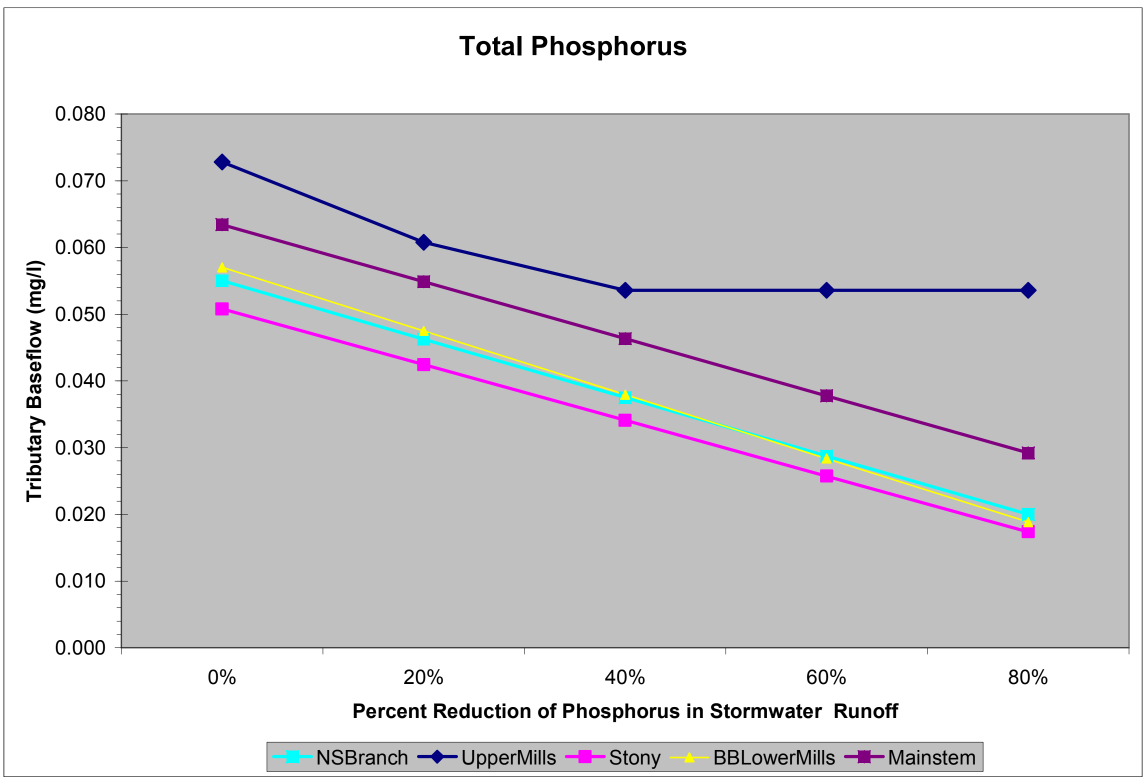
Figure 24: Relationship Between BFCs and EMCs



Stormwater quality improvements were related to baseflow phosphorus concentrations by multiplying the slope by the percent of NPS runoff reduction and modifying the BFCs associated with agricultural, urban and forest/wetlands land uses in each watershed area model. BFCs for TP were then recalculated for each subwatershed, except that the resultant BFC for each subwatershed was constrained so that the TP concentration would not be allowed to go below the BFC associated with forest/wetlands for each watershed area model. Figure 25 shows the average subwatershed BFC for TP in each watershed area model for various NPS runoff reduction percentages. The BFCs in Upper Millstone were constrained by the relatively high value of 0.054 mg/l TP associated with forest/wetland, indicative of the naturally high phosphorus levels in this particular watershed.

While the stormwater to baseflow quality relationships are based on TP, it is important to understand that the BFC reductions are applied to OrgP. The reason for this is that baseflow OrthoP concentrations do not show the relationship to land use that was observed with TP. OrthoP BFCs for future scenarios were assigned in the same manner as for the Existing Condition: OrthoP was set to 0.006 mg/l in North/South Branch, 0.02 mg/l in Upper Millstone and Mainstem, and to fixed percentages of the TP BFC in Stony Brook and Beden Brook/Lower Millstone (57% OrthoP in Stony Brook and 72% OrthoP in Beden Brook/Lower Millstone). OrgP BFC for each subwatershed was calculated simply as the difference between the TP and OrthoP BFCs. Baseflow data in the Stony Brook and Beden Brook watersheds did not support a fixed OrthoP concentration, but rather a fixed percentage of TP. This approach is strictly based on the best use of available data. Conceptually, however, the approach suggests that TP delivered in tributary baseflow is influenced by stormwater runoff impacts to the stream bed, but that the distribution between OrthoP and OrgP is influenced by the watershed characteristics such as soil types.

Figure 25: Influence of Stormwater Quality Improvements on Baseflow Concentrations



2. Impact of Phosphorus Reductions from Runoff Sources

NPS phosphorus reductions from urban and agricultural land areas exert a profound impact on TP concentrations in streams and lakes throughout the Raritan River Basin. In order to assess the impact of NPS phosphorus reductions, three diagnostic simulations were developed with all WWTP point sources effluent concentrations set to

0.05 mg/l TP, and NPS reductions set to 20%, 60%, and 80%. Even with minimal influence of WWTP point sources, stormwater sources would cause most streams in the Raritan River Basin to exceed 0.1 mg/l TP, and virtually all "in-line" lakes to exceed 0.05 mg/l during high flow periods. Examples are illustrated in Figure 26 and Figure 27.

The influence of NPS runoff on productivity (i.e. diurnal DO swing) is less important, but certainly not negligible. Figure 28 shows diurnal DO simulations in an agriculturally-dominated watershed with no WWTP point sources, the Neshanic River. Horizontal red lines indicate the minimum DO criterion of 4 mg/l and a high DO threshold near a level associated with pH peaks of 8.5 s.u. Summer DO peaks, which are correlated with pH peaks, are clearly attenuated during critical periods by NPS reductions.

Figure 26: Influence of NPS Reduction on TP Concentration in Lakes

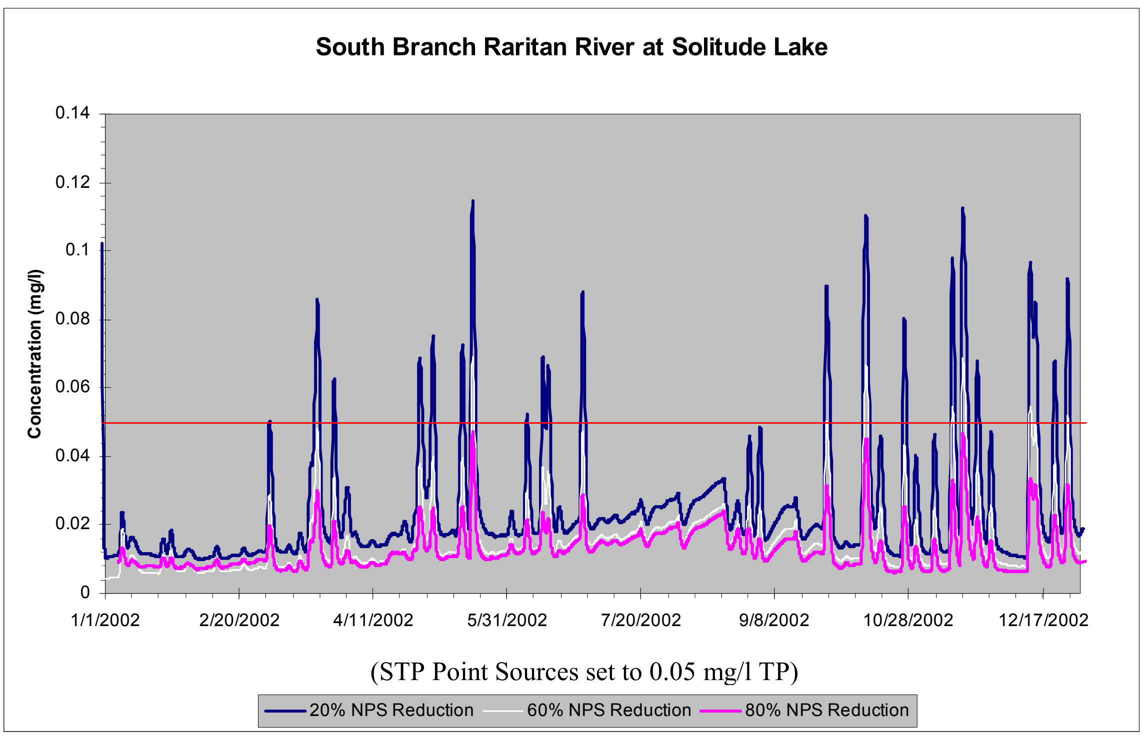


Figure 27: Influence of NPS Reductions on TP Concentration in Streams

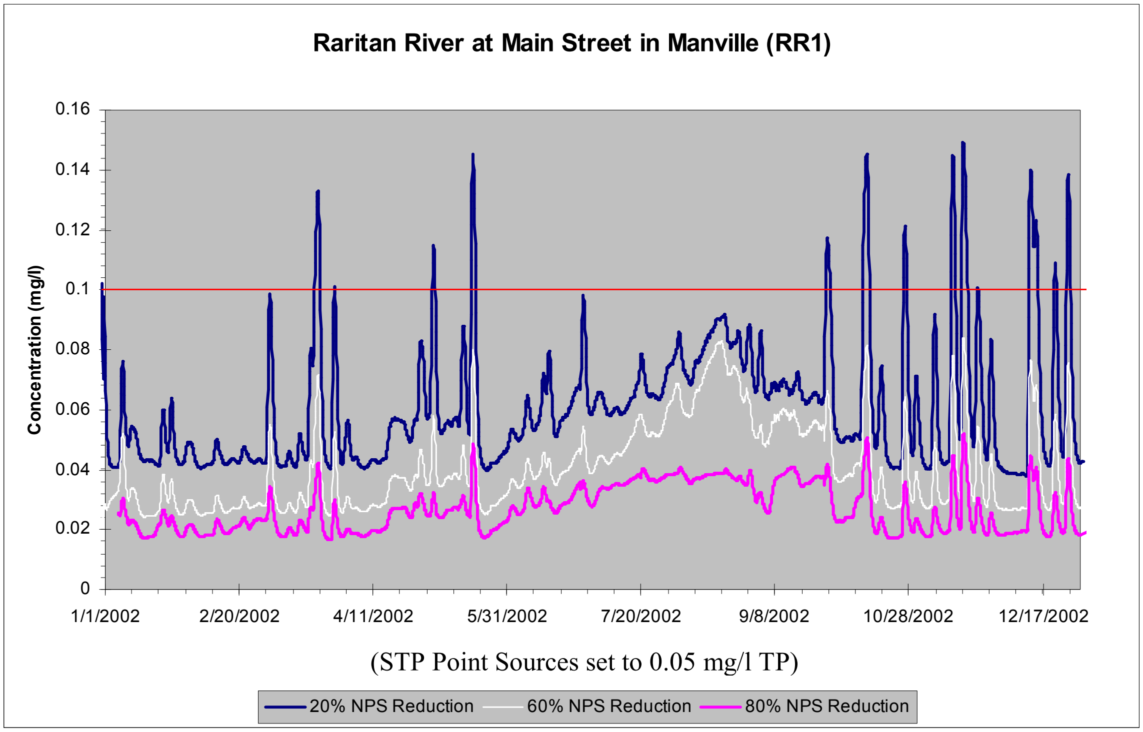
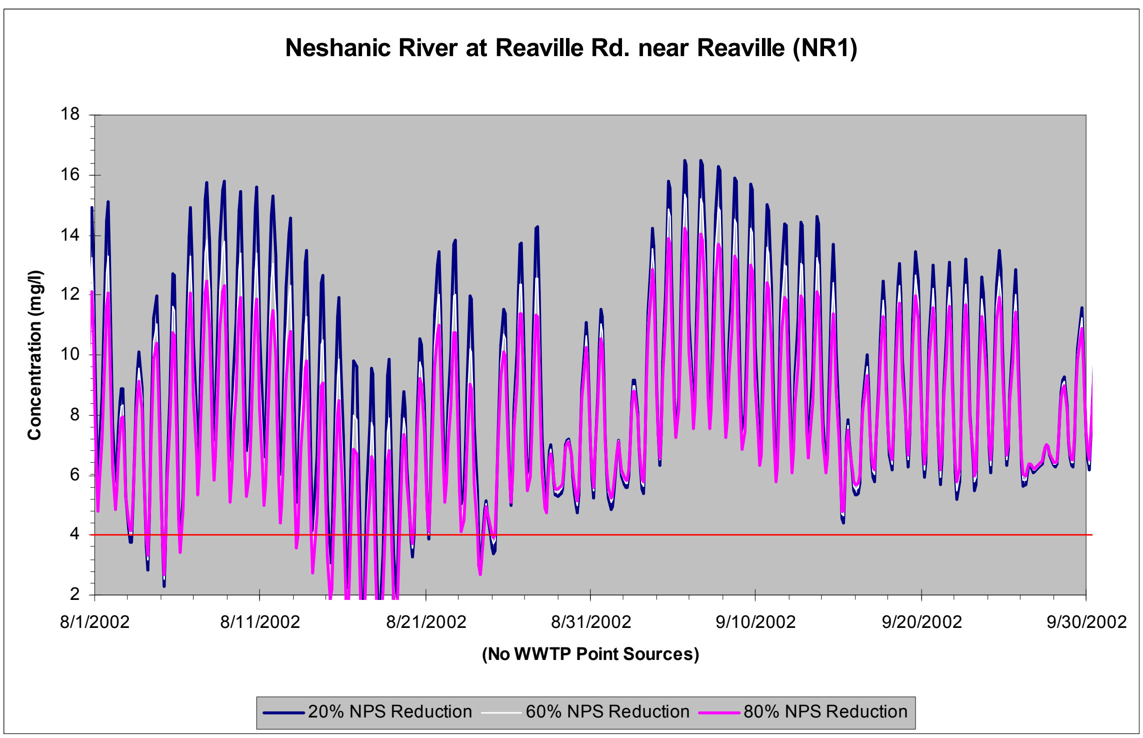


Figure 28: Influence of NPS Reductions on Diurnal DO (and pH) Peaks



3. Impact of Phosphorus Reductions from WWTP Point Sources

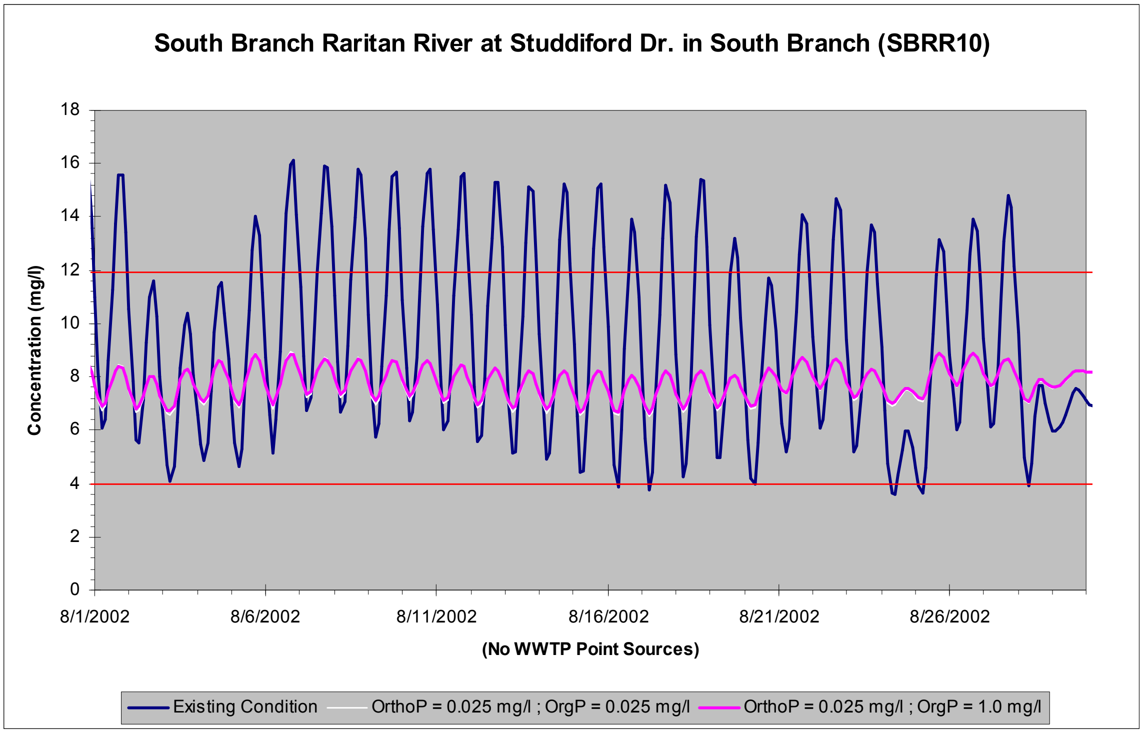
Because WWTP point sources supply a constant phosphorus load even during dry-weather low-flow conditions, they exert a major impact on productivity. Testing various effluent concentrations is complicated by the fact that it is necessary to make an assumption regarding the ratio of OrthoP to TP. This ratio varies greatly from one treatment plant to another depending on the type of effluent limit and the type of treatment process. Furthermore, the impact on productivity depends directly on the assumed ratio of OrthoP to TP. In fact, the impact on productivity depends directly on the concentration of OrthoP; the concentration of OrgP does not impact productivity noticeably within the stream system.

Only OrthoP is available for plant and periphyton uptake. To the extent that OrgP does affect productivity, the impact would be greatest at downstream locations such as the outlet of the South Branch Raritan River (SBRR10) where phosphorus has the highest retention time and opportunity to convert to available OrthoP. Figure 29 shows predicted DO at SBRR10 for three scenarios: the Existing Condition, MRC (OrthoP and OrgP in effluent = 0.025 mg/l), and a modified MRC with effluent OrgP set to 1 mg/l. Reducing phosphorus in WWTP effluent profoundly reduces diurnal DO swing at this location. However, diurnal DO remains the same whether the effluent OrgP is 0.025 mg/l or 1.0 mg/l. While OrgP does mineralize into OrthoP in the Raritan River Basin Model, the rate is not fast enough relative to residence time to generate enough OrthoP to affect productivity levels, as indicated by diurnal DO swing.

OrgP within a modeled stream is subject to mineralization, settling, and transport, which means it either converts to OrthoP, settles out, or flushes through the system. The model simulates all three of these fates; since sediment dynamics are not simulated, the model assumes that the OrgP that settles out is lost from the system. In reality, it is likely that OrgP is washed out of the system during large storm events, or permanently sequestered in some locations. There is no evidence that phosphorus within the sediment is acting as a source to the water column during low flow periods. In fact, the North and South Branch system exhibits a wide range of phosphorus concentrations, and in all cases the data show a net loss out of the water column, which is represented as settling. The insensitivity of DO swing to OrgP loads is not merely an artifact of the model’s conceptualization.

Given the fact that the ratio of OrthoP to TP in WWTP effluent cannot be assumed with any degree of certainty, and that it is the effluent OrthoP that drives productivity, iterative TMDL simulations were used to identify the effluent OrthoP concentration necessary to achieve water quality targets based on DO (and pH).

Figure 29: Impact of WWTP Effluent OrthoP and OrgP on Productivity



E. Model Assumptions and Limitations

The Raritan River Basin Model provides a strong technical basis upon which to relate sources of phosphorus and TSS to water quality targets, namely phosphorus concentration, dissolved oxygen, and (through correlation with DO peaks) pH peaks. However, there are a number of assumptions inherent in the model and the manner in which it was utilized to explore various source reduction scenarios. These assumptions represent limitations that must be considered when developing the TMDL and Margin of Safety, interpreting model predictions, and implementing the source reductions necessary to achieve the TMDL Condition. Some of the key assumptions and limitations are discussed below.

