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February 13, 2007
Job #6209.E04

Ms. Barbara Hirst, Chief
Bureau of Environmental Analysis and Restoration
Division of Watershed Management
New Jersey Department of Environmental Protection
401 East State Street
PO Box 418
Trenton, NJ 08625

Re: Wanaque Reservoir TMDL Development
New Model Scenario

Dear Ms. Hirst:

As part of NJDEP's current effort to integrate the Phase I and Phase II Passaic River TMDL studies, Najarian Associates has been contracted to conduct one (1) additional model simulation of the Wanaque Reservoir. As part of this integration effort, input related to the Two Bridges intake was obtained from Phase II model simulations provided by TRC-Omni. Further, a new Reservoir endpoint was established – one based on chlorophyll a rather than total phosphorus. A brief report discussing this scenario simulation, and its implications, follows:

Background

The Wanaque Reservoir is the centerpiece of the largest water supply system in northern New Jersey. The majority of Reservoir's inflows are high quality water from its upstream (tributary) watershed, which is relatively undeveloped and contains large tracts of State-owned land in both New Jersey and New York. However, these inflows are not sufficient to ensure that the Reservoir can meet the current demand for water on a long-term basis (i.e. its safe yield.). Thus, the tributary inflows are supplemented with diversions from the Ramapo River (at Pompton Lakes) and the confluence of the Pompton/Passaic Rivers (Two Bridges). The typical operational pattern for the Reservoir is for it to become drawndown during the low-flow periods of Summer, and to be refilled by diversion pumpage once river flows have recovered during the Fall. But the quality of these diversion waters can range from fair to poor, and they can degrade the Reservoir's water quality during/after periods of sustained diversion. To address these concerns, the Phase I Passaic River TMDL study (Najarian 2005) was conducted. This study combined the use of the two-dimensional Reservoir model, LA-WATERS, (to evaluate Wanaque

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Reservoir impacts) with a mass-balance model of the Watershed's various rivers (to predict the quality of the diversion waters).

Model Input and Simulations

The LA-WATERS/Wanaque Reservoir model was utilized for the current scenario in the same manner as it was for the Phase I TMDL study. To correspond with the Phase II study, model simulations were restricted to a three-year period (1999-2002). For this period, all model coefficients, meteorological conditions, and hydrologic input (tributary and diversion flows) remained unchanged from the 2005 TMDL study.

The specifications for NJDEP's new model scenario are as follows:

Watershed	**Scenario Specification**
Passaic River Watershed upstream of Two Bridges	LTA of 0.4 mg/l NPS removal rate of 60%
Pompton River watershed below Pompton Lakes and Raymond Dams	LTA of 0.4 mg/l NPS removal rate of 60%
Ramapo River watershed upstream of Pompton Lakes Dam	LTA of 0.4 mg/l NPS removal rate of 80%
Wanaque River watershed above Raymond Dam (not including Greenwood Lake watershed)	LTA of 0.4 mg/l NPS removal rate of 60%
Greenwood Lake watershed	Effluent load of 154 lbs/yr NPS removal rate of 43%*

* as per NJDEPs adopted TMDL (2004)

For this scenario, a time series of daily in-stream total phosphorus and dissolved phosphorus concentrations was provided by TRC-Omni for the Wanaque South (Two Bridges) intake site. Najarian Associates then used these data, and the daily schedule of Wanaque South diversions; to develop one portion of the Reservoir's loading input. The other two portions of the Reservoir's loading input (the diversion load from the Pompton Lakes intake and the Reservoir's direct tributary load) were developed using a mass-balance model in the same manner as in the Najarian 2005 TMDL study.

The LA-WATERS model provides simulated concentrations of all phosphorus species. As part of the Najarian 2005 TMDL study, a visual correlation was presented that links organic phosphorus concentrations with chlorophyll a concentrations. As the Reservoir endpoint has been re-specified and was now based on chlorophyll a concentrations, the phosphorus – chlorophyll a linkage (relationship) was re-examined to better ensure its defensibility. An extended discussion of the phosphorus – chlorophyll a relationship in the Wanaque Reservoir is included within the attached Appendix.

Model Output and Results

The results of the new model scenario are summarized in Figures 1-6 (pages 6-8). In these Figures, the projected daily concentration of six parameters (total phosphorus, chlorophyll a, organic phosphorus, dissolved inorganic phosphorus water temperature and dissolved oxygen) are presented for three locations within the Reservoir – Erskine in its northern portion, West Brook in its central area and Raymond Dam in its southern portion. A brief discussion of results follows:

1. For most parameters (such as total phosphorus), peak concentrations occurred during the late Winter and early Spring of 2002 (see Figure 1). This result reflects the hydrologic conditions that had occurred during the previous Winter (2001-2002). Year 2002 was a critical drought year that resulted in an exaggerated diversion impact. As the diversion water was phosphorus-rich in comparison to the normal Reservoir water quality, phosphorus levels in the Reservoir rose. Once a more "natural" hydrologic condition became re-established, phosphorus levels returned to normal over a period of several weeks.

   To further elaborate, the water years of 2000 and 2001 represented a relatively average hydrologic condition. Thus, the volume of river diversions was minimal during those two years. By contrast, the water year of 2002 represented a sustained drought condition. Further, the most severe portion of the drought extended from October 2001 through February 2002 – a period that would typically be associated with reservoir re-filling operations. This condition led to a sustained period of pumping throughout the winter (when the diversion rivers had low flow and poor quality) to maintain minimal Reservoir operational levels. Re-filling operations had to be delayed until Spring at which time they were greatly magnified. The total volume of diversion over this period exceeded the total storage capacity of the Reservoir and resulted in a serious increase in phosphorus concentrations.