1. Boundary Condition Assumptions

Boundary conditions are model inputs that represent assumptions; actual boundary conditions are not known. For instance, water temperatures were estimated based on air temperature. Other weather-related time series also represent boundary condition assumptions, namely solar radiation and precipitation. Finally, loads from simulated WWTPs, stormwater, and baseflow loadings were estimated based on concentration and flow of boundary conditions (effluent concentrations, EMCs, and BFCs). While there is a technical basis to estimate all these boundary conditions, they remain important assumptions. It is important when evaluating simulation results to remember that boundary conditions are assumed inputs.

2. Role of Sediment

The Raritan River Basin Model makes two important assumptions regarding the role of sediment that are important to understand. The first assumption is that modeled periphyton and aquatic macrophytes obtain their nutrients from the water column. The second assumption is that organic phosphorus in sediment does not get recycled to either aquatic macrophytes or to the water column. These assumptions, which are closely related to one another, are discussed below.

The uptake of phosphorus by aquatic macrophytes is complex and not completely understood. Rooted macrophytes, which are attached to the stream bottom, obtain their necessary phosphorus supply in the form of dissolved orthophosphate available in the water column or as interstitial orthophosphate available in the sediments. The role of sediment versus water column nutrition depends highly on the species of plant, available phosphate in the sediment and water column, and physical-chemical properties of the site.

Most of the research conducted to address the role of roots versus shoots and sediment versus open water in the nutrition of submersed aquatic macrophytes has focused on lentic alkaline waters (i.e., lakes). These studies performed in lake waters suggest that sediment is often the main source of phosphorus for aquatic plants (Barko and Smart, 1980; Rattray et al., 1991). However, the experiments that attempt to explore the relative importance of sediment or water as a source of nutrient in flowing waters are not conclusive because of the effects of a wide range of environmental variables (Thiebaut and Muller, 2000). Phosphate uptake from the water column by macrophytes in shallow streams is more common than for macrophytes in lakes (Pelton et al., 1998). More recent studies (Vindbæk and Cedergreen, 2002) demonstrate that macrophytes (*Elodea canadensis*, *Callitriche cophocarpa*, *Ranunculus aquatilis* and *Potamogeton crispus*) are able to satisfy their demand for nutrients through leaf uptake alone.

The Raritan River Basin Model does not simulate macrophytes or the sediment bed explicitly. Instead, it uses the periphyton module of WASP7.1 to mimic the effect of macrophytes in the stream. The periphyton module simulates orthophosphorus uptake from the water column. However, the settling of particulates and the nutrient luxury uptake algorithms allow the effects of macrophytes on phosphorus dynamics to be represented. The water column phosphorus constituents (dissolved orthophosphate and organic phosphorus) are calibrated independently. The dissolved orthophosphate is largely controlled by plant uptake, whereas organic phosphorus is controlled by settling and decay. A very small fraction of dissolved orthophosphate is assumed to settle, meaning that it is removed from the water column by a process that is not simulated; very likely, it binds to a particulate form and settles out. The periphyton and plants are assumed to uptake dissolved orthophosphate in the water column and to release organic phosphorus due to plant death/decomposition.

The absence of the sediment bed in the model, and consequentially the available interstitial orthophosphate for plant root uptake, is overcome by the nutrient luxury uptake algorithm. The calibration of the nutrient luxury algorithm parameters, such as cell quotas, allows the sediment phosphorus to be indirectly accounted in the model. The storage of nutrients in cells is essentially analogous to the storage of interstitial phosphorus in sediment. Furthermore, phosphorus that is taken up by periphyton and plants returns to the water column as attached algae excretion or in the form of organic phosphorus due to plant death/decomposition.

The assumption that periphyton and aquatic macrophytes obtain their nutrients from the water column represents the current state-of-the-art with respect to water quality modeling, as reflected in the WASP7.1 kinetic formulations. Furthermore, reduction of nutrient loadings from municipal sources has been documented to reduce macrophyte growth (Sosiak, 2002); the fact that a reduction in water column phosphorus led to a reduction in macrophyte growth indicates the macrophytes are obtaining their nutrients from the water column. Similarly, macrophyte density and diurnal DO swings have decreased noticeably in the South Branch Raritan River in Clinton following phosphorus removal at the Town of Clinton WWTP. Again, the fact that reductions of phosphorus from WWTPs result in reduced macrophyte growth demonstrates that macrophytes are dependent on water column phosphorus. While the assumption that macrophytes obtain their nutrients from the water column is generally supported and justified, there may well be localized areas within the Raritan River Basin where this assumption is violated. In particular, areas dominated by emergent macrophytes (as opposed to submerged aquatic vegetation) would be less likely to be wholly dependent on the water column. The upper Lamington River in Roxbury is one such area. However, the areas with pH and DO water quality targets on which the TMDL evaluations were based contain submerged macrophytes that would be expected to be dependent on water column nutrients.

Recall that OrgP within a modeled stream in the Raritan River Basin Model is subject to mineralization, settling, and transport, which means it either converts to OrthoP, settles out, or is transported through the system. The assumption that organic phosphorus that settles to the sediment does not get recycled to either aquatic macrophytes or to the water column is supported by the low SOD prevalent throughout much of the system. If nutrients were accumulating significantly in the sediment, associated organic material would also be accumulating and exerting an oxygen demand (SOD) on the water column. The fact that SOD rates are very low (as determined through calibration and limited field measurements) demonstrates that nutrients and organic matter are not accumulating significantly in the stream beds. The occurrence of SOD is relatively easy to detect through calibration, since actual DO levels would be lower than expected. Such was rarely the case in the Raritan River basin, indicating that significant SOD is not the typical condition. Given the slopes and flashy hydrology, it appears likely that settled particulates are resuspended and transported through the system during major storm events. This is consistent with the fact that the Raritan River Basin Model does not fully capture measured TSS peaks during large storm events at downstream locations.

It is also evident, based on the data collected and modeling performed, that phosphorus in sediment is not being recycled to the water column. Recall that the lower section of the Stony Brook, which seems to behave partially as a lake due to its proximity to Carnegie Lake, is the only area where benthic phosphorus loads were needed to explain observed data; this provides great assurance that nutrient loads from the sediment to the water column are not generally important in the system. There are many locations in the Raritan River Basin where water column orthophosphorus is already very low; these are the very conditions that would tend to maximize the importance of benthic nutrient loads. Indeed, the Raritan River basin exhibits a wide range of phosphorus concentrations, and yet in all cases a net loss of phosphorus from the water column to the sediment occurs. Both data and modeling demonstrate that benthic phosphorus sources are not important in the Raritan River basin and are not likely to become important under different loading scenarios.

While the assumptions regarding the role of sediment are generally well supported and justified, the Raritan River Basin Model may underestimate the benefit of phosphorus and sediment reductions in agriculturally-dominated watersheds such as the Neshanic River, Pleasant Run, and Holland Brook. Only the Neshanic River and the outlet of the Holland Brook were actually modeled; however, all three streams exhibit major sedimentation (e.g., Figure 30). Given the obvious sediment accumulation, it is likely that sediment dynamics, which are not modeled in WASP7.1, play a more important role in these watersheds. All three watersheds contain only NPS and stormwater sources (i.e., no WWTP sources). The Raritan River Basin Model predicts some amelioration of nutrient impacts associated with NPS and stormwater load reductions, but there may also be an additional long-term improvement that would occur as nutrients are washed out of the sediments. The TMDL allocations for stormwater sources were based on satisfying numeric phosphorus criteria; however, the model may underestimate the associated benefits to the stream in terms of reduced productivity and enhanced oxygen conditions. It should also be noted, based on the mucky conditions and high SOD, that the reduction of sediment loads and bank stabilization is at least as important as phosphorus reductions in these agriculturally-dominated watersheds.

Figure 30: Sedimentation in Pleasant Run

3. Tributary Baseflow Quality

As described previously in Section D.1, phosphorus reduction scenarios assume that decreasing phosphorus in stormwater will result in reductions of phosphorus in tributary baseflow concentration. The basis for this assumption is the same as the basis for the assignment of tributary baseflow phosphorus concentrations that vary according to land use composition in each subwatershed. The stormwater and baseflow data collected during the monitoring phase of the Raritan TMDL Study (TRC Omni, December 19, 2005) indicate that tributary baseflow TP is higher in developed areas than undeveloped areas. This is not attributable to groundwater contamination, since it is the particulate phosphorus component that varies with land use. The more mobile nutrient species such as orthophosphorus and nitrate do not show the same variation with land use, such as might be expected if groundwater contamination were responsible. Although baseflow obviously originates in groundwater, it is delivered to modeled streams in small surface tributaries similar to the manner in which it was measured. It is the interaction with the sediments within the tributary system that is therefore responsible for the observed variation of TP concentration with land use. Land use impacts are primarily caused by stormwater, which is obviously generated during storms.

However, the impacts to the stream bed are also apparent, albeit to a lesser degree, during baseflow conditions.

Measures designed to reduce stormwater loads, if effective, would theoretically also reduce the impact of those stormwater loads on tributary baseflow quality. Figure 25 shows the assumed influence of NPS runoff reduction on TP concentration in tributary baseflow. While this approach is strictly based on the best use of available data, it remains an assumption applied to future phosphorus reduction scenarios. It is not known whether or how long it might take, after stormwater improvements are made, for tributary baseflow quality to improve. The assumption that tributary baseflow phosphorus concentration would decrease toward natural baseflow quality with increasing NPS stormwater reductions is reasonable, given the variation in baseflow quality observed within different land areas, to prevent future scenarios from attributing anthropogenic sources of phosphorus to background.

While the stormwater to baseflow quality relationships are based on TP, it is important to understand that the BFC reductions are applied to OrgP only. As explained in Section D.1, the approach suggests that TP delivered in tributary baseflow is influenced by stormwater runoff impacts to the stream bed, but that the distribution between OrthoP and OrgP is influenced by the watershed characteristics such as soil types. OrgP in tributary baseflow is not a significant driver for compliance with instream 0.1 mg/l TP criterion, nor does it significantly influence diurnal DO. As a result, the assumption that decreasing phosphorus in stormwater will result in reductions of phosphorus in tributary baseflow concentration is not a major issue from a TMDL evaluation perspective.

4. DO Peaks as Surrogate for pH Peaks

As stated previously, pH was not modeled directly; this represents an important model limitation. Maximum DO thresholds were developed based on linear regressions of diurnal peak DO and pH measurements from mid-July through August. The fact that data were not abundant enough to establish thresholds during other seasons also represents a limitation. The DO thresholds (Table 2) were set to the DO value correlated with a pH of 8.5 s.u., the maximum pH criterion in the SWQS. DO and pH are not causally related, and in fact are each influenced by various different factors independently. For instance, DO is directly affected by temperature, while pH is directly affected by alkalinity. However, during periods of high productivity, both DO and pH exhibit strong diurnal variation. Under these conditions, the DO peaks and pH peaks correlate well because they are both affected by photosynthesis and respiration, which is a principal driver for both. The DO thresholds are site-specific, and are applied only for the peak summer period of mid-July through August. This period is used as a temporal control window to restrain productivity during other seasons, which is generally less critical. Periods of high productivity with pH criteria exceedances are observed during seasons outside this temporal control window. The TMDL Condition maintains year-round the nutrient conditions necessary to satisfy the DO thresholds during the temporal control window, resulting in a significant decrease in diurnal DO swings throughout the growing season. The DO thresholds are intended to addresses pH violations that are induced by diurnal DO swings.

V. WATERSHED TMDL EVALUATIONS

Evaluations were performed in order to calculate TMDLs for impaired watersheds throughout the Raritan River Basin. Watershed modeling tools, including the Raritan River Basin Model, were developed in order to relate phosphorus and TSS sources to water quality targets, specifically TP, DO, pH, and TSS concentrations. The TMDL objectives and approach to margin of safety and reserve capacity that were applied to all watershed evaluations are described in the ensuing sections. The phosphorus TMDL evaluations are described for each major watershed area throughout the Raritan River Basin; the TSS TMDL evaluations are much simpler, and are described in Section V.D below. Finally a summary of the TMDL Condition and resultant water quality outcomes for all impairments identified in Section II.B is provided.

A. TMDL Objectives

A uniform set of water quality objectives was applied to all watersheds in order to develop phosphorus and TSS TMDLs throughout the Raritan River Basin. The phosphorus TMDL objectives were designed to satisfy the water quality targets for TP, DO, and pH described in Section II.C; the TSS TMDL objective was designed to satisfy the applicable TSS criteria in the SWQS, namely a maximum TSS concentration of 40 mg/l and 25 mg/l for non-trout waters (FW2-NT) and trout waters (FW2-TM and FW2-TP), respectively. As directed by NJDEP, the following specific TMDL evaluations were applied in order to develop the TMDL Condition:

- Watershed evaluations were performed for all modeled streams to ensure that the outlet of all HUC14 subwatersheds exhibits 0% exceedance of the 0.1 mg/l TP criterion (where the instream TP criterion was applied) and 0% exceedance of the applicable TSS criterion;
- Lake evaluations were performed for all lakes listed in Section II.C to ensure 0% exceedance of the 0.05 mg/l TP criterion OR attainment of the natural condition, whichever is higher. For lakes analyzed at an annual scale, the 0.05 mg/l maximum TP criterion was expressed as an annual average based on a site-specific value; and

- pH impairment evaluations were performed at three locations in the North South Branch watershed area model where summer maximum DO targets (Table 2) were defined to ensure 0% exceedance of the thresholds.

Percent exceedances were calculated based the entire 3.67-year simulation period, except that a few time periods were excluded when stream flows were below the critical 7Q10 flow (USGS, 2005) at one or more gages in the respective watershed area model. Table 32 shows the periods of time excluded from percent exceedance calculations in each of the watershed area models.

Table 32: Periods of Time Excluded from Percent Exceedance Calculations

Watershed Area Model	North – South Branch	Stony Brook
Periods When Flow < 7Q10	2002: 7/31 – 8/28 9/3 – 9/14 9/22 – 9/26 10/1 – 10/10 2005: 8/24 – 8/26	2002: 8/13 – 8/23
Stream Flow Gages Where Flow < 7Q10	01396190 01396500 01397000 01398000 01399500 01399670 01398500 01400000 01400500	0140100

B. Approach to Margin of Safety and Reserve Capacity

1. Margin of Safety

A Margin of Safety (MoS) is provided to account for "lack of knowledge concerning the relationship between effluent limitations and water quality" (40 CFR 130.7(c)). A MoS is required in order to account for uncertainty in the loading estimates, physical parameters and the model itself. The MoS can be either explicit, implicit (i.e., addressed through conservative assumptions used in establishing the TMDL), or both. For these TMDL calculations, an explicit MoS is provided. MoS was calculated independently based on two broad types of pollutant load reductions. The amount of MoS for each type of pollutant load reflects the uncertainty associated with reducing each type of pollutant load as well as the importance of the pollutant load in terms of attaining water quality targets; the total reflects a significant MoS for the overall analysis. A transparent and meaningful method for calculating and applying MoS was developed as described below.

A 10% MoS was assigned to the phosphorus load associated with WWTP effluent limits for the TMDL Condition. WWTP effluent limits are regulated under NJPDES permits with monthly monitoring and strict enforcement provisions, making the uncertainty associated with this type of pollutant load very low. On the other hand, most WWTPs discharge continuously, including during low flow and peak productivity periods, making them important in terms of attaining DO and pH water quality targets. A 10% MoS was selected in order to reflect the low uncertainty but relatively high importance of this type of pollutant load. For example, a WWTP discharger simulated as 0.3 mg/l TP would be assigned an effluent limit based on 0.27 mg/l TP as a long-term average (LTA). The difference between the load associated with the higher simulated effluent concentration and load associated with the actual effluent concentration represents the MoS, which is set equal to 10% of the simulated phosphorus load associated with WWTP effluent limits:

$$MoS_{WWTP} = \left(WWTP_{Simulated} - WWTP_{Actual}\right) = 10\% \times WWTP_{Simulated}$$

The second type of pollutant load that was assigned a MoS was the load associated with stormwater and NPS reductions. Percent reductions were assigned to Urban (Residential and Other Urban) and Agricultural land areas in order to achieve water quality targets for TP and TSS. A 20% MoS was assigned to the phosphorus and TSS loads associated with reduced stormwater and NPS loads for the TMDL Condition. Stormwater and NPS load reductions are accomplished primarily through Best Management Practices (BMPs), which can be either structural or non-structural. The uncertainty associated with reducing pollutant loads from stormwater and NPS loads is much higher than for other types of pollutant loads. For this reason, a 20% MoS was selected to reflect the higher uncertainty associated with reducing stormwater and NPS pollutant loads. For example, a land area type (e.g. agricultural) in a particular subwatershed that was simulated as a 60% NPS reduction would be assigned a 68%

NPS reduction. Recall from Section IV.D.1 that a 60% NPS reduction is equal to (100% – 60%) × $NPS_{Existing}$ = 0.4 × $NPS_{Existing}$, where $NPS_{Existing}$ is equal to the existing stormwater load. A 68% NPS reduction, on the other hand, is equal to (100% – 68%) × $NPS_{Existing}$ = 0.32 × $NPS_{Existing}$. The simulated 60% NPS reduction represents a higher stormwater load than the actual stormwater load based on the assigned 68% NPS reduction for the TMDL Condition in this example. The difference between the higher simulated stormwater load and the actual stormwater load associated with the TMDL Condition represents the MoS, which is set equal to 20% of the simulated stormwater load associated with TMDL Condition:

$$MoS_{NPS} = \left(NPS_{Simulated} - NPS_{Actual}\right) = 20\% \times NPS_{Simulated}$$

Since:

$$NPS_{Simulated} = \left(1 - \text{NPSReduction\%}_{Simulated}\right) \times NPS_{Existing} \text{; and}$$

$$NPS_{Actual} = \left(1 - \text{NPSReduction\%}_{Actual}\right) \times NPS_{Existing}$$

Then, re-arranging terms and expressing actual NPS reduction percentage as a function of simulated NPS reduction percentage:

$$\text{NPSReduction\%}_{Actual} = \text{NPSReduction\%}_{\text{Simulated}} + \left(1 - \text{NPSReduction\%}_{Simulated}\right) \times 20\%$$

This formula provides a simple way to convert the simulated percent NPS reduction to the actual percent NPS reduction that should be assigned to any particular land area and subwatershed. Going back to the example cited previously, a 60% simulated NPS reduction would be implemented as 68% NPS reduction: 60% + (100% - 60%) × 20% = 68%. This source of MoS applies to both TP and TSS. Since the percent NPS reduction for future scenarios also reduced the tributary baseflow load to some degree (Section IV.D.1), additional MoS_{NPS} was calculated by taking into account the additional decrease in tributary baseflow concentration, if any, that would be associated with the actual percent NPS reduction as opposed to the simulated percent NPS reduction.

The total MoS is simply the sum of the two types of MoS described above:

$$MoS_{Total} = MoS_{WWTP} + MoS_{NPS}.$$

This MoS methodology provides real margin of safety to the analysis by simulating higher pollutant loads in the TMDL Condition than the actual loads associated with the required pollutant reductions. Furthermore, the MoS methodology is targeted to those loads for which reductions are required, and scales the percentage of MoS to the uncertainty associated with each type of pollutant load. This innovative approach satisfies USEPA requirements for MoS much more efficiently than a MoS applied across-the-board to all types of pollutant loads. Furthermore, the approach adds a genuine safety factor to the TMDL analysis. The total MoS is expressed both as a load and as a percentage of the total loading capacity. The total MoS for the TP and TSS TMDLs developed for the Raritan River Basin varied from 4.1% to 14.4% of the loading capacity depending on the TMDL parameter and the basin (Appendices R and S).

2. Reserve Capacity

Reserve Capacity (RC) is an optional component of a TMDL that is intended to provide an allocation for future growth (new or expanded WWTP discharges). Reserve capacity is important because the Raritan River basin is a large watershed with potential for new waste load demands. Inclusion of Reserve Capacity in the TMDL is an efficient way to accommodate new growth without impacting existing permittees in the future. In addition, the Department's experience in the Passaic River (a similarly large watershed) has shown immediate demands on reserve capacity occurred quite soon after adopting the TMDL. NJDEP therefore elected to include a RC to provide a reasonable accommodation for new growth without the need to revise the TMDL and associated permit limits. Reserve Capacity was therefore included in each of the modeled subbasins within the TMDL study area to allow for new or expanded wastewater treatment plant(s) as part of the overall allowable loading capacity. Reserve capacity was calculated for each subbasin and added to the tributary baseflow by increasing the phosphorus and TSS BFCs in each subwatershed. This method provides flexibility in terms of locating new or expanded discharges within the subbasin. The percent increases applied to the BFCs in each watershed area are provided in Table 33. The percent increases were selected to ensure that the resultant Reserve Capacity would provide a reasonable allocation for future growth. Less TP Reserve Capacity (2.3% of the WWTP allocations) was allocated to the South Branch Raritan River subbasin, as much of this area falls under Category One anti-degradation protection.

Table 33: Percent Baseflow Increase Used to Simulate Reserve Capacity

Watershed Area	Phosphorus	TSS
North South Branch Raritan River	10%	10%
Upper Millstone River	5%	10%
Stony Brook	5%	10%
Beden Brook	8%	10%
Lower Millstone / Mainstem Raritan	n/a	110%

For example, baseflow phosphorus loads in subwatersheds within the NSBranch model were increased by 10% to provide reserve capacity. This amounts to 0.72 kg/d additional TP in the Lamington River subbasin, and 1.1 kg/d additional TP throughout the North Branch Raritan River (including the Lamington) subbasin. The sum of TMDL point source allocations in the North Branch Raritan River basin is 17.7 kg/d TP. Therefore, the TP Reserve Capacity in the North Branch Raritan River subbasin (as a percentage of WWTP allocations) is: $\frac{1.1}{17.7} = 6.1\%$.

Simulating additional baseflow load and assigning it as RC provides a meaningful means of calculating RC. The resultant RC loads for each watershed are provided in Appendices R and S. The RC loads can be utilized directly by new or expanded discharges without any further modeling or analyses. Kleinfelder/Omni recommends applying the RCs on a watershed scale as provided in the last column of the RC tables in Appendices R and S. The RC loads are already included in the simulation of the TMDL condition, which demonstrates compliance with the TP and TSS criteria.

C. Phosphorus TMDL Evaluations

Phosphorus TMDL evaluations were performed in an iterative fashion from upstream to downstream throughout the Raritan River Basin TMDL Study Area of Interest (Figure 2) in order to satisfy the TMDL Objectives. TMDL evaluations were performed for each of the TMDL Study Evaluation Areas shown in Figure 31, which were delineated based on the applicable water quality targets and the type of analysis performed.

The goal of each phosphorus TMDL evaluation was to find the combination of point and nonpoint source reductions (i.e., the “TMDL Condition”) that would result in compliance with all applicable water quality targets (Section II.C). In theory, there are many combinations of point and nonpoint source reductions that would satisfy the TMDL. However, the reality is that WWTP point sources are much more important for DO and pH water quality targets as well as TP targets during low flow periods, while stormwater runoff is more important for TP water quality targets (0.1 mg/l in streams and 0.05 mg/l in lakes) during high flow periods. As a result, the stormwater and WWTP point source reductions were determined independently.

The PermittedFlow Condition (Section IV.C.3) was used as the baseline future condition and was modified as necessary to develop the TMDL Condition simulation. WWTP effluent levels were adjusted from upstream to downstream; TP was adjusted to satisfy TP targets during low flow periods, while OrthoP was adjusted upstream of the three locations with maximum summer DO thresholds to satisfy pH water quality targets. While large dissolved oxygen and high pH peaks appears to be a year-round issue in the North/South Branch Raritan River Basin, data were not sufficient to develop maximum DO thresholds outside the late summer period. Summer OrthoP levels in WWTP effluent (determined through iteration) were adjusted upward by the ratio of winter to summer 7Q10 flows[8] in order to account for higher flows in winter, and to maintain approximately the same concentration of OrthoP in the stream during low flow periods. In situations where WWTP dischargers of grossly disproportionate flow contributions (more than 10× different) had to be reduced in order to satisfy the same target, iterations were performed with effluent concentrations of the smaller dischargers (designated “very small dischargers”) set to 3× the level for the other WWTP dischargers that affect the same target. This was a policy decision made by NJDEP – although these dischargers are not so insignificant as to be considered negligible, they have a much smaller impact on the water quality target and therefore were assigned less stringent allocations.

In order to satisfy TP targets during high flow periods, a 50% NPS reduction from urban and agricultural land use areas (this is equivalent to 60% NPS reduction with the 20% MoS) was applied throughout all subwatersheds. This is the minimum amount of stormwater load reduction necessary to achieve 100% compliance with the water quality

[8] A winter/summer 7Q10 ratio of 1.4 was applied to dischargers in the South Branch Raritan River subbasin; a winter/summer 7Q10 ratio of 2.1 was applied to dischargers in the North Branch Raritan River subbasin. These values represent the average winter/summer ratio of 7Q10 values published by USGS (USGS, 2005) for gages within the respective subbasins.

criteria. Finally, percent NPS reductions were increased as necessary to satisfy remaining TP water quality targets. For subwatersheds that required a relatively small increase in NPS reductions beyond 50%, and where most of the stormwater load was being generated from agricultural areas, the NPS reduction for agricultural areas was increased independently from urban areas.

A detailed description of the point and nonpoint source reductions necessary to achieve the TMDL Condition is provided in Appendix P. Also, a table of TMDL outcomes is provided in Appendix Q. Significant results for each TMDL Evaluation Area are highlighted below.

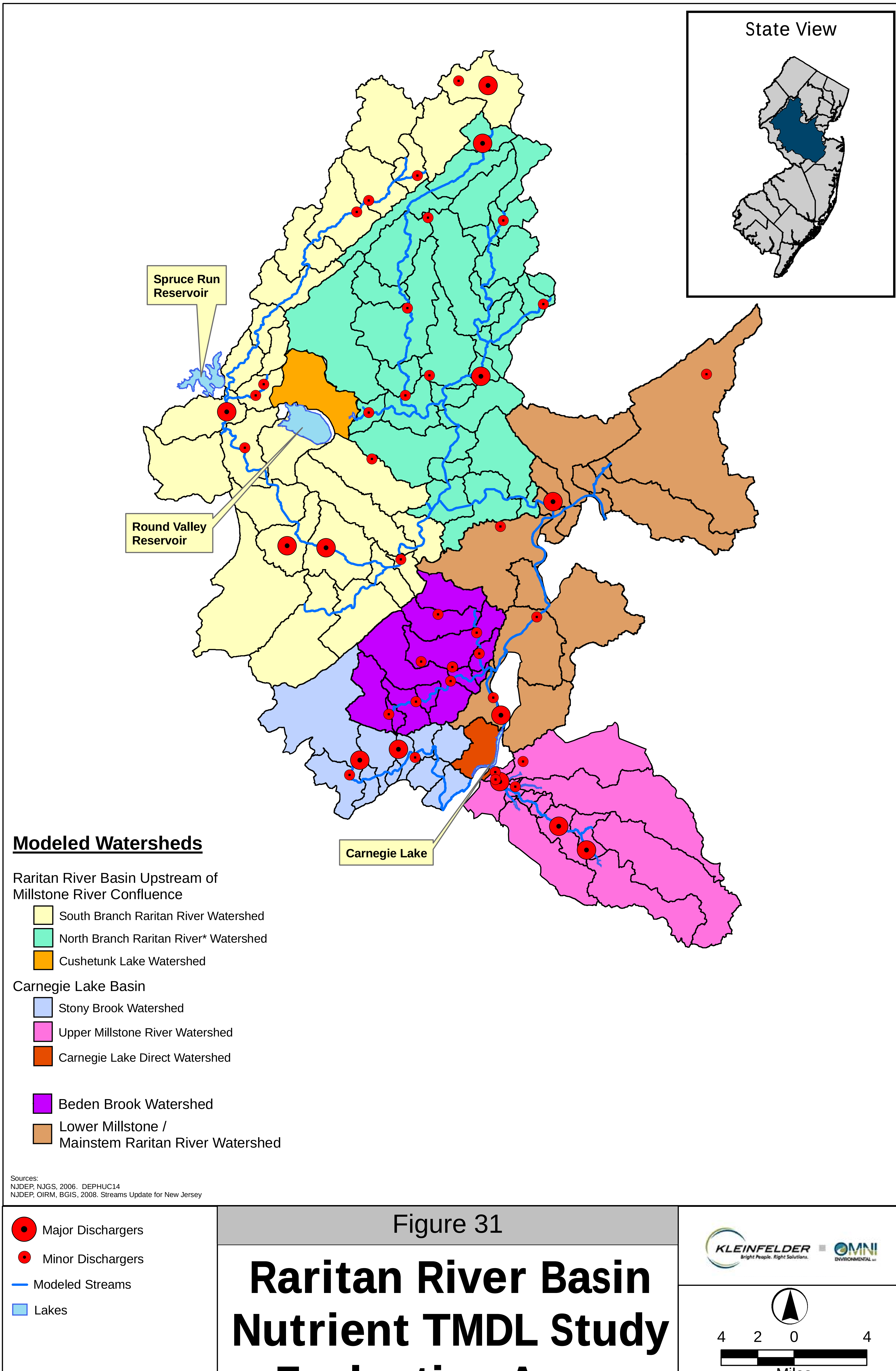


Figure 31

Raritan River Basin Nutrient TMDL Study Evaluation Areas

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August 2013

1. Raritan River Basin Upstream of Millstone River Confluence

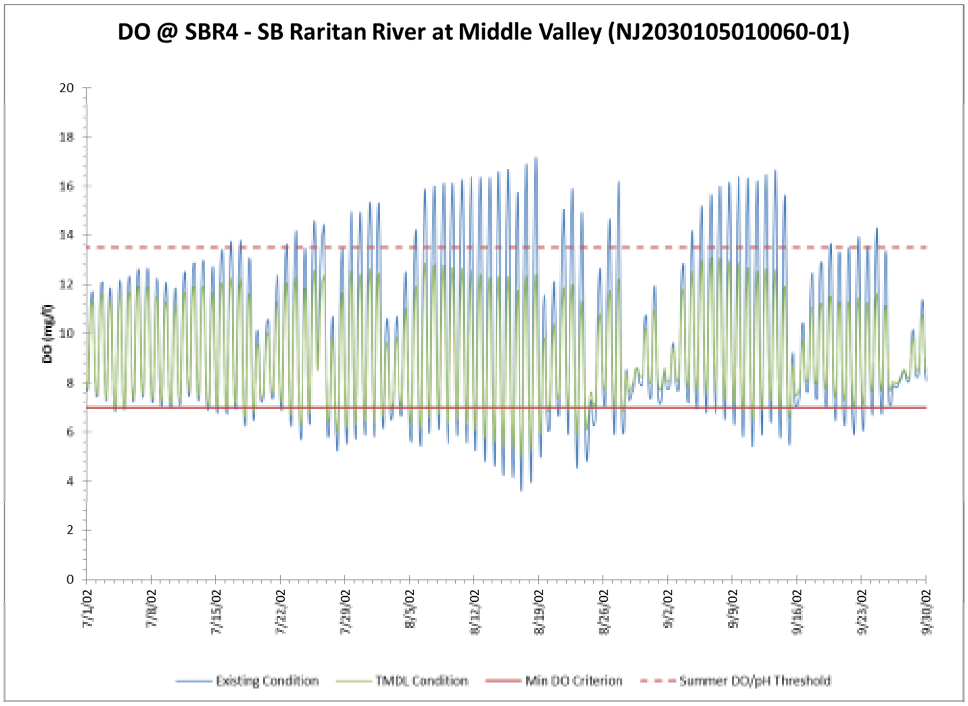
The North/South Branch watershed area model (Section III.A.1) was divided into the South Branch Raritan River Watershed and the North Branch Raritan River Watershed for the purpose of performing TMDL evaluations. The North Branch Raritan River Watershed TMDL Evaluation Area also includes the portion of the mainstem Raritan River, namely the mainstem Raritan River between the North/South Branch confluence and the confluence with the Millstone River at Manville. The South Branch Rockaway Creek downstream of Cushetunk Lake served as a boundary input to the North/South Branch model. A separate TMDL analysis was therefore performed for the Cushetunk Lake watershed based on satisfying water quality targets in Cushetunk Lake.

Generally, NPS phosphorus percent reductions of 50% and 60% were simulated for the TMDL Condition in the Raritan River Basin upstream of the Millstone River confluence for urban and agricultural land use areas, respectively. This combination of NPS percent reduction was found to reduce the high flow peak concentrations below 0.1 mg/l TP in almost every HUC outlet. Further NPS reductions were simulated as necessary in specific areas to bring the TP concentrations into 100% compliance with applicable TP criteria for the final TMDL Condition.

a. South Branch Raritan River Watershed

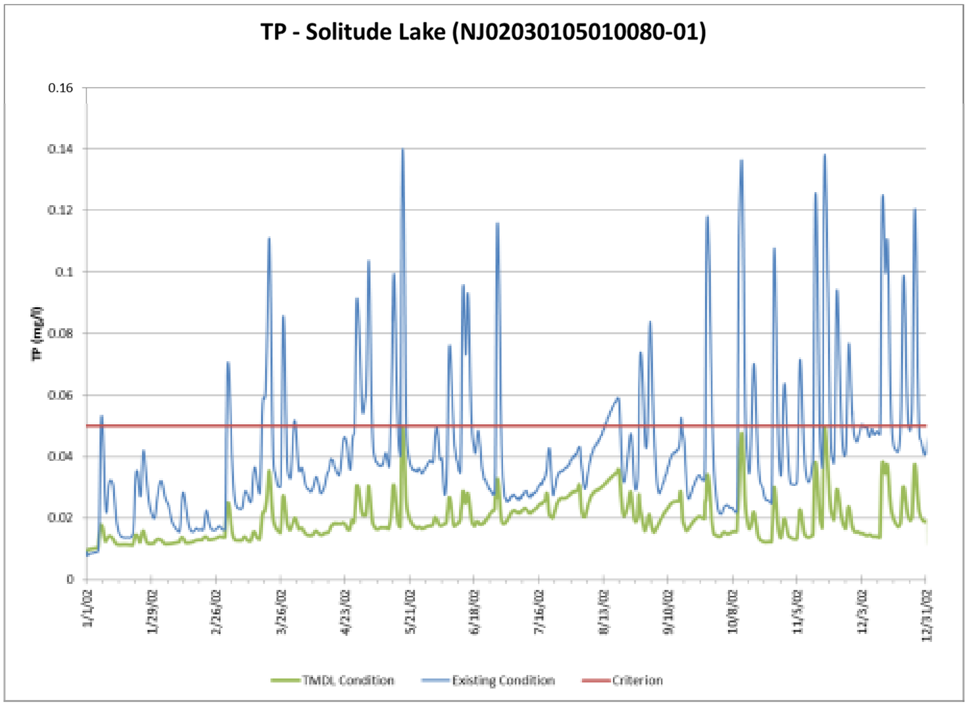
The South Branch Raritan River in Middle Valley (SBR4) was identified by the Upper South Branch Raritan River Phosphorus Evaluation Study (TRC Omni, March 8, 2005) as a critical location for productivity impacts, namely large diurnal DO swings leading to nighttime decreases of DO below the 7 mg/l minimum criterion for trout production waters. In addition, diurnal pH peaks exceed the maximum pH criterion of 8.5 s.u. Effluent OrthoP concentrations in upstream WWTPs were decreased to constrain the summer DO peaks below the pH threshold. In addition, the percent violation of the minimum DO criterion was reduced to 1%, which is the same as the natural condition; the predicted DO improvement is noteworthy. Further decreases in WWTP OrthoP concentrations or other phosphorus sources do not improve the predicted percent exceedance of the minimum DO criterion; furthermore, SOD is insignificant at this location and does not impact the predicted minimum DO. The TMDL Condition represents a major decrease in productivity and improvement in water quality in the upper South Branch Raritan River, as shown in Figure 32.

Figure 32: Dissolved Oxygen in Upper South Branch Raritan River



The changes in WWTP effluent concentrations necessary to satisfy DO and pH water quality targets at SBR4 also decreased the TP concentration downstream in Solitude Lake such that there would no longer be exceedances of the 0.05 mg/l TP criterion for lakes during dry weather periods. However, peak TP concentrations during storm events would still regularly exceed 0.05 mg/l TP. Therefore, the percent NPS stormwater reduction was increased in order to prevent the TP peaks from exceeding the lake criterion, as shown in Figure 33.

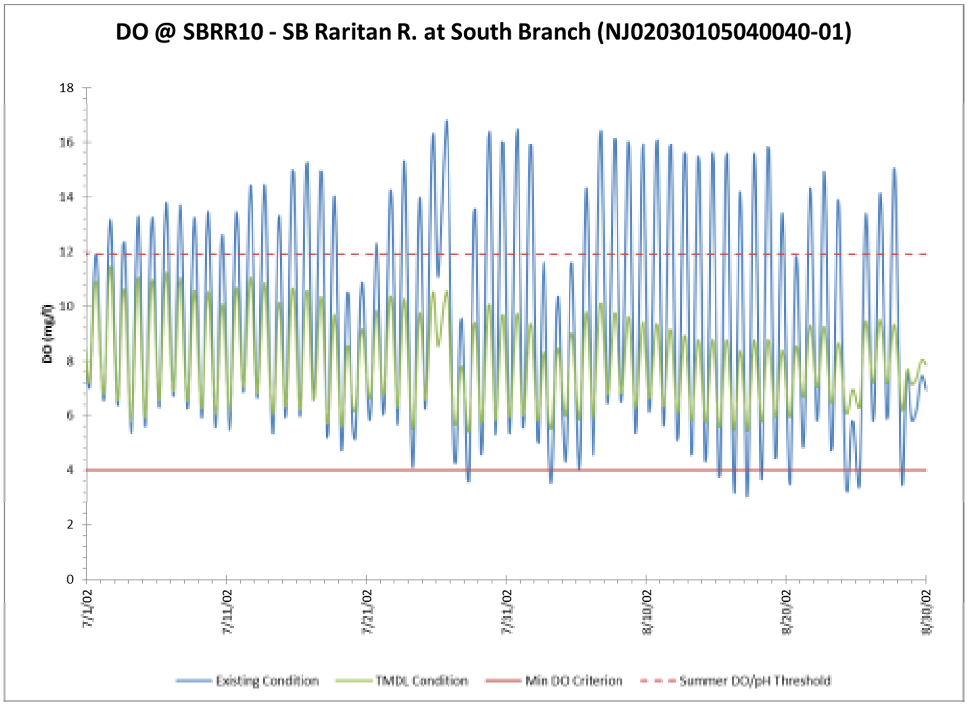
Figure 33: Total Phosphorus in Solitude Lake



The next productivity-related control point in the South Branch Raritan River (location with a maximum summer DO threshold) is the South Branch Raritan River in South Branch (SBRR10), just upstream of the confluence with the North Branch Raritan River. SBRR10 experiences the most extreme diurnal DO swings in the Raritan River Basin. These are accompanied by regular exceedances of the maximum pH criterion and low DO near the minimum DO criterion. Furthermore, modeling simulations demonstrate that this location is among the most sensitive to reductions in phosphorus loads; in particular, reductions in OrthoP from upstream WWTP dischargers will significantly reduce diurnal DO swings at this location and satisfy DO and pH water quality targets.

Figure 34 shows DO at SBRR10 during the summer of 2002 for both the Existing Condition and the TMDL Condition. This represents a dramatic improvement, attenuating both the daytime high DO and nighttime low DO, as well as preventing the peak DO from exceeding the summer pH threshold. This enormous water quality benefit is achieved almost entirely by the reduced OrthoP in upstream WWTP dischargers that was simulated for the TMDL Condition.