2. With regard to phosphorus and chlorophyll a, there is a longitudinal concentration gradient across the Reservoir with highest concentrations being present in its southern portion (near Raymond Dam) and the lowest concentrations being present in its northern portion (near Erskine). This result reflects the basic morphology of the Reservoir. Most of the tributary inflows (high quality water) enter near the northernmost point of the Reservoir. By contrast, the diversion inflows (which are phosphorus rich) and the Reservoir intake are located near the southernmost point of the Reservoir – a location 7 miles south of most tributary inputs. Thus, the water quality effects of diversion pumpage are emphasized within the Reservoir's most southern reaches.

3. During 2002, there is a roughly three-month time lag between the peak concentrations of total/dissolved inorganic phosphorus and organic phosphorus/chlorophyll a. This result reflects both original composition of the diversion waters and the biological processes that occur in the Reservoir. The diversion waters are typically rich in total phosphorus – most of which is in the form of dissolved inorganic phosphorus. Thus, peak concentration of these parameters occurred in the Spring of 2002. In the Reservoir, inorganic phosphorus is converted (via uptake) into organic phosphorus and chlorophyll a during the Summer, which results in a summer peak for these parameters.

4. Dissolved oxygen concentration and variations (Figure 6) are primarily the result of seasonal temperature fluctuations. Results show no indication of problems with regard to the dissolved oxygen criteria.

As previously stated, the endpoint constituent for these scenarios was changed from total phosphorus to chlorophyll a. Consequently, the Reservoir's new target concentration for any year would be specified as 10 µg/l chlorophyll on a seasonally averaged basis from June 15th through September 1st. The results of the new scenario – in term of seasonal total phosphorus and chlorophyll a concentration – are presented in Tables 1 and 2. **An examination of these Tables indicates that the specified scenario is in accordance with this endpoint requirement.** A summary of corresponding TMDL loadings to the Reservoir is included in Table 3.

As the Phase II study did not address the water quality conditions in the Ramapo River watershed, the results of the Phase I study have been updated for the current scenario. A summary of the associated TMDL loadings for the Ramapo River watershed is included in Table 4.

Table 1: Seasonally Averaged Total Phosphorus Concentrations (µg/l)

Location	Year 2000	Year 2001	Year 2002	Pct. Comp.*
Raymond Dam	19.49	22.71	44.05	86.9%
West Brook	14.99	14.78	23.61	100.0%
Erskine	12.79	12.31	18.29	100.0%

* percent compliance with a 50 µg/l criterion on a daily basis

Table 2: Seasonally Averaged Chlorophyll a Concentrations (µg/l)

Location	Year 2000	Year 2001	Year 2002	Pct. Comp.*
Raymond Dam	2.61	3.49	9.20	96.9%
West Brook	2.58	3.26	6.62	100.0%
Erskine	2.59	3.13	5.85	100.0%

* percent compliance with a 10 µg/l criterion on a daily basis

We thank you for this opportunity to provide continued support to NJDEP in its TMDL-development process. Please contact me if you have any questions regarding this submittal.

Very truly yours,
NAJARIAN ASSOCIATES

Tavit O. Najarian, Sc.D.
President

Attachments

cc: Mr. Lawrence J. Baier
Ms. Kimberly Cenno
Ms. Karen Ward
Mr. Marzooq Al-Ebus

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Table 3: TMDL calculations for Wanaque Reservoir*
(average daily loads based on water years 2000-2002 model simulation)

	Existing Conditions[1]		TMDL Specification		Percent
	lbs TP/day	% of LC	lbs TP/day	% of LC	Reduction[2]
Loading Capacity (LC)	130.06	100%	55.42	100%	57%
Point Sources other than Stormwater					
NJPDES Dischargers[3,4]	0.70	0.5%	0.43	0.8%	39%
Loading from Intake Diversions					
Diversions from Ramapo River[5]	7.12	5.5%	1.49	2.7%	79%
Diversions from Two Bridges[6]	82.62	63.5%	24.69	44.6%	70%
Internal Loading					
Sediment/Base Flow	6.92	5.3%	6.92	12.5%	0%
Land Use Surface Runoff[7,8]					
Low Intensity Residential	4.19	3.2%	1.93	3.5%	54%
High Intensity Residential	9.13	7.0%	4.20	7.6%	54%
Commercial/Industrial/Transportation	4.01	3.1%	1.85	3.3%	54%
Mixed Urban/Recreational	1.47	1.1%	0.68	1.2%	54%
Crops/Pasture/Hay	1.23	0.9%	0.56	1.0%	54%
Deciduous Forest	7.44	5.7%	7.44	13.4%	0%
Evergreen Forest	0.75	0.6%	0.75	1.3%	0%
Mixed Forest	1.82	1.4%	1.82	3.3%	0%
Shrubland	0.11	0.1%	0.11	0.2%	0%
Woody Wetlands	0.65	0.5%	0.65	1.2%	0%
Herbaceous Wetlands	0.07	0.1%	0.07	0.1%	0%
Open Water	1.48	1.1%	1.48	2.7%	0%
Disturbed Areas	0.36	0.3%	0.36	0.6%	0%