Figure 34: Dissolved Oxygen in Lower South Branch Raritan River



Additional point and nonpoint source phosphorus reductions were driven by satisfying 0.1 mg/l TP at the HUC outlets. For instance, percent NPS reductions in both Neshanic River and Holland Brook watersheds were increased in order to achieve the required 100% compliance with 0.1 mg/l TP at the HUC outlets (Figure 35 and Figure 36).

Figure 35: Total Phosphorus in Neshanic River (NR2)

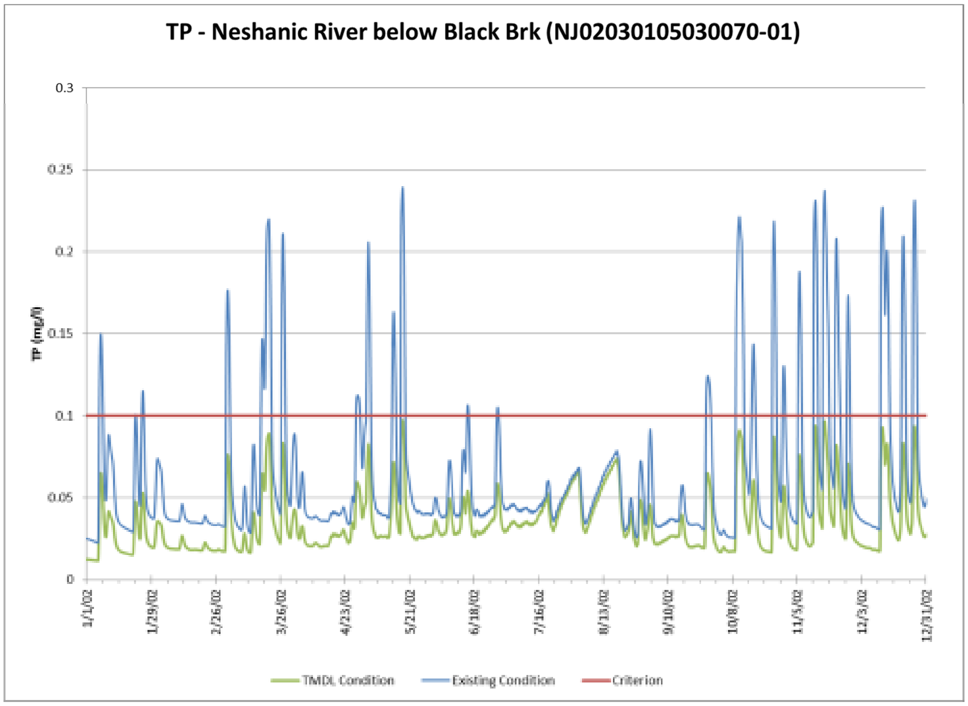
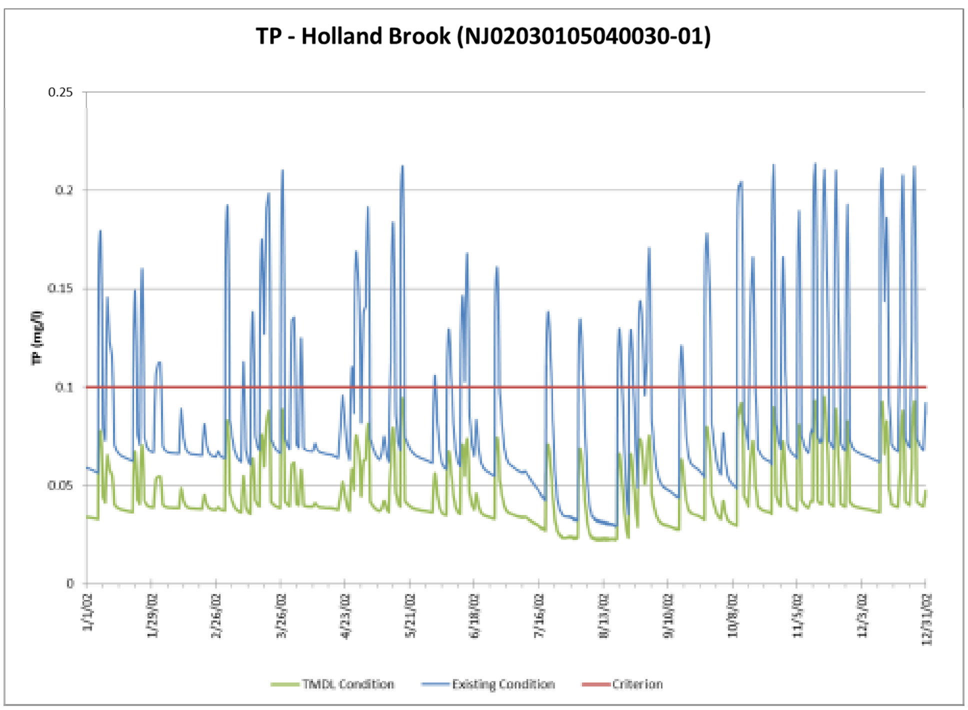


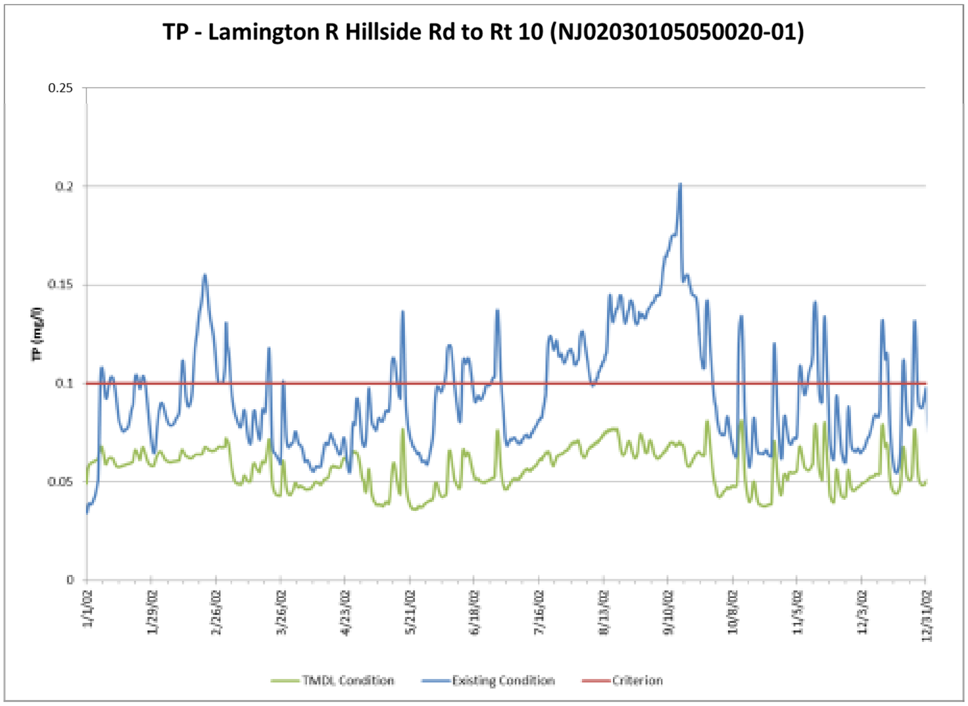
Figure 36: Total Phosphorus in Holland Brook (HB1)



b. North Branch Raritan River Watershed

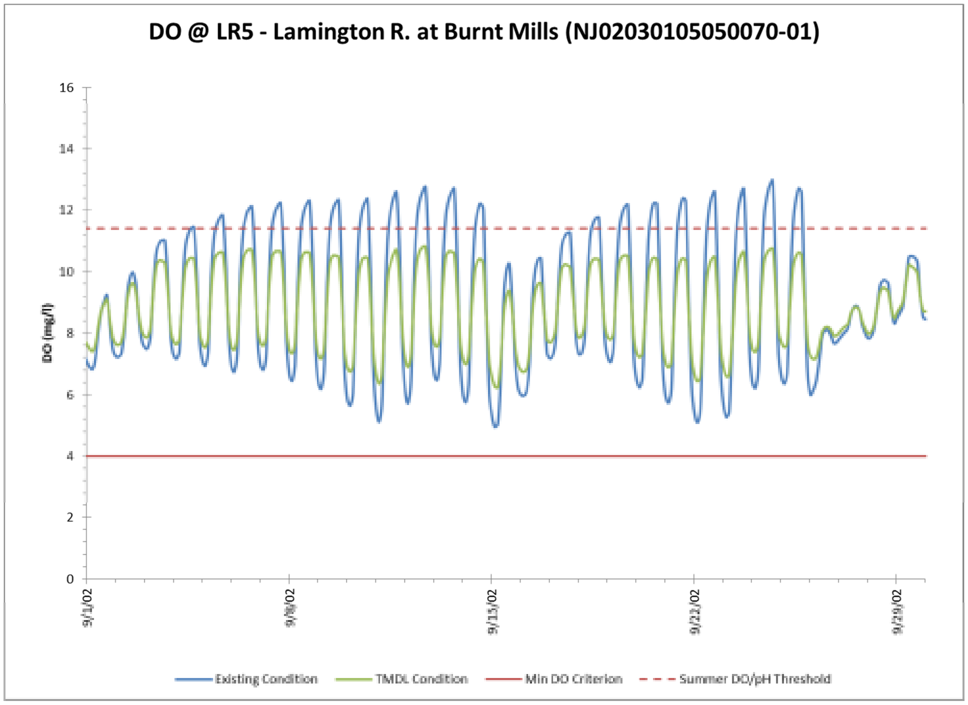
Point and nonpoint source phosphorus reductions for the TMDL Condition at the upper Lamington River downstream of Roxbury Township – Ajax Terrace WWTP were based on compliance with the 0.1 mg/l TP criterion at the downstream HUC outlet (Figure 37).

Figure 37: Total Phosphorus in Upper Lamington River



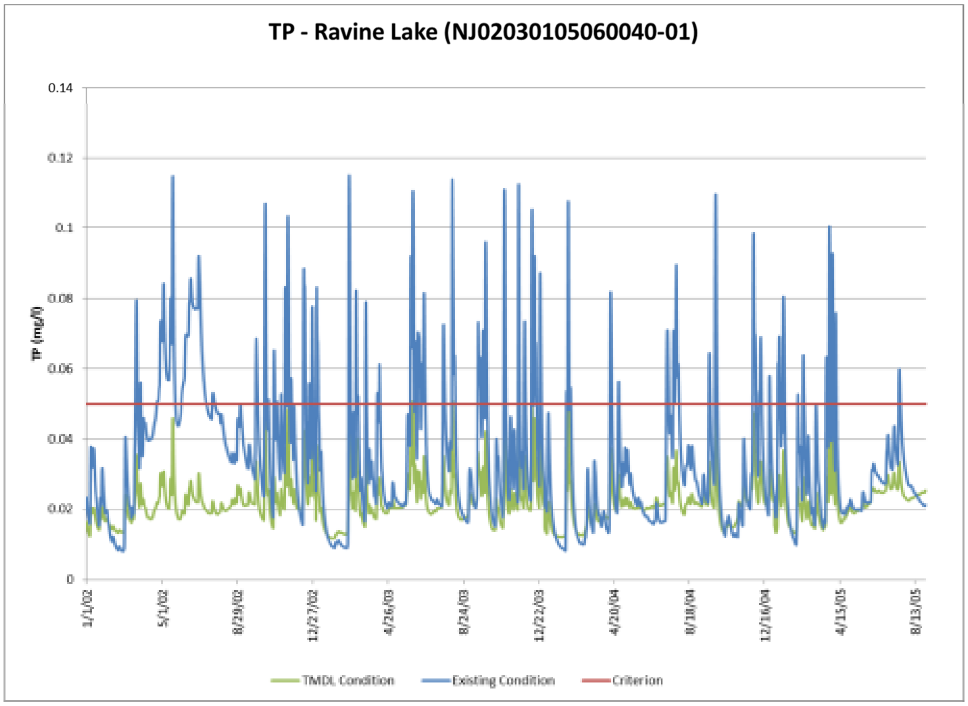
The lower Lamington River (LR5) experiences substantial diurnal DO swings that are accompanied by regular exceedances of the maximum pH criterion during critical productivity periods. Furthermore, modeling simulations demonstrate that this location is sensitive to reductions in phosphorus loads; in particular, a reduction in OrthoP from the upstream WWTP discharger (RLSA) will significantly reduce diurnal DO swings at this location and prevent DO peaks from exceeding the summer maximum DO threshold. September of 2002 is the most critical time period for productivity-related impacts at this location because the release from Round Valley attenuates productivity impacts during other periods that would otherwise be more critical. Figure 38 shows DO at LR5 during September of 2002 for both the Existing Condition and the TMDL Condition. This represents a dramatic improvement, attenuating both the daytime high DO and nighttime low DO, as well as preventing the peak DO from exceeding the summer pH threshold. This enormous water quality benefit is achieved almost entirely by the reduced OrthoP in RLSA effluent TP concentration.

Figure 38: Dissolved Oxygen in Lower Lamington River



Ravine Lake exceeds the lake TP criterion of 0.05 mg/l due to stormwater runoff sources. The percent NPS reduction was increased in order to achieve the required 100% compliance with the 0.05 mg/l criteria (Figure 39).

Figure 39: Total Phosphorus in Ravine Lake

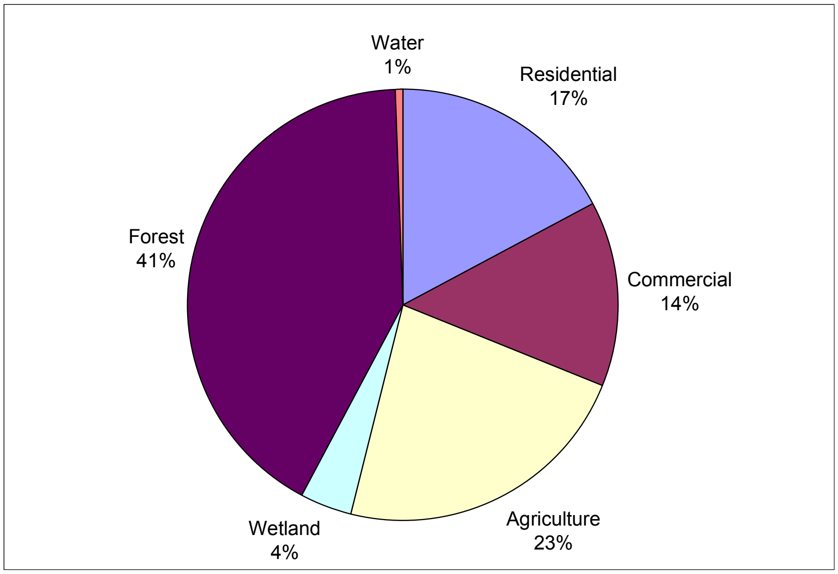


c. Cushetunk Lake

Cushetunk Lake is located just east of the Round Valley Reservoir on the South Branch Rockaway Creek. The lake has a mean depth of 2.8 feet and a surface area of 25.4 acres. The contributing watershed to the lake is 11.3 square miles. The Cushetunk Lake watershed formed a boundary input to the North/South Branch model based on the USGS stream flow gage in the South Branch Rockaway Creek (USGS #01399670).

In order to perform a TMDL evaluation for Cushetunk Lake, a hydrologic model for the Cushetunk Lake watershed was developed similar to the one developed for North/South Branch watershed area model. The land use distribution in the Cushetunk Lake watershed is shown in Figure 40. The hydrologic parameters and monthly parameters used for model calibration were the same as those used for the North Branch Rockaway Creek subwatershed in the North/South Branch watershed area model due to its proximity and similar land use distribution. The simulated flows compared favorably with the flows from the USGS gage at Cushetunk Lake (01399670), as shown in the last page of the hydrologic model calibration graphs in Appendix J. The mean percent error (difference from gage) was 6.7%, well within the accuracy of the gage. NPS pollutant loads were calculated using HydroWAMIT, and the estimated load from the single small WWTP discharger within the watershed (Clinton BoE – Round Valley) was added directly to the baseflow load without attenuation.

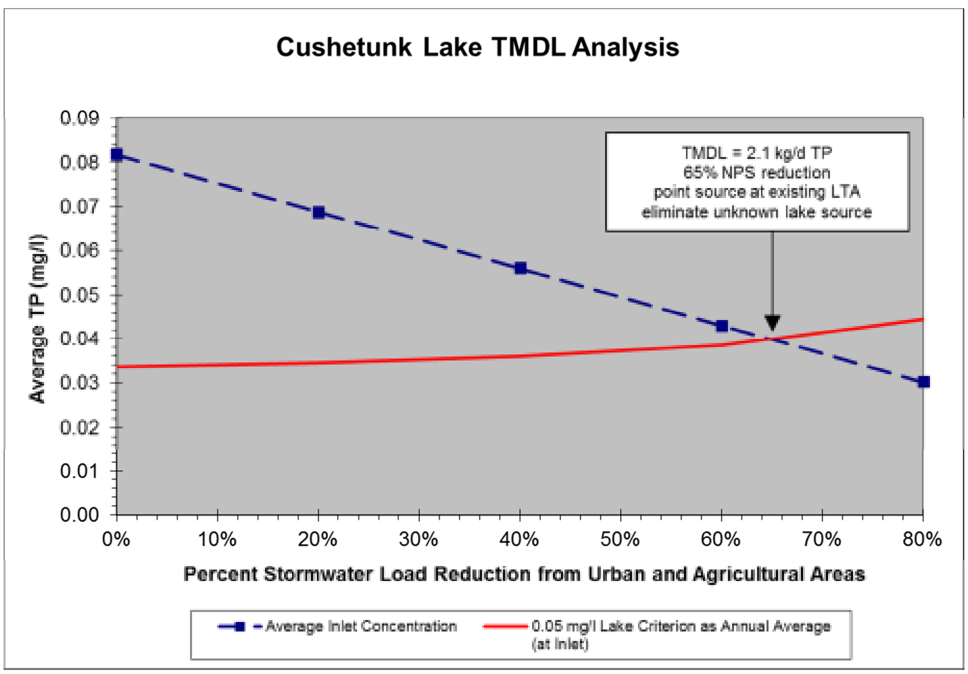
Figure 40: Land Use Distribution in Cushetunk Lake Watershed



While a daily scale hydrologic and pollutant loading model (HydroWAMIT) was applied to estimate loads, the TMDL analysis for Cushetunk Lake was performed on an annual scale. The TMDL evaluation methodology and calculations for Cushetunk Lake are presented in Appendix O, and the results are shown in Figure 41. The loading calculations based on data collected at the inlet and the outlet of Cushetunk Lake reveal an unknown TP source between the inlet sampling location and the outlet sampling location. Historical data also show that a substantial source of TP (and TSS) contributes loads during both low and high flow conditions. While it is not uncommon for a lake to be acting as a source of TP and TSS under certain flow conditions, the magnitude of the difference between inlet and outlet loads indicates an additional source. For the purpose of calculating a TMDL for Cushetunk Lake, the unknown source is not included in the loading capacity. This is the same as assuming that the unknown source is identified and remediated; it is necessary to make this assumption in order to be able to demonstrate compliance with the lake criterion.

The TMDL evaluation was therefore performed without considering the influence of the lake, which currently acts as a major source that increases the average inlet TP concentration by 75%. The small WWTP point source in the Cushetunk Lake watershed has little influence on the reduction of stormwater needed to achieve compliance with the 0.05 mg/l lake criterion, since it is stormwater that causes the lake to exceed the criterion. For this watershed, the reserve capacity of 0.3 kg/d TP was calculated by increasing the simulated WWTP point source load until just before it would begin to impact the amount of stormwater reduction required to meet the criterion. The difference between the maximum simulated WWTP load and the currently permitted WWTP load was calculated as the RC (Appendix R) for the watershed. TMDL allocations for the Cushetunk Lake watershed are included with the North Branch Raritan River subbasin allocations in Appendices R and S.