* an explicit MOS has been specified in terms of chlorophyll a
1 average annual loads for existing conditions based on 1993-2002 model simulation
2 = 1 - (TMDL load /Existing load)*100
3 WLA derived from NJDEP TMDL study for Greenwood Lake (2004)
4 facilities within Reservoir tributary watershed -- existing condition based on 1997-2000 DMR data
5 diversion load typically equals 3%-5% of the annual river load - for river load see Table 6.2 (Najarian 2005)
6 phosphorus concentrations at diversion intake were computed by TRC-Omni
7 see Table 6.9 for associated land use areas (Najarian 2005)
8 removal rates are an areal-weighted average of the Greenwood Lake watershed (an NPS removal rate of 43%) and the rest of the Wanaque Reservoir watershed (an NPS removal rate of 60%)

Table 4: TMDL calculations for Ramapo River watershed (average daily loads based on water years 1993-2002 model simulation)

	Existing Conditions[1]		TMDL Specification		Percent
	lbs TP/day	% of LC	lbs TP/day	% of LC	Reduction[2]
Cumulative Watershed Load (CWL)	120.3	100%	38.2	100%	68%
Point Sources other than Stormwater					
NJPDES Dischargers[3]	0.1	0.1%	0.8	2.1%	0%
Internal Loading					
Sediment/Base Flow	4.5	3.7%	4.5	11.7%	0%
Boundary Inputs					
New York[4]	77.6	64.5%	18.8	49.1%	76%
Land Use Surface Runoff					
Low Intensity Residential	8.5	7.0%	1.7	4.4%	80%
High Intensity Residential	13.0	10.8%	2.6	6.8%	80%
Commercial/Industrial/Transportation	7.6	6.3%	1.5	4.0%	80%
Mixed Urban/Recreational	3.9	3.2%	0.8	2.0%	80%
Crops/Pasture/Hay	0.5	0.4%	0.1	0.3%	80%
Deciduous Forest	3.3	2.7%	3.3	8.7%	0%
Evergreen Forest	0.0	0.0%	0.0	0.0%	0%
Mixed Forest	0.1	0.1%	0.1	0.3%	0%
Shrubland	0.1	0.1%	0.1	0.3%	0%
Woody Wetlands	0.4	0.3%	0.4	1.0%	0%
Herbaceous Wetlands	0.0	0.0%	0.0	0.1%	0%
Open Water	0.4	0.3%	0.4	1.0%	0%
Disturbed Areas	0.4	0.3%	0.4	1.1%	0%
Other Allocations					
Margin of Safety	n/a	n/a	2.3	6.0%	n/a
Reserve Capacity	n/a	n/a	0.4	1.0%	n/a

1 average annual loads for existing conditions based on 1993-2002 model simulation
2 = 1 - (TMDL load /Existing load)*100
3 a detailed listing of individual discharge facilities is provided within Table 6.9 (Najarian (2005)
4 includes PS and NPS discharges to the Ramapo River within New York State

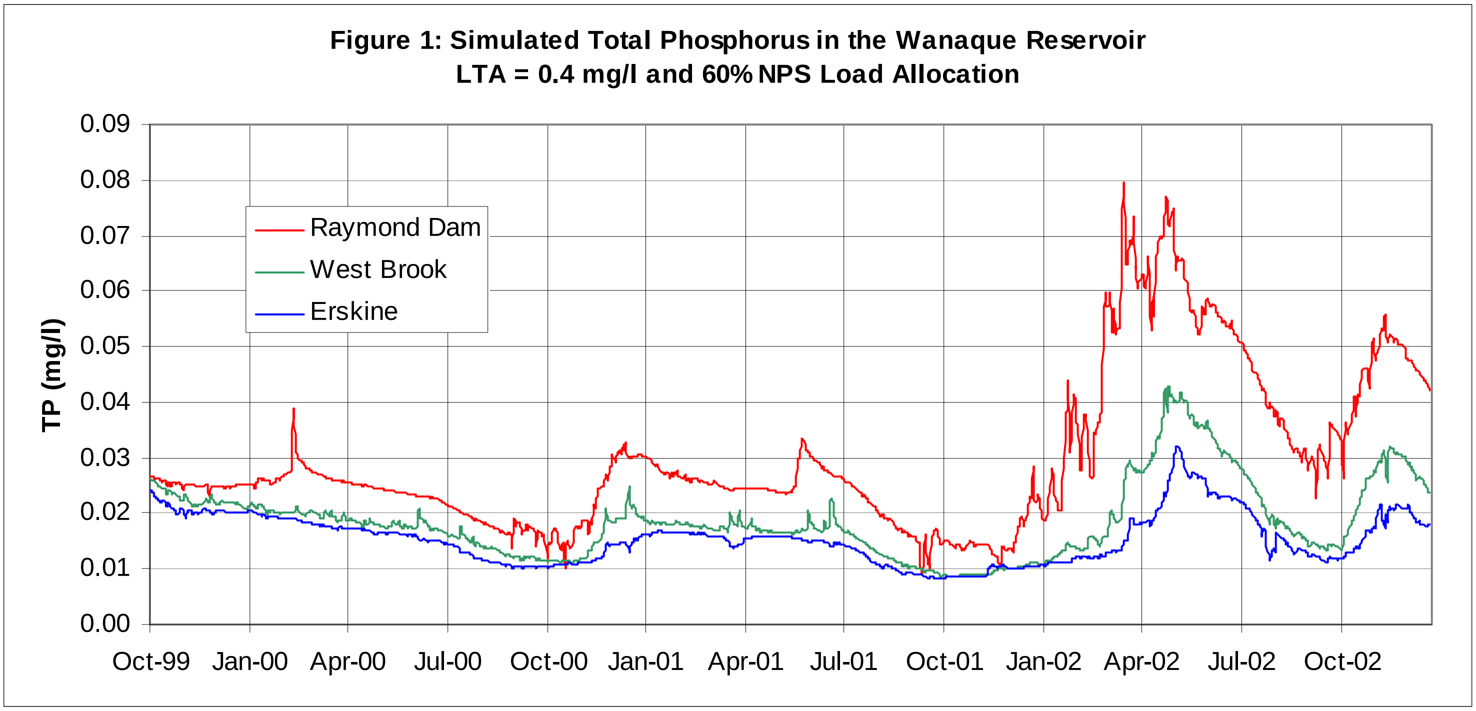


Figure 1: Simulated Total Phosphorus in the Wanaque Reservoir
LTA = 0.4 mg/l and 60% NPS Load Allocation
TP (mg/l)
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
Raymond Dam
West Brook
Erskine
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Oct-02

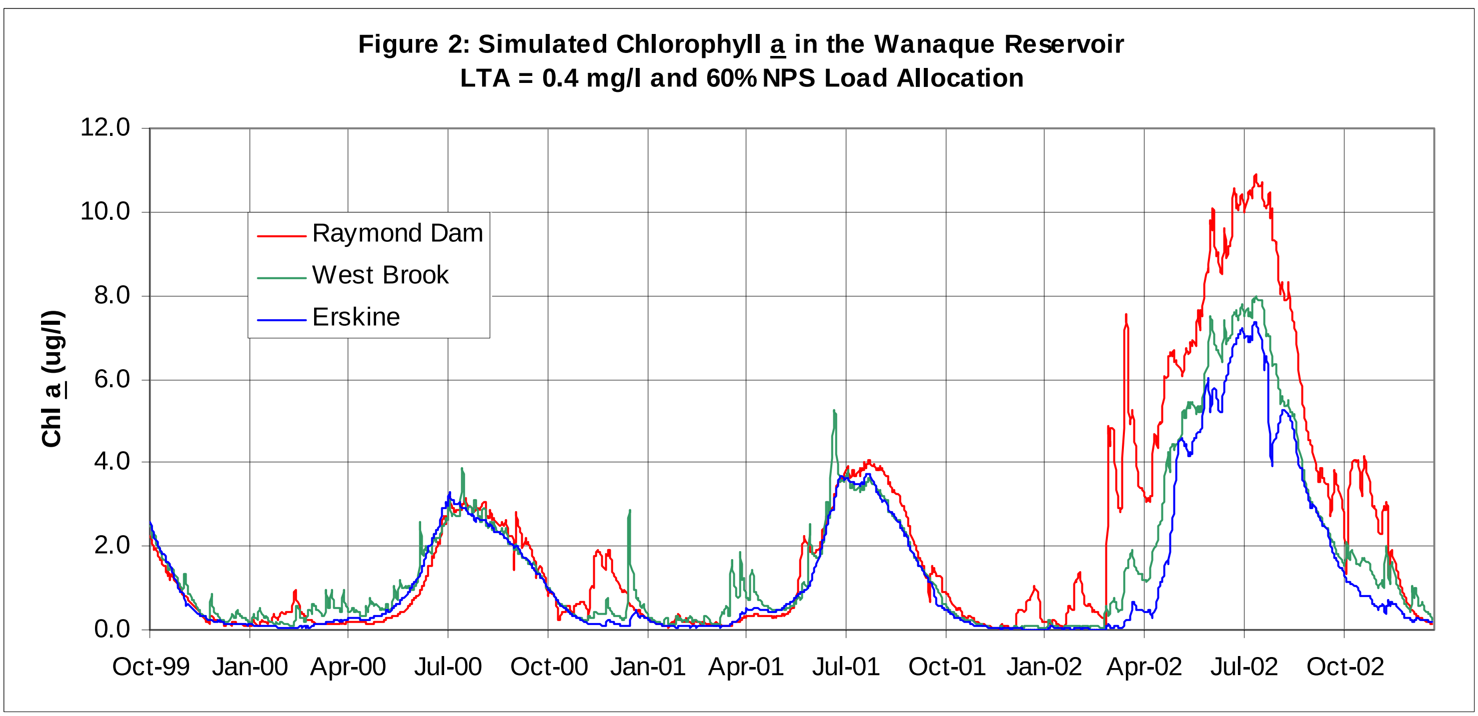


Figure 2: Simulated Chlorophyll a in the Wanaque Reservoir
LTA = 0.4 mg/l and 60% NPS Load Allocation
Chl a (ug/l)
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Raymond Dam
West Brook
Erskine
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Oct-02