Figure 41: Cushetunk Lake TMDL Evaluation

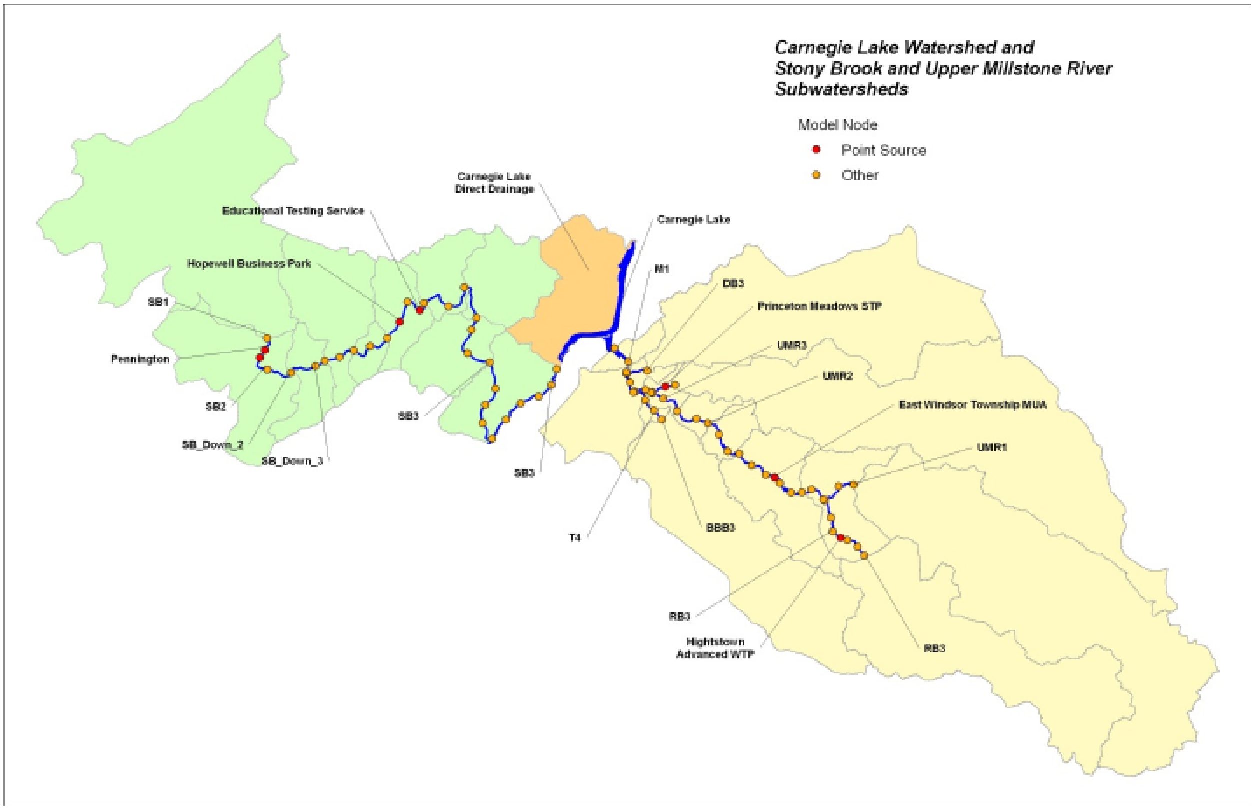


2. Carnegie Lake Basin

Carnegie Lake separates the upper Millstone River from the lower Millstone River, and its drainage area consists of three watersheds: the upper Millstone River watershed, the Stony Brook watershed, and the direct watershed of Carnegie Lake (Figure 42). Phosphorus TMDL evaluations for the upper Millstone River and Stony

Brook watersheds are presented independently, followed by the TMDL evaluation for Carnegie Lake.

Figure 42: Carnegie Lake Basin



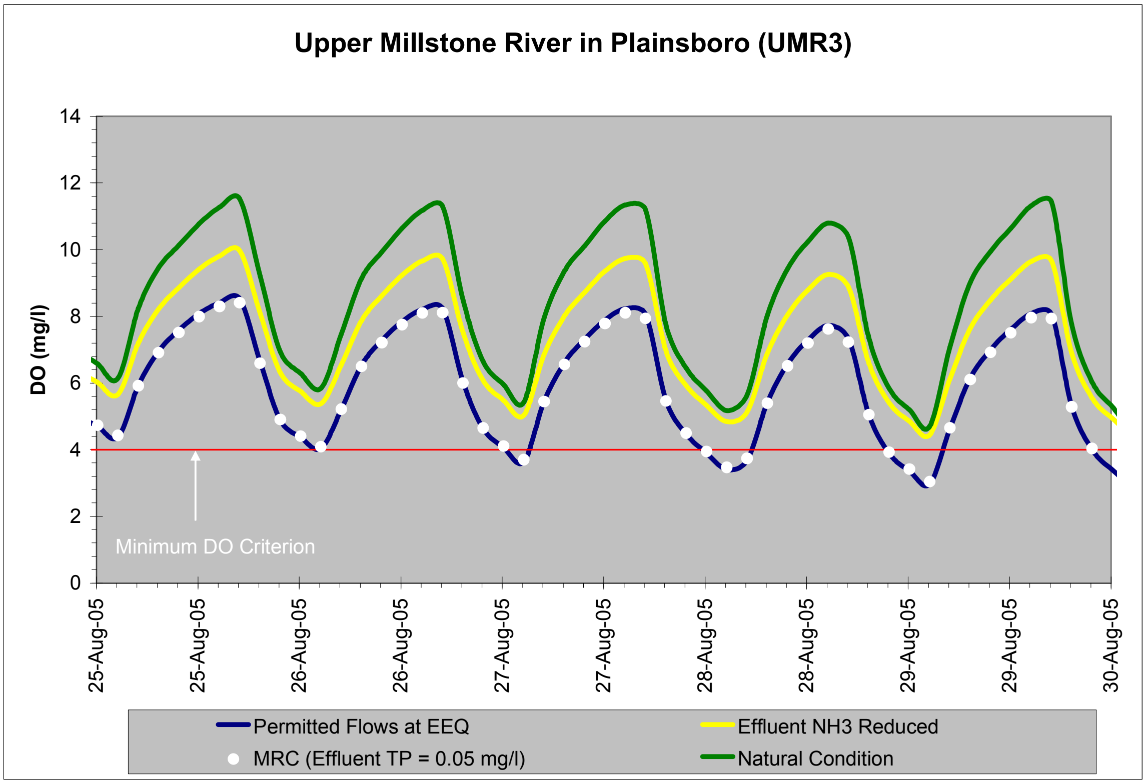
a. Upper Millstone River Watershed

Streams in the upper Millstone River watershed generally exhibit moderate diurnal DO swings, little to no diurnal pH swing with pH levels well below the maximum criterion of 8.5 s.u., moderately high periphyton densities below the thresholds used by NJDEP to assess excessive productivity (NJDEP, 2003), and low phytoplankton concentrations (TRC Omni, December 19, 2005). In addition, modeling simulations demonstrate that streams in the upper Millstone River are not sensitive to phosphorus source reductions; productivity, as reflected in diurnal DO swings, does not change with reductions in point and nonpoint sources of phosphorus. This reflects the fact that natural levels of phosphorus are sufficient to drive the level of productivity observed in the streams. The headwaters of the upper Millstone River originate in glauconitic soil formations, and the streams share many of the same characteristics found in the nearby Matchaponix Brook watershed (TRC Omni, April 11, 2005).

The upper Millstone River in Plainsboro (UMR3) was assessed by NJDEP as impaired due to low DO, and is the most critical location in the upper Millstone River in terms of productivity and DO impacts. A careful modeling evaluation at this study demonstrated that the low DO issue in the upper Millstone River is caused by high ammonia loads, which exert an oxygen demand on the stream. Figure 43 shows the results of the modeling evaluation, namely diurnal DO predictions for various diagnostic scenarios during a critical low flow event. The blue line in Figure 43 is the PermittedFlow scenario (IV.C.3), which simulates WWTPs discharging their existing effluent quality at their maximum permitted flows. Overall DO is low, with the predicted diurnal minimums dropping below 4.0 mg/l at night. The white circle series is the MRC scenario (IV.C.4), which simulates 80% reduction of NPS TP from urban and agricultural areas and WWTP effluent concentrations reduced to 0.05 mg/l TP. The MRC represents a drastically reduced phosphorus scenario compared to the PermittedFlow scenario, yet it produces no change in diurnal DO.

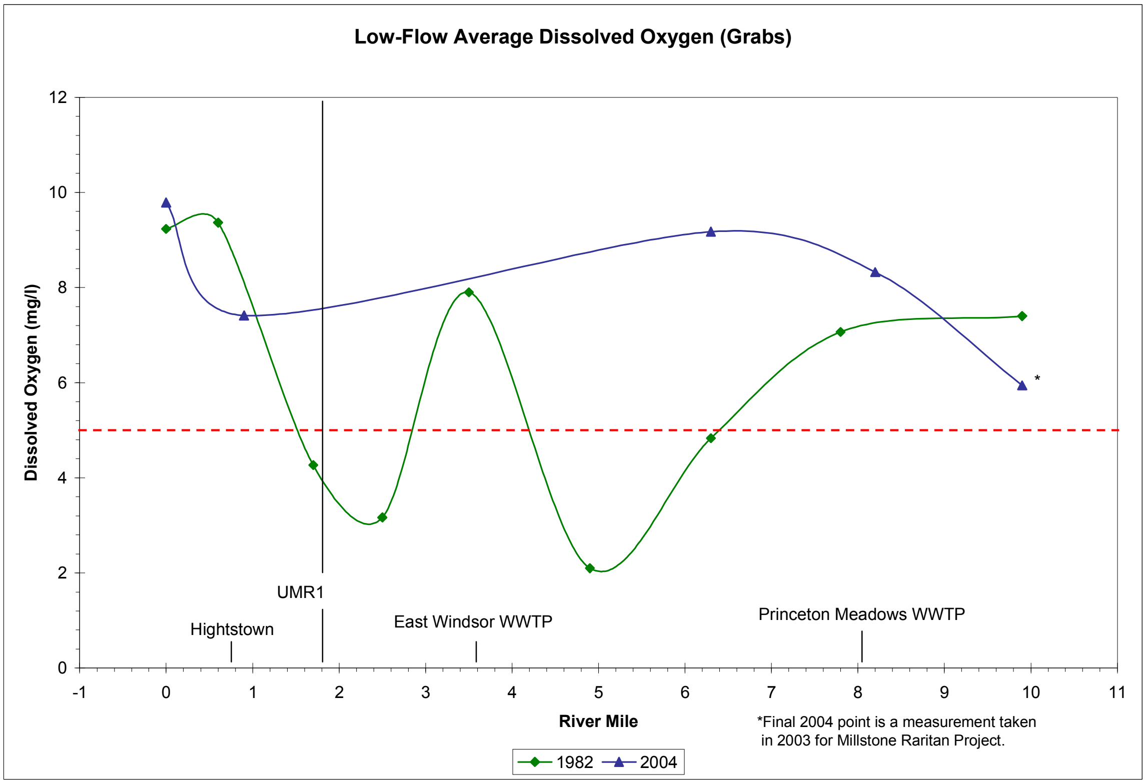
On the other hand, the yellow line represents the PermittedFlow scenario with only one modification: the effluent ammonia concentration from one WWTP that is currently operating under an average monthly effluent limitation of 25.5 mg/l (as ammonia nitrogen) was reduced. Specifically, the existing ammonia concentration for Princeton Meadows WWTP was replaced with the average monthly effluent limits (8 mg/l summer; 13 mg/l winter) as calculated in its draft NJPDES permit renewal issued January 28, 2011. Consistent with the way all non-TMDL parameters were simulated, the ammonia limits were input to the model as long-term averages (6.64 mg/l summer; 10.33 mg/l winter). These new ammonia WQBELs were developed based on a site-specific ammonia toxicity study, and are expected to become effective three years after the TMDL is established. The reduced ammonia increases predicted oxygen levels in the stream such that the diurnal minimums remain above 4.0 mg/l at all times. Furthermore, the diurnal minimums are very similar to those predicted for the Natural Condition (IV.C.5) shown in green. The ammonia effluent limits already calculated by NJDEP for a future permit action will improve DO conditions at this location.

Figure 43: Impact of Ammonia on DO in Upper Millstone River



A careful evaluation of historical data (e.g., Omni, 1992) indicates that reductions in ammonia loads have improved oxygen conditions in the portion of the upper Millstone River (and Rocky Brook) that is upstream of Cranbury Brook, which is where Princeton Meadows (UWPM) WWTP enters the system. There are two other major WWTPs in the upper Millstone River watershed: Hightstown Borough and East Windsor. Both have implemented major treatment upgrades in the last 15 years that have dramatically reduced their phosphorus and ammonia discharges. While the level of productivity, as indicated by diurnal DO swings, does not appear to have changed in the stream, the overall DO average has improved upstream of UWPM (Figure 44).

Figure 44: Historical Comparison of DO Conditions in Upper Millstone River

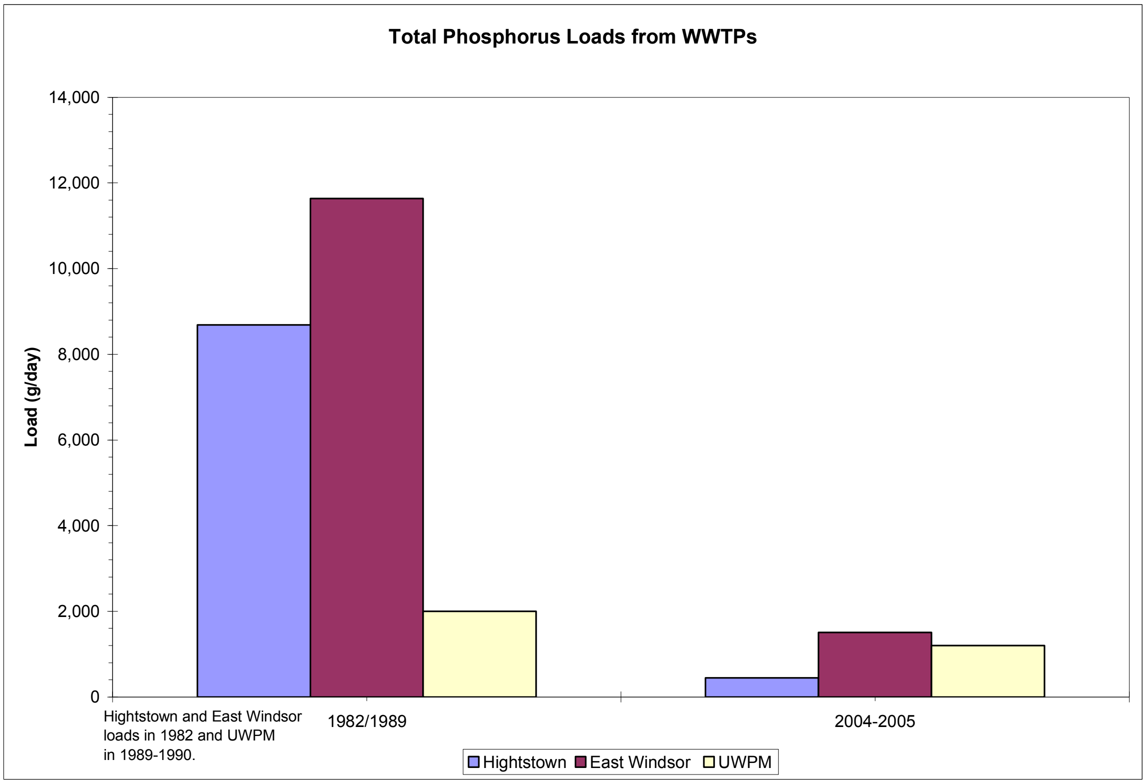


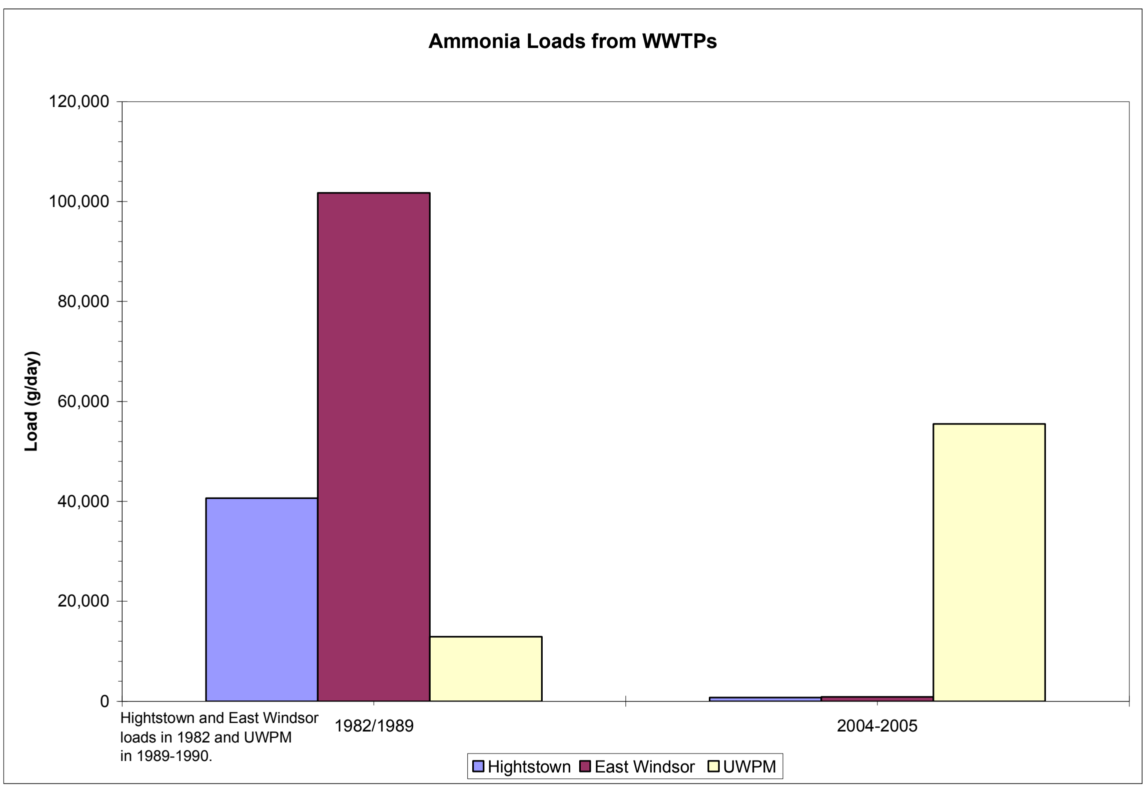
As a frame of reference, historical comparisons of WWTP TP and ammonia loads from the three major WWTPs in the upper Millstone River watershed are provided in Figure 45. Clearly, the point source improvements in the watershed, particularly the ammonia reductions, have improved DO conditions in the streams. The reduction of ammonia loading from UWPM in order to satisfy its final permit conditions will produce the same benefits in the upper Millstone River downstream of Cranbury Brook.

Because the low DO observed at station UMR3 is caused by ammonia and would not be improved by phosphorus reductions, and because natural levels of phosphorus in the upper Millstone River watershed are sufficient to drive the level of productivity observed in the streams, the instream 0.1 mg/l TP criterion was not applied as a water quality target to streams in the upper Millstone River watershed. However, most of the headwater streams are impounded to form small ponds (e.g., Peddie Lake). In addition, the upper Millstone River drains directly to Carnegie Lake, an urban lake feature in Princeton, New Jersey, especially significant for its recreational uses. All of the lake and pond features in the upper Millstone River watershed, including Carnegie Lake into which the upper Millstone River drains, are subject to the 0.05 mg/l TP criterion (N.J.A.C. 7:9B). The following four ponds in the upper Millstone River watershed were explicitly studied as part of the Raritan Basin TMDL Study based on bathymetric and water quality data collected during Phase I (TRC Omni, December 19, 2005).