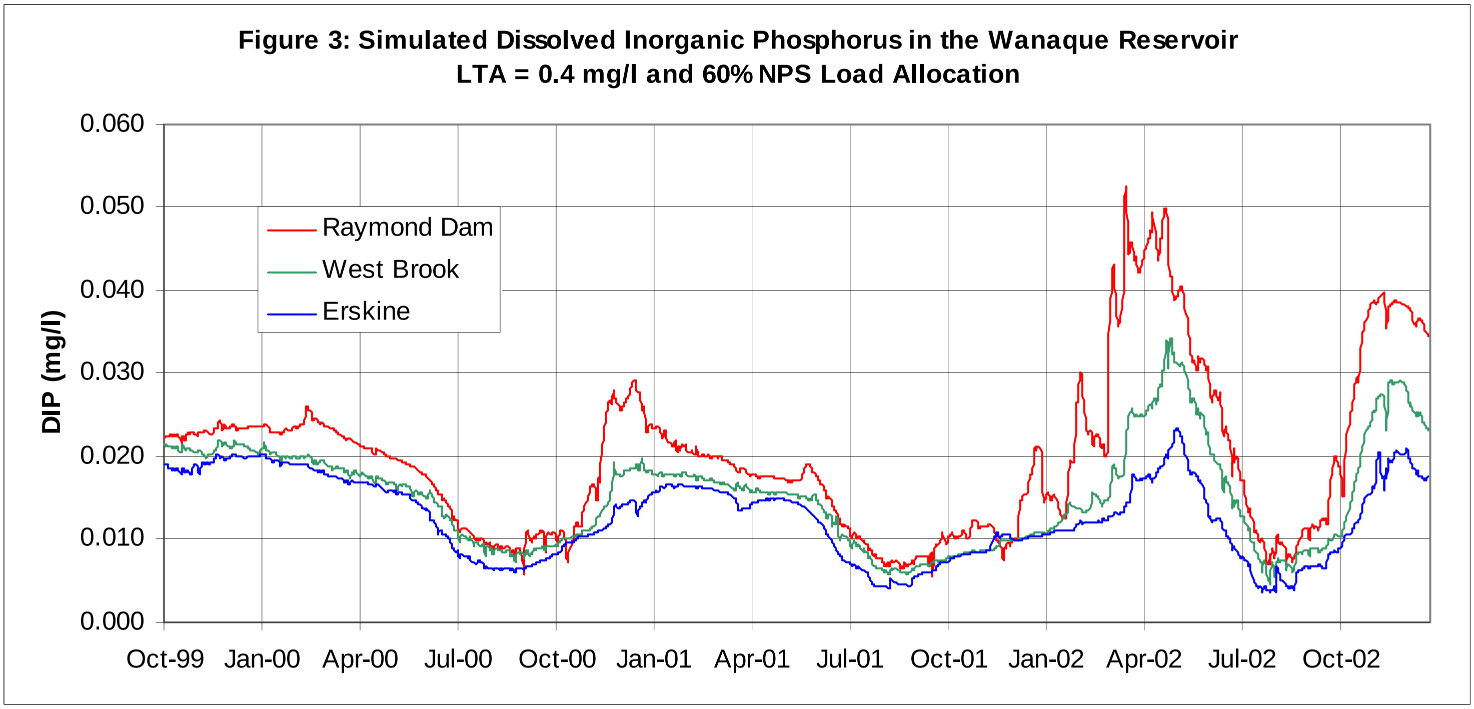


Figure 3: Simulated Dissolved Inorganic Phosphorus in the Wanaque Reservoir
LTA = 0.4 mg/l and 60% NPS Load Allocation
DIP (mg/l)
0.060
0.050
0.040
0.030
0.020
0.010
0.000
Raymond Dam
West Brook
Erskine
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Oct-02