- **Peddie Lake** is located on Rocky Brook in Hightstown. The lake has a mean depth of 6.5 feet and a surface area of 16.5 acres. The contributing watershed to the lake is 13.6 square miles.
- **Plainsboro Pond** is located on Cranbury Brook in Plainsboro. The lake has a mean depth of 3.0 feet and a surface area of 36.5 acres. The contributing watershed to the lake is 22.1 square miles.
- **Grovers Mill Pond** is located on Big Bear Brook in West Windsor. The lake has a mean depth of 3.0 feet and a surface area of 30.5 acres. The contributing watershed to the lake is 11.8 square miles.
- **Gordon Pond** is located at the confluence of Bee Brook and Devils Brook in Plainsboro. The lake has a mean depth of 3.9 feet and a surface area of 15.6 acres. The contributing watershed to the lake is 16.3 square miles.

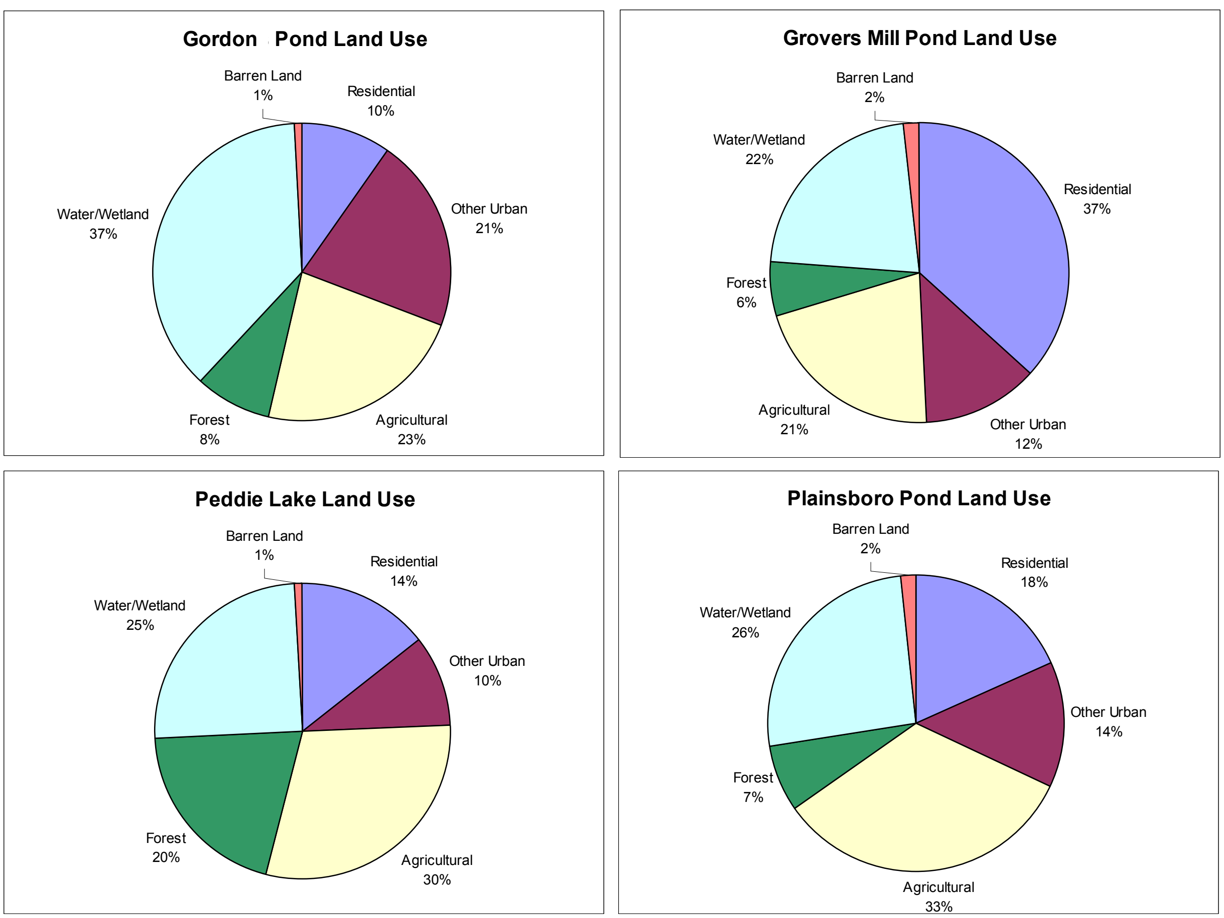
Figure 45: Historical Comparison of WWTP Loads to Upper Millstone River Watershed





Land use composition in the watersheds that drain to each of these ponds is provided in Figure 46 (2002 land use data from NJDEP). The TMDL evaluation methodology and calculations for all four of the ponds in the upper Millstone River watershed are presented in Appendix O. The natural condition is especially relevant for lakes in the upper Millstone River watershed, because the natural condition is higher than the average concentration associated with the 0.05 mg/l phosphorus criterion for lakes. The reason is that naturally-occurring tributary baseflow concentration in this watershed is relatively high. In other words, the phosphorus concentration of water flowing into these lakes during low-flow conditions would be fairly high even in the absence of anthropogenic influences. Any run-of-the-river lakes in this watershed, such as the headwater lakes being studied, can expect to receive high phosphorus loads even under natural conditions during both low and high flow conditions.

Figure 46: Land Use Composition of Upper Millstone Lake Watersheds



The natural condition for each of the four headwater lakes in the upper Millstone River watershed was calculated to be 0.059, 0.043, 0.040, and 0.053 mg/l total phosphorus as an annual average for Peddie Lake, Plainsboro Pond, Grovers Mill Pond, and Gordon Pond, respectively. TMDLs for each of these lakes were developed to satisfy the natural condition, since the Surface Water Quality Standards [N.J.A.C. 7:9B-1.5(c)1] state that the natural condition becomes the criterion if it is shown to exceed the criterion that would otherwise be applicable (i.e., the 0.05 mg/l not-to-exceed criterion). The percent reduction of NPS stormwater loads from urban and agricultural areas necessary to achieve the natural condition in terms of average phosphorus concentration was calculated for each lake: 64%, 63%, 73%, and 70% NPS reductions for Peddie Lake, Plainsboro Pond, Grovers Mill Pond, and Gordon Pond, respectively (Appendix O). However, an 80% NPS reduction was assigned to the entire upper Millstone River watershed in order to achieve the natural condition in Carnegie Lake, as described in Section V.C.2.c.

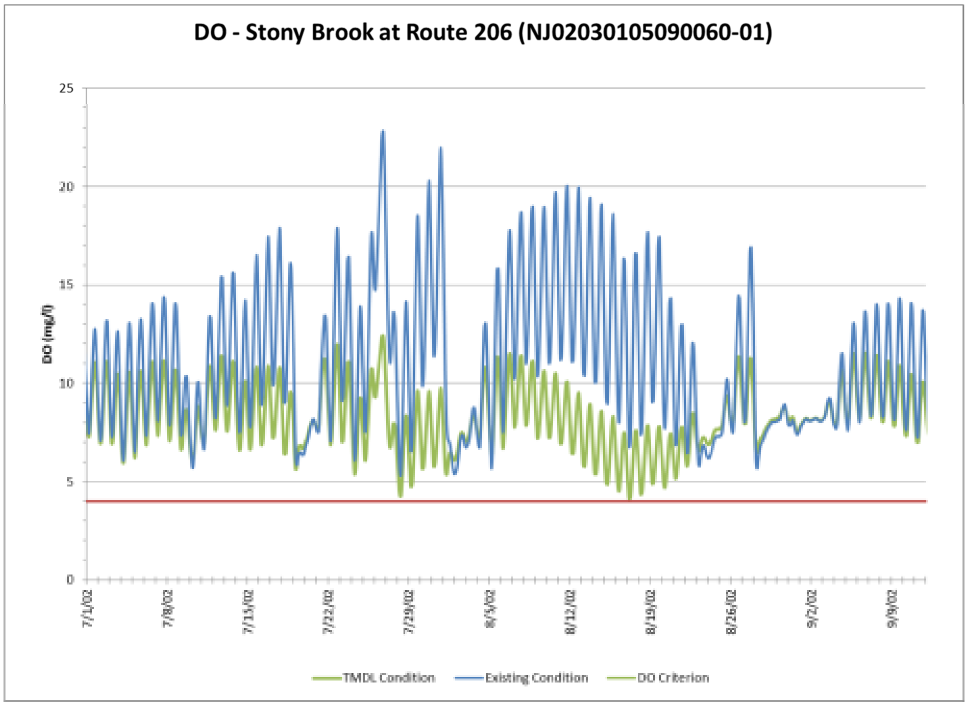
Stringent WWTP phosphorus reductions were necessary in the upper Millstone River watershed in order to satisfy the water quality target in Carnegie Lake. Except for one small discharger, all WWTP phosphorus limits in this watershed are driven by loads delivered to Carnegie Lake at the outlet of the watershed. USDoE-PPPL discharges to a small tributary to Gordon Pond; the TMDL Condition for this WWTP was driven by the water quality target in Gordon Pond (Appendix O). Since the TMDL Condition for all WWTPs in the upper Millstone River watershed is driven by loads to lakes, the TMDL can be satisfied by load based effluent limits.

b. Stony Brook Watershed

The phosphorus TMDL evaluation for the Stony Brook watershed was driven primarily by two water quality end points: TP in the Stony Brook and TP in Carnegie Lake. As for the upper Millstone River watershed, an 80% NPS stormwater reduction from urban and agricultural areas is necessary to achieve the water quality target in Carnegie Lake (Section V.C.2.c), in addition to substantial WWTP phosphorus reductions. Stringent phosphorus limits for WWTPs are necessary to reduce the load delivered to Carnegie Lake and to satisfy 0.1 mg/l TP at HUC outlets in the stream.

The point and nonpoint source phosphorus reductions proscribed in the TMDL Condition for the Stony Brook watershed result in a dramatic decrease in productivity (Figure 47). The critical location SB3 is the outlet of the impaired HUC and the only location where diurnal pH peaks were observed to exceed 8.5 s.u. The difference in diurnal DO between the Existing Condition and the TMDL Condition represents a very significant improvement in water quality at that location.

Figure 47: Dissolved Oxygen in Stony Brook

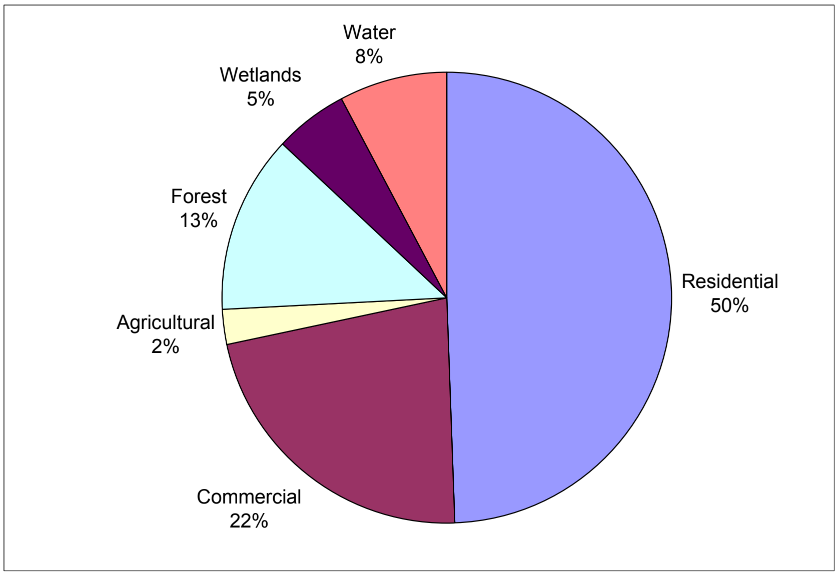


c. *Carnegie Lake Analysis*

Carnegie Lake is an important urban lake feature in Princeton known for its recreational and aesthetic uses. Most of the Carnegie Lake watershed drains to its two major inlets, the Stony Brook and the upper Millstone River, both of which comprised separate watershed area models with the Raritan River Basin Model. A separate HydroWAMIT model for the Carnegie Lake direct watershed was developed to generate flows and pollutant loads to supplement the models developed for Stony Brook and Upper Millstone watersheds. The area of the Carnegie Lake direct watershed is very small compared to the areas of the Stony Brook and upper Millstone River watersheds (Figure 42, p. 170). As a result, the NPS loads generated from the direct lakeshed are minor compared to those generated from the

Stony Brook and upper Millstone River watersheds. The land use distribution within the direct lakeshed (2002 land use data from NJDEP), shown in Figure 48, is similar to the Stony Brook watershed. Due to this similarity and the proximity of the direct lakeshed to the Stony Brook watershed, the hydrologic and monthly parameters from the most downstream subwatersheds of Stony Brook were used to simulate flows for the direct lakeshed.

Figure 48: Land Use Composition in Carnegie Lake Direct Watershed



Lake physical data were obtained from a field study performed in 2003 by Princeton Hydro on behalf of the Army Corps of Engineers (Princeton Hydro, 2007). According to this study, Carnegie Lake has a surface area of 259 acres, and average depth of 3.7 feet, and a volume of 888 acre-feet. HydroWAMIT was run in the direct lakeshed for the 3.67 year simulation period (1/1/2002 – 8/31/2005) for 0%, 20%, 40%, 60%, and 80% NPS reduction scenarios. Consistent with the methodology used to simulate NPS reductions throughout the Raritan TMDL study, percent reductions were applied to runoff phosphorus concentrations from urban and agricultural areas and baseflow phosphorus concentrations were reduced using the same methodology described in Section IV.D.1 and shown in Figure 25. The baseflow phosphorus concentrations assigned to the direct lakeshed are provided in Table 34.

Table 34: Baseflow Concentrations for Carnegie Lake Direct Watershed Simulations

Percent NPS Reduction	OrthoP	OrgP
0%	0.031	0.024
20%	0.025	0.019
40%	0.020	0.015
60%	0.014	0.011
80%	0.009	0.007
Natural Condition	0.006	0.004

HydroWAMIT simulations of the Carnegie Lake direct watershed were considered together with output from the outlets of Upper Millstone and Stony Brook watershed area models. A mass balance budget model was performed for Carnegie Lake, similar to the approach described for the headwater lakes in Appendix O, to quantify a first order loss rate for the lake. The following equation can be used for a well-mixed lake:

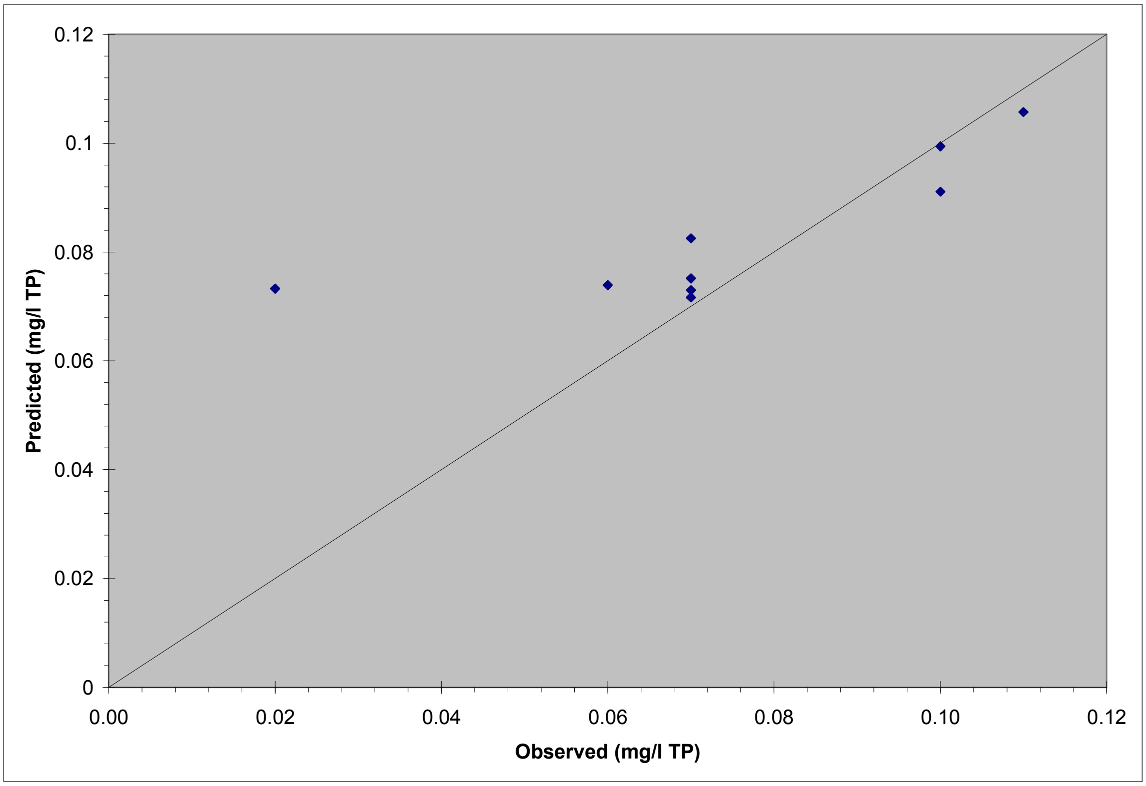
$$V\frac{dp}{dt} = W - Qp - k_s Vp$$

Where:

V = Volume (m^3)
p = total phosphorus concentration (mg/m^3)
W = total P loading rate to inlet (mg/yr)
Q = outflow (m^3/yr)
k_s = a first order loss rate (yr^{-1})

Predicted loads from the Upper Millstone and Stony Brook watershed area models, as well as the HydroWAMIT simulations of the direct lakeshed, were summed to calculate the annual phosphorus load into Carnegie Lake. Annual load out of Carnegie Lake was calculated using a concentration and flow relationship at the outlet using data collected at the lake outlet (M2) during Phase 1 of the TMDL study (TRC Omni, December 19, 2005). Flow at the outlet was available from the Beden Brook/Lower Millstone watershed area model based on a strong correlation with the continuous stream flow gage at Blackwells Mills. In order to validate the concentration and flow relationship, predicted concentrations were compared with surface measurements in the lake performed by Princeton Hydro (Princeton Hydro, 2007). The validation of concentration predictions was very strong, as shown in Figure 49. This provides a very strong basis to estimate annual phosphorus load leaving the lake.

Figure 49: Validation of Carnegie Lake Phosphorus Concentration



A per year loss rate of -46.5 yr^{-1} was calculated as a function of annual loads for the Existing Condition, flow, and lake volume:

$$LossRate = \frac{(LoadOut - LoadIn)}{LoadOut \times \left(\frac{LakeVolume}{Qout}\right)}.$$

A negative "loss rate" indicates that Carnegie Lake is acting overall as a source of TP on an annual basis. This is consistent with the calibration of the Stony Brook watershed area model, which required a benthic flux in the final segment to account for the observed increase in TP concentration at the lake inlet. It should be noted, however, that most of the data available for this analysis were collected during low flow conditions. Therefore, the characterization of load at the outlet of Carnegie Lake may not be representative of high flow conditions; this may have skewed the calculation of loss rate. The loss rate did not affect the TMDL evaluation, which was based on the Natural Condition (see below).

The per year phosphorus loss rate was calculated based on existing condition and applied to future conditions. The difference between annual load out and annual load in the lake was represented as the internal lake load. Inlet concentrations were available directly from the Upper Millstone and Stony Brook watershed area models as well as the HydroWAMIT simulation of the direct lakeshed. The average phosphorus concentration in the lake was calculated by adding up all the annual loads (including the internal lake load) and dividing by the annual flow rate. The methodology provides continuous phosphorus concentration at the various inlets to Carnegie Lake, and annual phosphorus concentration in the lake itself. Natural condition simulations were performed for each of the inlets as described in Section IV.C.5. Natural condition for Carnegie Lake (as for all lakes evaluated for Raritan TMDL Study) assumes the lake exists, despite the reality that the lake itself is a constructed impoundment of the Millstone River. The natural condition for Carnegie Lake was calculated to be an average concentration of 0.05 mg/l TP. The TMDL evaluation was performed to satisfy the natural condition, since the Surface Water Quality Standards [N.J.A.C. 7:9B-1.5(c)1] state that the natural condition becomes the criterion if it is shown to exceed the criterion that would otherwise be applicable (i.e., the 0.05 mg/l not-to-exceed criterion).

The TMDL Condition for the upper Millstone River and Stony Brook watersheds was described previously. An 80% NPS stormwater reduction was also assigned for the Carnegie Lake direct watershed. Compliance with the natural condition was evaluated in two ways. First, the percent exceedance of 0.05 mg/ TP at the inlets was compared to the natural condition for those inlets. The composite inlet represents a flow-weighted average of all three simulated inlets. Second, the average TP concentration in Carnegie Lake was compared with the natural condition. Results are provided in Table 35 below. It is important to recognize that achieving the water quality target (natural condition) in Carnegie Lake requires substantial reductions of both point and nonpoint phosphorus sources. Reducing either WWTP point sources or NPS stormwater alone would not be sufficient to achieve the desired water quality result.

Table 35: Carnegie Lake TMDL Results

Scenario	Carnegie Lake Inlets Percent Exceedance Over 0.05 mg/l				Carnegie Lake Average TP (mg/l)
	Stony Brook	Upper Millstone	Direct Watershed	Composite Inlet	
Existing Condition	99%	98%	92%	100%	0.11
TMDL Condition	18%	4%	0%	7%	0.05
Natural Condition	16%	3%	0%	7%	0.05

3. Beden Brook Watershed

The Beden Brook and Pike Brook watersheds have been the subject of previous nutrient impact evaluations (TRC Omni, May 6, 2004). These watersheds present TP over 0.1 mg/l, substantial DO swing, high periphyton densities in excess of the thresholds used by NJDEP to assess excessive productivity (NJDEP, 2003), and occasional diurnal pH peaks above 8.5 s.u. Point and nonpoint source phosphorus reductions for the TMDL Condition in the Beden Brook watershed were based on compliance with the 0.1 mg/l TP criterion at the Beden and Pike Brook HUC outlets (e.g., Figure 50). The TMDL will reduce productivity in the Beden Brook watershed and result in improved water quality conditions, as shown in Figure 51; the diurnal DO peaks in Beden Brook are greatly attenuated due to the point and nonpoint source reductions in the TMDL Condition.

Figure 50: Total Phosphorus at Pike Brook HUC Outlet

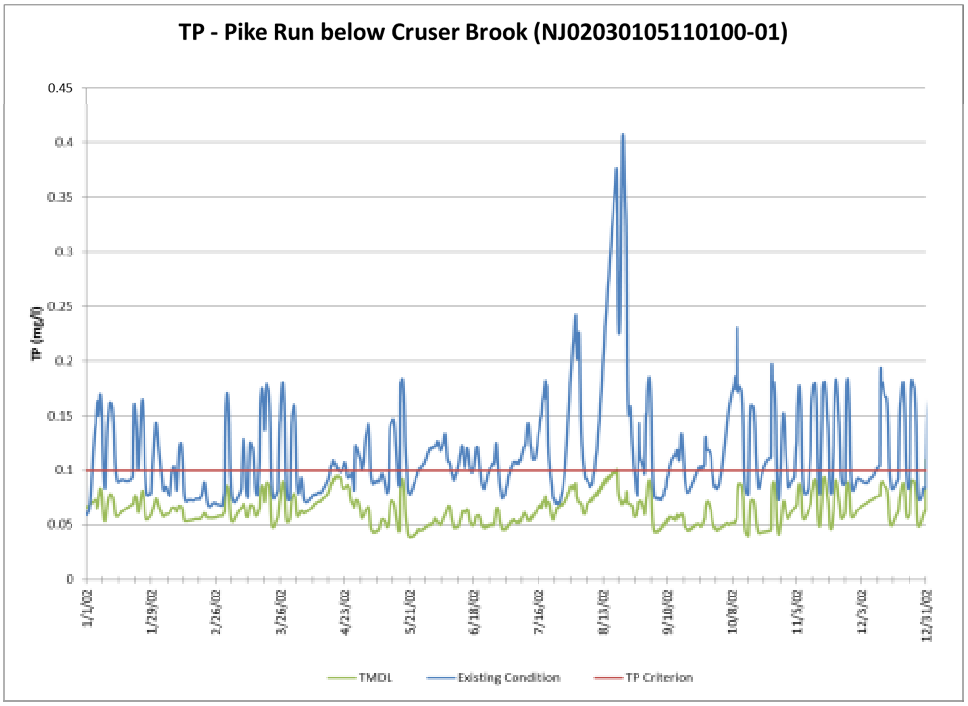
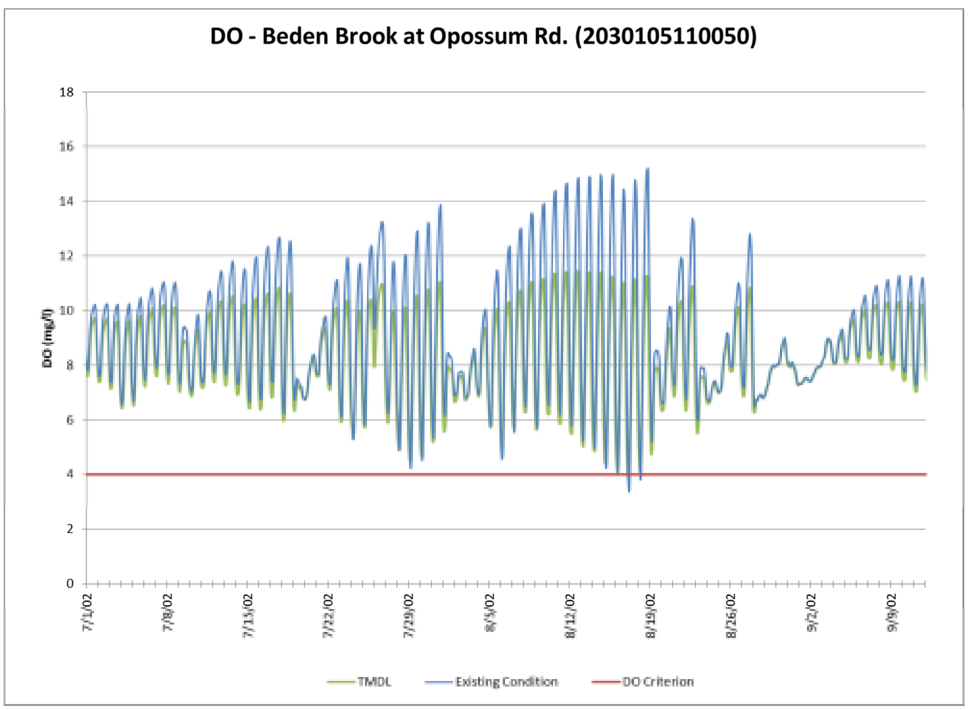


Figure 51: Dissolved Oxygen in Beden Brook

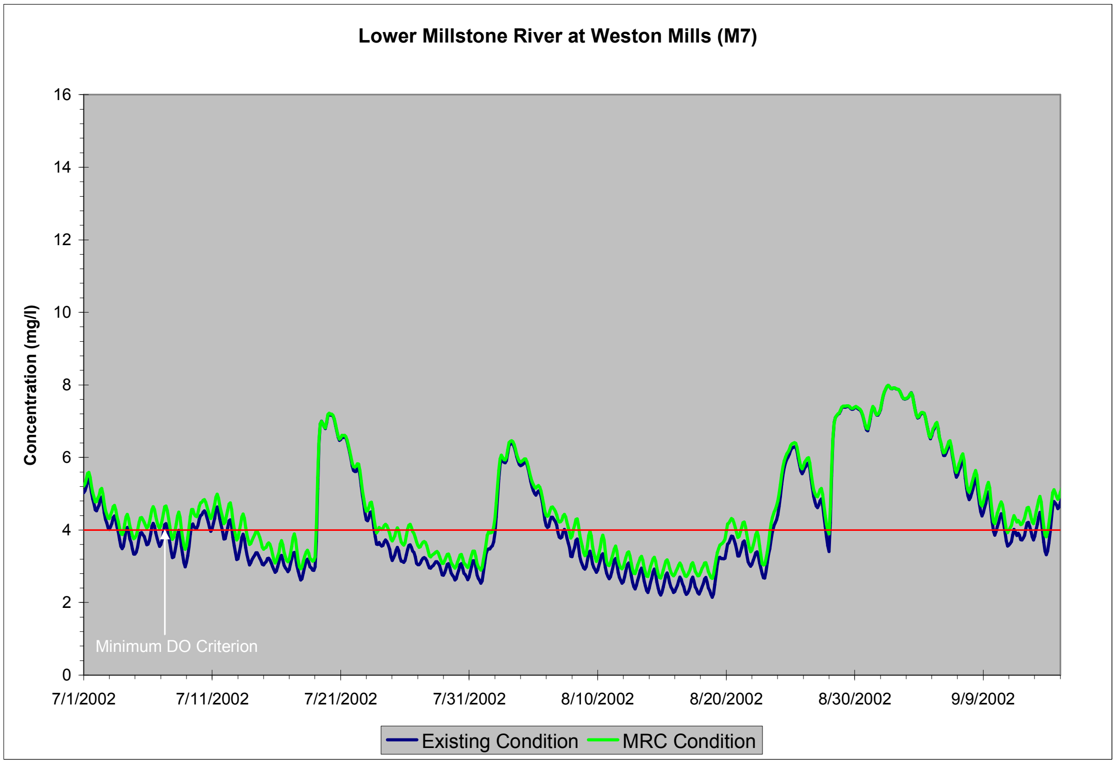


4. Lower Millstone/Mainstem Raritan River Watershed

The lower Millstone River and the mainstem Raritan River downstream of the Millstone River confluence were both the subject of previous phosphorus studies (TRC Omni, May 6, 2004; TRC Omni, December 8, 2004). The lower Millstone River between Carnegie Lake and its confluence with the Raritan River exhibits overall low DO and little to low (less than 3 mg/l/d) diurnal DO variation, low periphyton density, and pH on the low side of the acceptable range (6.5 to 8.5 s.u.) with little to no diurnal pH variation. Phytoplankton concentrations, which are occasionally high as they enter the lower Millstone River due to growth that occurs in Carnegie Lake, quickly attenuate within the lower Millstone River.

The water in the lower Millstone River is fairly dark, canopy cover is dense, depth is greater than most other streams in the basin, and substrate does not support high densities of plants or periphyton. The stream bottom is soft and mucky, and exerts a high sediment oxygen demand on the stream. This appears to be a natural condition for the lower Millstone River, caused in part by the very slow moving water and minimal slope. Sections of the stream immediately downstream of WWTP discharges are generally higher in DO due to the discharge itself and the local increase in stream velocity that results. Due in part to the low slope, this stream is subject to relatively frequent flooding; in fact, its terminus in Manville is known to have experienced some of the worst flooding in the State of New Jersey. There is significant phosphorus in the lower Millstone River from both point and nonpoint sources; the fact that there is so little diurnal DO variation under existing condition demonstrates that productivity in the system is not controlled by phosphorus. This is confirmed by comparing DO predictions for the Existing Condition with the MRC Condition in Figure 52. Recall from Section IV.C.4 that the MRC Condition reflects an unrealistically reduced phosphorus condition compared to the Existing Condition; predicted DO remains essentially the same, being influenced only by the flow differences between the two simulations. Given that phosphorus is not controlling productivity or rendering the waters unsuitable, the 0.1 mg/l TP criterion was not applied as a water quality target for the lower Millstone River.

Figure 52: Dissolved Oxygen in the Lower Millstone River



The mainstem Raritan River between its confluence with the Raritan River and the non-tidal spatial extent boundary at Fieldville Dam exhibits higher oxygen levels and much more diurnal DO and pH variation during summer low-flow conditions than the lower Millstone River. Existing phosphorus levels are especially high in this stream due to the influence of major WWTP dischargers in the lower Millstone River and the mainstem Raritan River. This stream has been the subject of extensive monitoring and evaluation to determine whether the instream 0.1 mg/l TP criterion properly applies to the stream (TRC Omni, May 6, 2004; TRC Omni, December 8, 2004). The data and evaluations performed indicate the following:

- The critical location is the downstream terminus of the spatial extent, the Raritan River above Fieldville Dam (R4);
- Phosphorus under current conditions is not controlling productivity levels because available phosphorus is supplied to the system faster than it can be utilized by plants and algae;
- Periphyton density is substantial, but not in excess of the thresholds used by NJDEP to assess excessive productivity (NJDEP, 2003);

- Phytoplankton concentrations are low; productivity is driven by periphyton and aquatic macrophytes in this wide, shallow stream;
- Diurnal DO and pH swings are substantial during low flow summer periods; and
- DO remains well above the minimum DO criterion of 4.0 mg/l, even during nighttime lows.

Diurnal pH peaks exceeded 8.5 s.u. for four days during one monitoring event performed in late June and early July of 2003. In addition, 2 of the 20 grab samples collected mid-day between May and October during low flow conditions exceeded a pH of 8.5 s.u. (8.77 s.u. on 7/2/2003 and 8.65 s.u. on 8/28/2003).

It is worth noting that the model calibration for the Mainstem watershed area model does not capture the DO peaks observed at R4 during the June/July 2003 event. Without additional data and information, it is not possible to reconcile the high DO peaks observed at R4 during the June/July 2003 event with the more moderate DO peaks observed in 2004 and 2005 under more critical flow conditions. The elevated pH values and large diurnal DO swings observed in early July 2003, remain unexplained. As stated in section II.D.5, extensive follow-up monitoring was performed at this location to determine whether phosphorus is rendering the waters unsuitable and to better understand the system dynamics. However, these data provided inconclusive results that could not be explained from a water quality perspective. Data analysis and modeling in this area could not explain the pattern of responses observed, suggesting the influence of an unknown factor variable that is not understood at this time. As a result, NJDEP has determined to defer the TMDL for this part of the watershed until additional information can be developed and analyzed.

Since the TMDL Conditions for upstream boundary conditions (i.e., North/South Branch, Carnegie Lake, and Beden Brook) would contribute insignificant phosphorus loads to the mainstem Raritan River under the TMDL Condition, any water quality target selected in the future for the mainstem Raritan River (if additional monitoring indicates that phosphorus is rendering the waters unsuitable) would affect phosphorus sources within the lower Millstone River and mainstem Raritan River watersheds. Specifically, Stony Brook Regional Sewerage Authority – River Road, Montgomery Township Stage

II, Somerset Raritan Valley Sewerage Authority, and the other small dischargers listed in the "Lower Millstone – Raritan" page of Appendix P would be potentially affected by any future TMDL to address a nutrient impairment in the mainstem Raritan River.

D. TSS TMDL Evaluations

Several stream segments in the Raritan River Basin (e.g. South Branch Raritan River, North Branch Raritan River, mainstem Raritan River, Stony Brook, and upper Millstone River) exhibit high TSS concentrations under high flow conditions, occasionally exceeding the TSS criterion. Elevated TSS concentrations are primarily the result of two processes. One is stormwater inputs from contributing watersheds; this process is modeled in the Raritan River Basin Model. The other process is bank and bed erosion within the streams. This process was not modeled within the Raritan River Basin Model. The Raritan River Basin Model was not developed with the intent to simulate all TSS processes or to perform TMDL calculations for TSS. Had TSS simulation been deemed important to model formulation, a sediment transport model might have been selected. Such a model would have been even more data intensive.

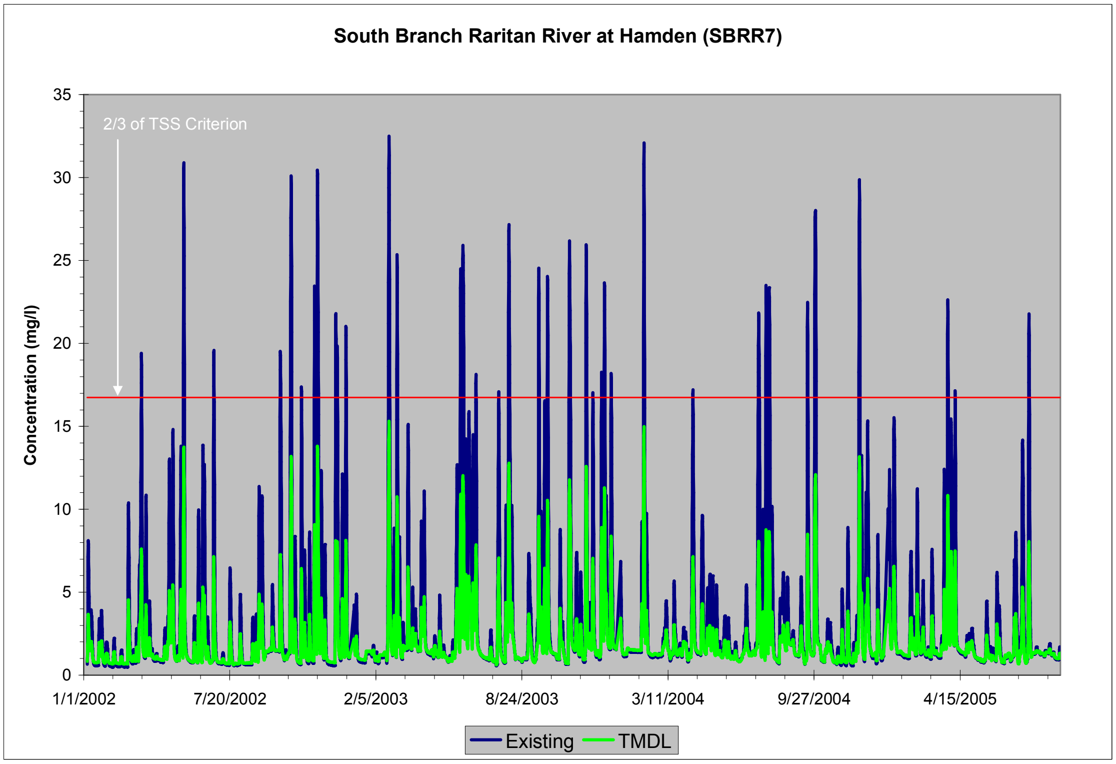
Although instream erosion is not modeled, TSS is one of the constituents simulated in the Raritan River Basin Model. The calibration of TSS during low flow periods helps to establish settling characteristics that are important for the calibration of phosphorus and other constituents (Section III.G.1). The overall calibration of TSS in the Raritan River Basin Model, even under high flow conditions, was surprisingly good (Appendices K and M). Headwater stations capture the range of observed TSS values very well, indicating that the NPS pollutant loading model is well-conceived and parameterized. The fact that instream TSS even at more downstream locations compares so favorably to observed data indicates that, in general, instream TSS concentrations can be explained by watershed loads without accounting for instream erosion processes. However, the simulation does not capture TSS concentrations measured near the peak of a hydrograph following a major storm (e.g. July 28-29, 2004), especially at downstream locations where the impact of instream erosion would be expected. These results indicate that, even without simulating instream erosion, the Raritan River Basin Model captures TSS concentrations very well and can therefore be used as the basis for TMDL calculations.

1. Watershed Evaluations

Percent reductions of TSS in stormwater from urban and agricultural areas were set to the same percent reduction assigned to each subwatershed for TP reductions. This is a conservative assumption, since TSS reductions in stormwater are easier to achieve than TP reductions. Structural BMPs generally target TSS. It is reasonable to assume that any successful effort to reduce TP in stormwater will also reduce TSS by a greater percentage. No other source reductions are necessary, since the simulated TSS peaks are driven only by stormwater loads. Since instream erosion cannot be quantified, it is not included in the TMDL evaluation; in other words, no allocation is assigned to instream erosion. This is the equivalent of assuming that erosion impacts were mitigated to the point where they no longer increase the TSS peaks.