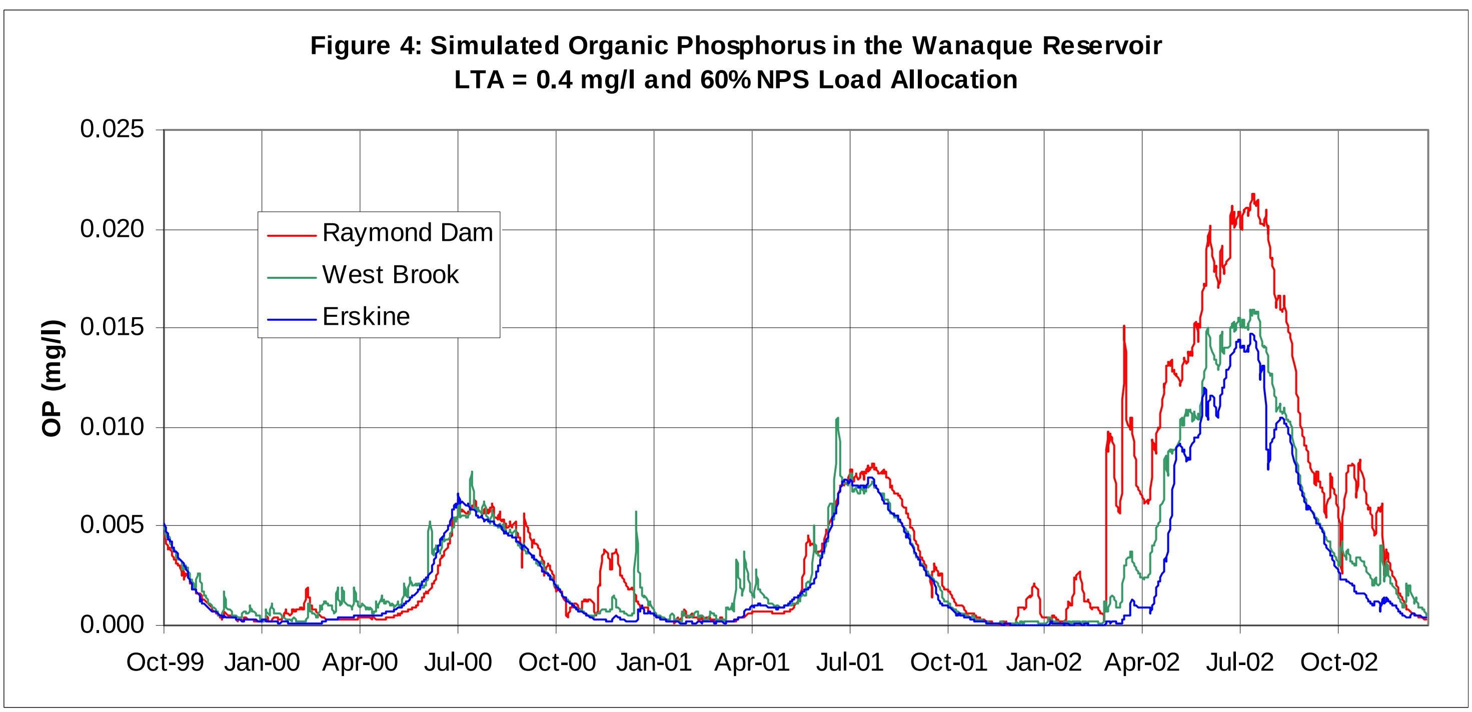


Figure 4: Simulated Organic Phosphorus in the Wanaque Reservoir
LTA = 0.4 mg/l and 60% NPS Load Allocation
OP (mg/l)
0.025
0.020
0.015
0.010
0.005
0.000
Raymond Dam
West Brook
Erskine
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Oct-02

Figure 5: Simulated Temperature in the Wanaque Reservoir
LTA = 0.4 mg/l and 60% NPS Load Allocation

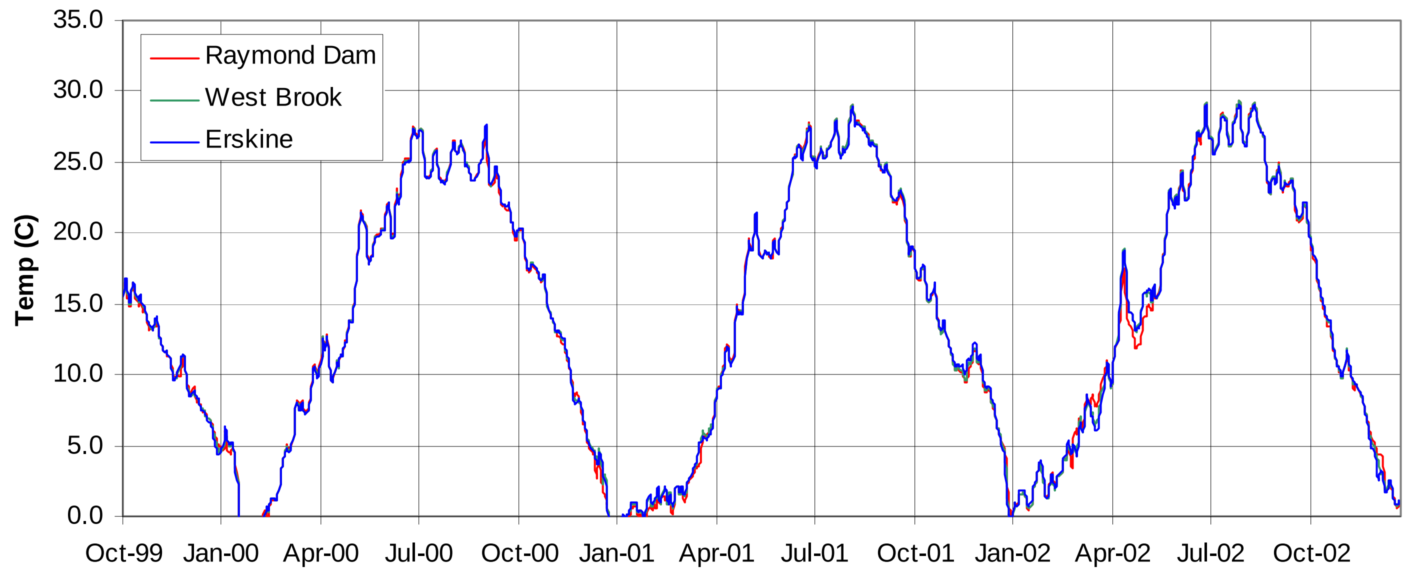
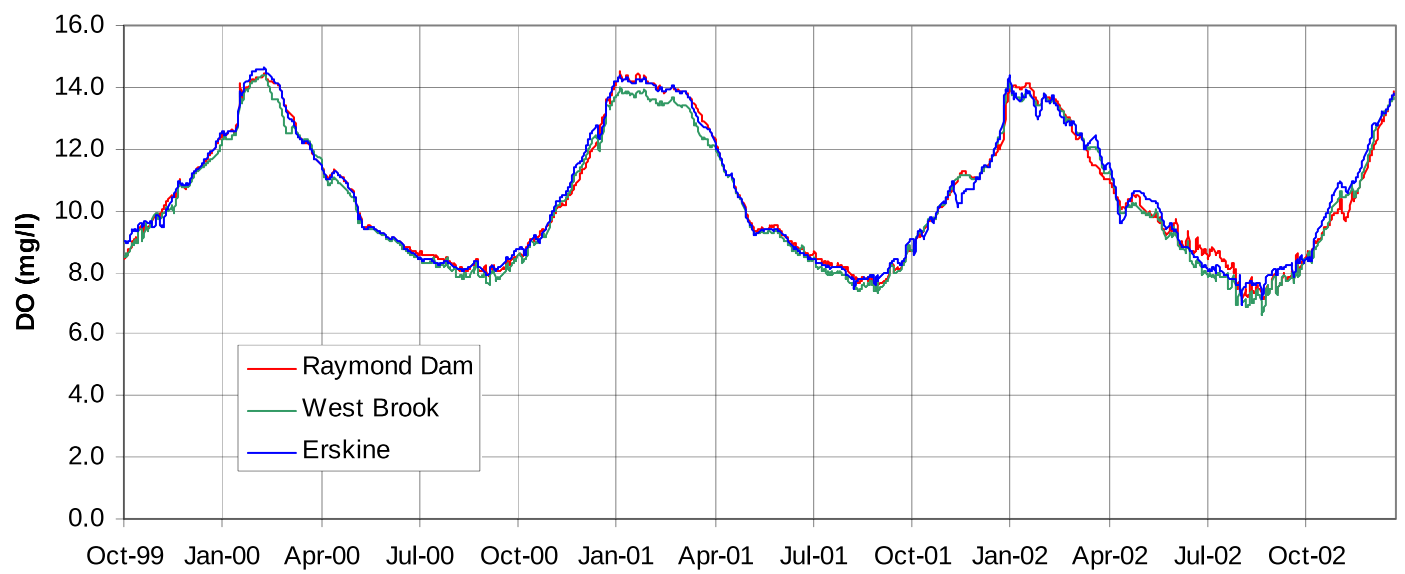