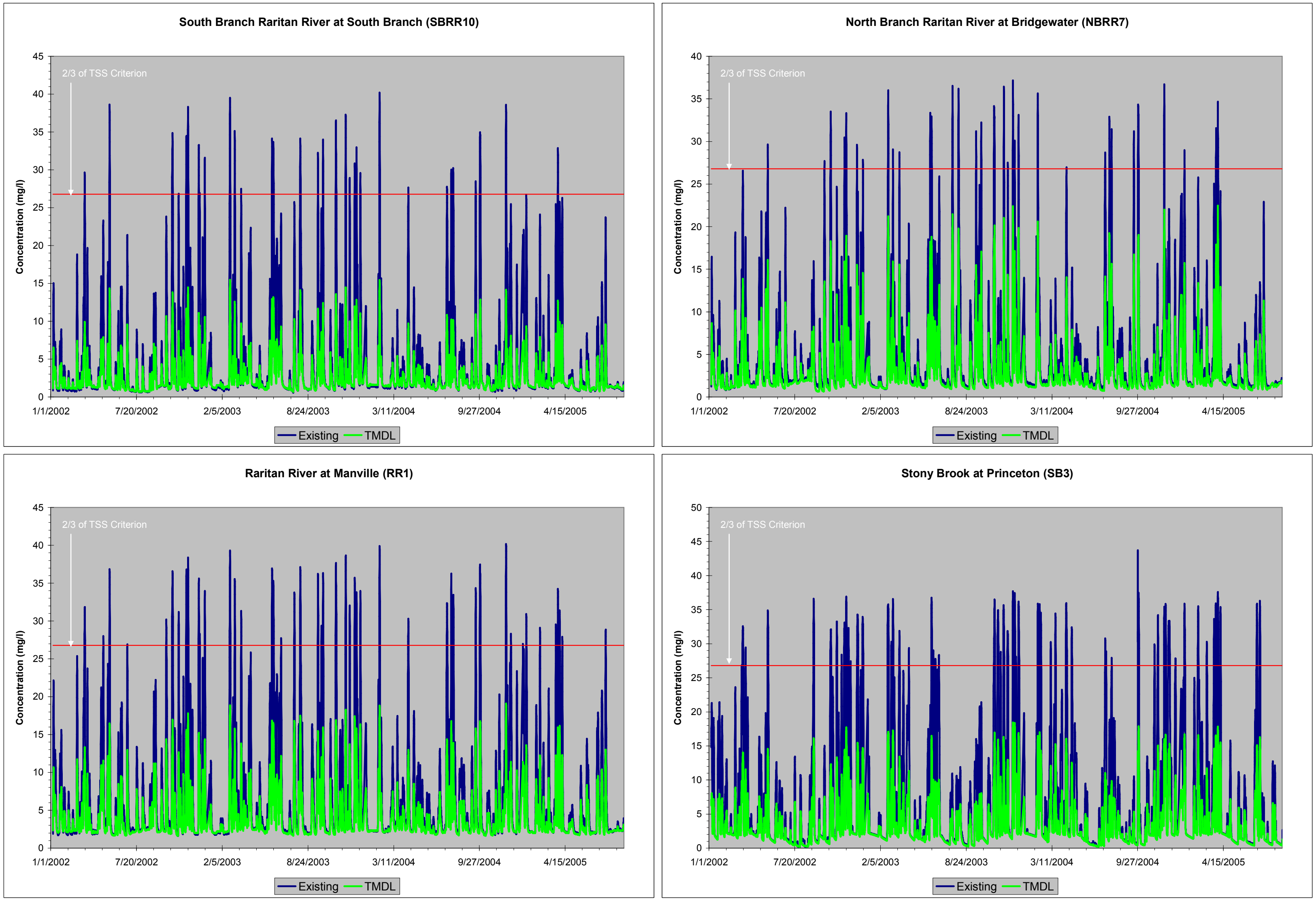
Reducing TSS in stormwater by the same percentage already required for the TP TMDLs, and mitigating the impacts of instream erosion, will result in compliance with TSS water quality targets at all HUC outlets. Figure 53 shows TSS results over the entire simulation period at a trout maintenance location in the South Branch Raritan River. Figure 54 shows TSS results at the outlets of major watersheds in the basin. While it is not possible to quantify the impact of instream erosion, the applicable TSS water quality target was multiplied by two-thirds in order to display the TSS results. The value of two-thirds is not important for the TMDL analysis, nor is it scientifically derived. It represents professional judgment as to the proportion of the TSS peaks that might be due to watershed inputs as opposed to instream erosion. The professional judgment was informed by evaluating the degree to which the calibrated model underpredicts TSS during the July 28-29 (2004) storm event at downstream sampling locations in the North/South Branch Raritan River. Showing a line that is equal to two-thirds of the TSS criterion visually reserves one-third of the water quality target to account for instream erosion, which is relevant only for the Existing Condition. The TMDL Condition assumes that instream erosion is mitigated such that it no longer increases TSS peaks. The fact that the TMDL Condition results in maximum TSS peaks less than two-thirds of the applicable water quality target provides a safety factor in the event that instream erosion continues to drive peak TSS concentrations.

Figure 53: TSS in South Branch Raritan River (Trout Waters)



It is important to understand that, for subwatersheds in which TP TMDLs were developed, the TMDL Condition for TSS is based on a conservative estimate of the TSS reductions that would be associated with the TP TMDL allocations. The TSS TMDL Condition in these watersheds was not based on the percent reduction that would satisfy the TSS water quality criteria; rather, it was simply based on the premise that a given percent TP reduction would result in at least that percent TSS reduction as well. In subwatersheds within the lower Millstone River and mainstem Raritan River subbasins, in which TP TMDLs are not being developed at this time, a 50% reduction of TSS in stormwater from urban and agricultural areas was sufficient to satisfy applicable TSS targets in the stream.

Figure 54: TSS at Outlets of Major Watershed Basins



2. Erosion Vulnerability Index

There are two principal means to mitigate instream erosion. The first is to reduce peak flow rates in the streams through improvements to stormwater infrastructure. The second is to stabilize stream banks to reduce the erosion impacts of peak flow rates when they occur. While the impact of instream erosion on TSS concentrations could not be quantified or predicted, a tool was developed in order to guide instream erosion restoration efforts: the Erosion Vulnerability Index for the North/South Branch watershed areas model is provided in Appendix N.

The tool makes use of the stream characteristics predicted by the hydraulic model to calculate shear stress in each stream segment over a particular storm. A critical shear stress, above which erosion is likely, was also calculated for each segment. The ratio of actual shear stress over a particular design storm to critical shear stress provides a relative ranking among stream segments in terms of vulnerability to instream erosion. The absolute value of the shear ratio is not important, given the uncertainties involved in the methodology. As a relative ranking, however, the shear ratio provides a useful mechanism to prioritize instream erosion restoration efforts (i.e., a stream having a shear ratio of 10 will be far more likely to erode than a stream with a shear ratio of 1.)

While not directly related to the TSS TMDL, the Erosion Vulnerability Index for the North/South Branch watershed area model is provided in Appendix N as a tool for NJDEP to prioritize streambank stabilization efforts according to the relative vulnerability of each reach to instream erosion.

E. <u>Summary of TMDL Condition and Impairment Outcomes</u>

The point and nonpoint source reductions necessary to achieve the TMDL Condition, including all Margin of Safety considerations, are provided in the tables in Appendix P. The simulated WWTP effluent concentrations and associated long-term average (LTA) effluent concentrations are provided for each WWTP discharger. The TMDL Condition is based on LTA effluent concentrations; actual effluent concentrations vary under normal operational conditions, and can be expected to be higher or lower than the LTA at any given time. Effluent limits will be established by NJDEP. Stormwater and NPS reductions associated with the TMDL Condition are also provided in Appendix P for each HUC14 watershed in the study area.

The TMDL outcomes are provided in the Tables in Appendix Q. The HUC Outlet Evaluation shows the percent exceedances for TP and TSS water quality targets at each HUC outlet. Subsequent tables in Appendix Q show the TMDL outcomes for TP, pH, DO, nitrate, and TSS impairments throughout the system.

VI. TMDL CALCULATIONS

Water quality targets were established as described previously (Section II.C), and a TMDL Condition was developed in order to satisfy water quality targets as described in Section V. The TMDL calculations provided below define the Loading Capacity (LC) and associated allocations, including Margin of Safety (MoS) and Reserve Capacity (RC), associated with the TMDL Condition for TP and TSS.

A. Margin of Safety and Reserve Capacity

A Margin of Safety (MoS) is provided to account for "lack of knowledge concerning the relationship between effluent limitations and water quality" (40 CFR 130.7(c)). A MoS is required in order to account for uncertainty in the loading estimates, physical parameters and the model itself. The MoS can be either explicit, implicit (i.e., addressed through conservative assumptions used in establishing the TMDL), or both. For these TMDL calculations, an explicit MoS is provided. The approach for calculating the MoS, which targets sources based on their level of uncertainty, is described in Section V.B.1.

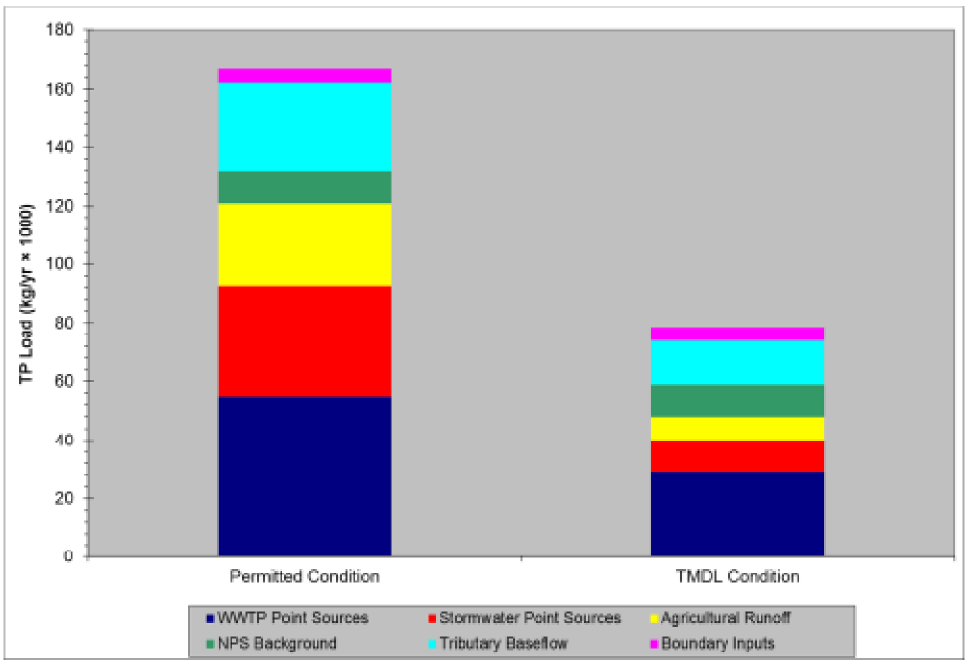
Reserve Capacity (RC) is a means of reserving a portion of the loading capacity to allow for future growth. While RC is not a required component of a TMDL, NJDEP chose to incorporate it nonetheless in order to accommodate future growth in the basin. RC was incorporated implicitly through the design of the future scenarios for wastewater flow. Wastewater flows were set equal to their maximum permitted flows, thereby accommodating the future growth that would be necessary to generate those additional wastewater flows. In addition, an explicit RC is provided in order to provide allocable load for new and expanded discharges in each watershed. The approach for calculating the RC is described in Section V.B.2.

B. Loading Capacity

Across all watersheds within the Raritan River Basin where a TMDL for TP was defined, the TMDL Condition represents a 53% decrease in total phosphorus loads compared to the Permitted Condition, as shown in Figure 55. Recall from Section IV.B that the existing (permitted) load from WWTP discharges was characterized as the long-term average concentration associated with each discharger's effective effluent limitation multiplied by their permitted flow. This allows an apples-for-apples comparison with the

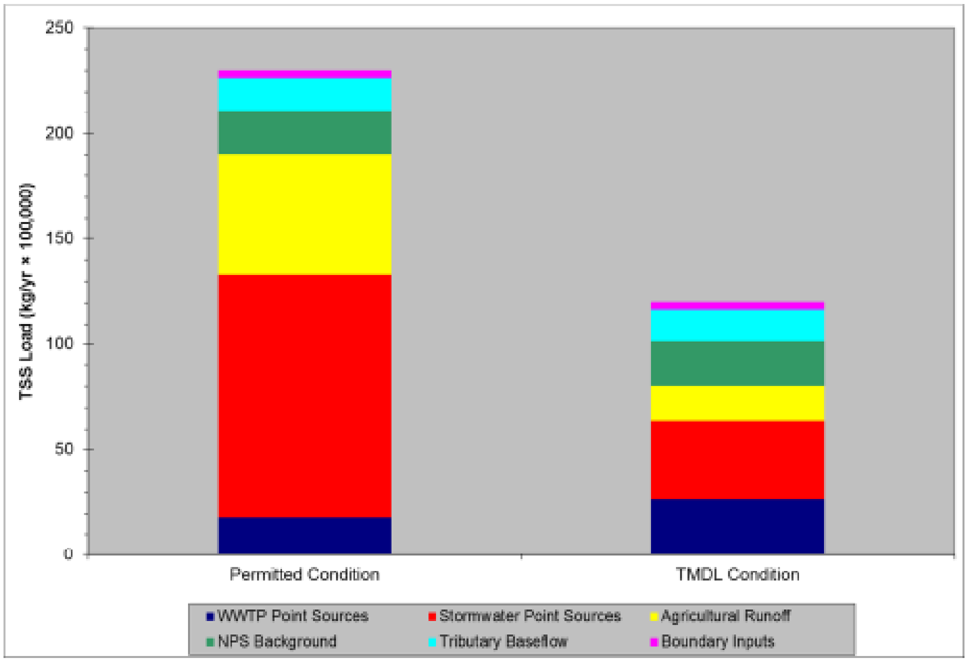
TMDL Condition, which is also based on long-term average concentration and permitted flow. WWTP point source loads decrease by 47% from the Permitted Condition to the TMDL Condition, accounting for 29% of the total decrease in phosphorus load between the two scenarios. Stormwater point source loads (runoff from urban areas) decrease by 70%, accounting for 30% of the total decrease; Agricultural runoff loads decrease by 72%, accounting for 23% of the total decrease. The remainder of the total decrease (~17%) comes from the reduction in tributary baseflow load that is associated with the stormwater load reductions.

Figure 55: Average Annual TP Loads: Permitted vs. TMDL



Across all watersheds within the Raritan River Basin where a TMDL for TSS was defined, the TMDL Condition represents a 48% decrease in TSS loads compared to the Permitted Condition, as shown in Figure 56. Stormwater point source loads (runoff from urban areas) decrease by 67%, accounting for 66% of the total decrease; Agricultural runoff loads decrease by 72%, accounting for 34% of the total decrease.

Figure 56: Average Annual TSS Loads: Permitted vs. TMDL



A TMDL is defined by the simple equation:

$$TMDL = LC = \sum WLA + \sum LA + MoS + RC$$

Where:
- TMDL = Total Maximum Daily Load;
- LC = Loading Capacity;
- WLA = Wasteload Allocation for point sources;
- LA = Load Allocation for nonpoint sources;
- MoS = Margin of Safety; and
- RC = Reserve Capacity.

LCs for TP and TSS were calculated for each TMDL Evaluation Area (Figure 31) where a TMDL was defined, and are shown in the allocation tables in Appendices R and S. LC is equal to the total maximum daily phosphorus (or TSS) load allocated among all point and nonpoint sources. It is important to recognize that LC is based on long-term average loads and calculated as an average over the entire simulation period. The nature of the pollutant sources and water quality targets demand that LC be expressed as a long-term average. In the case of phosphorus, plant and algal growth responds to the long-term nutrient concentration condition, not day-to-day peaks. Furthermore, a LC based on the maximum loads associated with high runoff periods would not be protective during dry weather periods; similarly, a LC based on acceptable loading conditions during a particular low flow period would be exceeded every time the flows increase. On the other hand, TSS is stormwater driven; any maximum daily load would depend on the storm characteristics. The only meaningful way to characterize LC for phosphorus and TSS is a long-term average load. The requirements for critical conditions and seasonal variation are satisfied by the simulation methodology, as explained in Section IV.A.

C. TMDL Allocations

WLAs are established for NJPDES-regulated point sources (including NJPDES-regulated stormwater sources) within each source category, while LAs are established for nonpoint sources and stormwater sources that are not subject to NJPDES regulation. Stormwater runoff sources were quantified according to land use type, as described previously. The land use runoff categories previously defined were used to determine whether runoff sources receive WLAs or LAs. Specifically, WLAs were calculated for runoff from urban land use types, namely residential and commercial. As described previously, commercial includes all non-residential urban land uses; for this reason, it is labeled "Other Urban" on the TMDL allocation tables in Appendices R and S.

Appendices R and S also provide specific TMDL allocations for individual WWTP dischargers by major basin for TP and TSS, respectively. The TMDL allocation for each facility was obtained by multiplying the long-term average (LTA) effluent concentration associated with the TMDL Condition by the Permitted Flow, and is expressed as an average load (kg/d TP). More information regarding what the TMDL Condition means for individual WWTP dischargers can be found in Appendix P.

VII. CONCLUSIONS

This study addresses TP, pH, and TSS impairments in lakes and streams to provide NJDEP with the technical basis to establish TMDLs in the non-tidal Raritan River Basin. Based on applicable water quality criteria, water quality targets were defined in terms of TP, DO, and TSS. Peak diurnal DO thresholds were defined to relate predicted DO to the maximum pH criterion of 8.5 s.u.

The Raritan River Basin Model was developed as a family of five independent flow and water quality models that are calibrated and validated for nutrients, dissolved oxygen, and TSS. Watershed modeling analyses were performed to assess the impact of point and nonpoint source reductions on dissolved oxygen, phosphorus concentrations, and TSS in streams throughout the system. Continuous simulations from January 2002 to August 2005 were used to account for seasonal variations and demonstrate compliance with water quality standards under critical conditions. This time period includes a range of hydrologic conditions, both seasonal and year-to-year.

A phosphorus TMDL Condition was defined as the combination of point and nonpoint source reductions that will satisfy water quality targets throughout the system. Point and nonpoint source reductions varied significantly among the various basins and even from one watershed to the next within a basin. WWTP point source allocations were expressed as total phosphorus. In areas that are not upstream of lakes, effluent limits vary from summer to winter due to the variable flow conditions. The TSS TMDL Condition was simply based on the stormwater TSS improvements that would result from the implementation of the phosphorus TMDL, which was found to satisfy TSS water quality targets at all subwatershed outlets.

The Loading Capacity was calculated for each of the nine TMDL Evaluation Areas defined throughout the basin, and allocated among point sources (wasteload allocations) and nonpoint sources (load allocations) accordingly. Individual allocations were also calculated for all WWTP dischargers. The TMDL will be implemented through NJPDES regulation of wastewater and stormwater sources, and programs designed to encourage the application of agricultural BMPs.

The Raritan River Basin Nutrient TMDL Study provides a rigorous technical basis for the TMDL solutions defined herein, and represents a hallmark achievement for NJDEP. Point and nonpoint source reductions are targeted specifically toward satisfying relevant water quality standards. The approach carves new ground in several respects: 1) it requires phosphorus reductions specifically developed to address dissolved oxygen and pH impairments; 2) it has identified dissolved orthophosphorus levels in wastewater that will restrain instream productivity; and 3) it takes the results from several phosphorus evaluation studies in the same basin, combined with significant new data collected specifically for the TMDL, to develop a comprehensive TMDL evaluation of an entire basin. Kleinfelder/Omni is proud to have been associated with this ground-breaking, innovative project.

The phosphorus reductions required to implement the TMDLs defined in this study will produce significant water quality benefits in many locations throughout the Raritan River basin. Specifically, WWTP upgrades and improvements will produce a significant water quality improvement in streams throughout the North and South Branch Raritan River watershed, the Stony Brook, and the Beden Brook/Pike Brook watershed, independent of the timing and efficacy of stormwater and nonpoint source reductions. Achieving water quality targets for lakes, most notably Carnegie Lake, will require significant reductions of both point and nonpoint sources, as quantified by this TMDL study.

This report and all appendices, as well as data and modeling-related files, are provided electronically in Appendix T.

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