Figure 6: Simulated Dissolved Oxygen in the Wanaque Reservoir
LTA = 0.4 mg/l and 60% NPS Load Allocation



APPENDIX

Discussion of Phosphorus-Chlorophyll a Relations

Chlorophyll a is an important indicator of primary productivity. In reservoir systems, water quality constituents such as chlorophyll a exhibit a high degree of variability (i.e., patchiness) in both space and time. Such variability is due to complex physical and biogeochemical processes that regulate algal abundance, nutrient availability and species diversity. Nevertheless, overall model results can be compared to observed chlorophyll a concentrations using an approximate approach developed in a previous related study (Najarian 2000). This study revealed an association between simulated *organic* phosphorus concentrations in the lower Wanaque Reservoir and observed chlorophyll a concentrations –an association that is further explored in the present analysis.

As indicated in Figure A-1 (upper panel), observed chlorophyll a concentrations appear to be almost unrelated to variations in *total* phosphorous concentrations in the Reservoir. Total phosphorous concentrations appear to be related to the magnitude of flow diversions. Substantial increases (over 50 µg/l) in TP occur immediately following large diversions from the Passaic and Pompton Rivers during the fall/winter seasons.

In contrast, the limited available chlorophyll a data exhibit a pattern of seasonal variability that is similar to simulated organic phosphorus concentrations (Figure A-1, lower panel). Both observed chlorophyll a and computed organic phosphorus show episodic increases during the summer seasons. Seasonal-average Reservoir chlorophyll a concentrations are typically below 10–15 µg/l. Peak spring/summer concentrations may exceed 25 µg/l, especially during drought years (e.g., 1999 and 2002). This apparent association between organic phosphorous and chlorophyll a suggests that most of the organic phosphorous is tied up in living biomass.

Note that the observed chlorophyll a concentrations are plotted *at half-scale* in Figure A-1 (i.e., at a scale of 0-100 µg/l for chlorophyll a vs. 0-200 µg/l for organic phosphorus). This plot suggests a simple linear relationship between simulated organic phosphorus and chlorophyll a, that is:

$$[chl\text{-}a] = 0.5*[Org\text{-}P]. \qquad (1)$$

At half-scale, simulated organic phosphorus concentrations generally track the observed chlorophyll a data, and peak during the growth seasons (Figure A-1, lower panel).

To explore this empirical relationship further, model sensitivity was examined over a range (0.4-0.6) of possible proportionality constants (Figure A-2). Results indicate that only peak chlorophyll a levels are sensitive to the selection of such factors. Moreover, the proposed 0.5 factor appears best to reproduce many of the peak chlorophyll a values, including the critical year-2002 peak of the TMDL calculation.

As an additional check, the proposed empirical relation (Eq. 1) was compared to corresponding relations (Table A-1) reported in peer-reviewed studies by Canfield (1983), Dillion and Rigler (1974) and Jones and Bachmann (1976). As before, organic phosphorus concentration was used as the independent variable (instead of TP) to improve the goodness of fit. As displayed in Figure A-3, comparable seasonal variations were obtained with all four relations. Greatest differences occurred for peak values, with the curve corresponding to the 0.5 factor matching the observed peak value in 2002. Thus, the proposed simple empirical relation (Eq. 1) provides a reasonable means for estimating chlorophyll a levels, despite the complexities involved (e.g., luxury uptake, algal composition, population shifts, species diversity, etc).

Table A-1: Phosphorus-Chlorophyll a Relations

Author	**Relation**	**Number of samples**
Najarian Associates	[chl-a] = 0.5*[Org-P] or, equivalently: Log [chl-a] = -0.30 + Log [Org-P]	55
Canfield* (1983)	Log [chl-a] = -0.15 + 0.744Log [TP]	85
Dillion & Rigler* (1974)	Log [chl-a] = -1.136 + 1.449Log [TP]	85
Jones and Bachmann* (1976)	Log [chl-a] = -1.09 + 1.46Log [TP]	85

* Note that [Org-P] was substituted for [TP] in this application

References

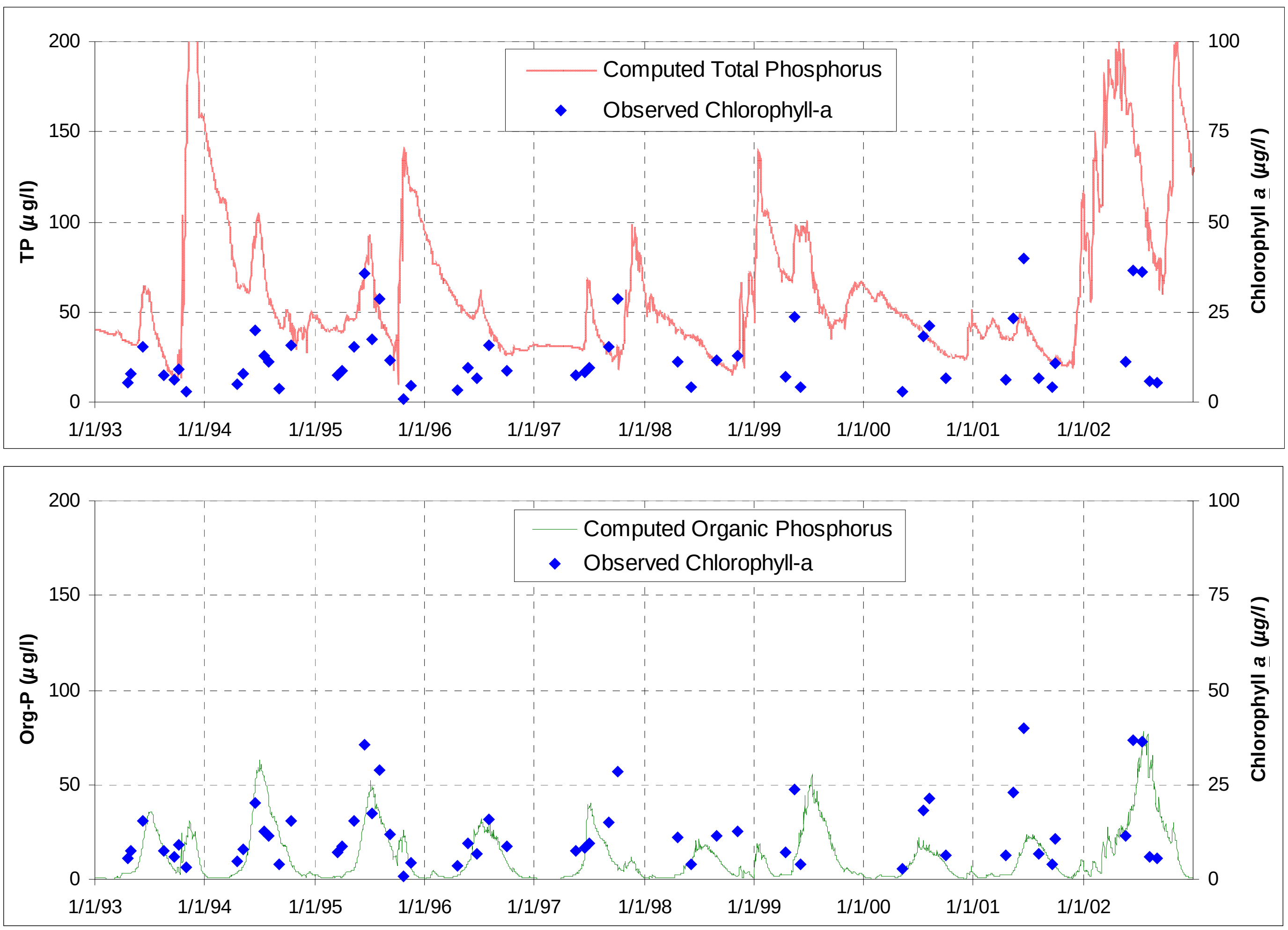
Canfield, D.E. (1983). "Prediction of chlorophyll a concentration in Florida Lakes: the importance of P and N." *Water Resources Bulletin*, 19: 255-262.

Dillion, P.J., and F.H. Rigler (1974). "The phosphorus-chlorophyll relationship in lakes." *Limnology and Oceanography*, 19: 767-773.

Jones, J.R. and R.W. Bachmann (1976). Prediction of phosphorus and chlorophyll levels in lakes." *Journal Water Pollution Control Federation*, 48: 2176-2182.

Najarian Associates (2000), "Water Quality Assessment of the Upper Passaic River Watershed and the Wanaque Reservoir," prepared for New Jersey Department of Environmental Protection, Watershed Management – Northeast Bureau.

Figure A-1: Plots of Computed Phosphorus and Observed Chlorophyll a Concentrations



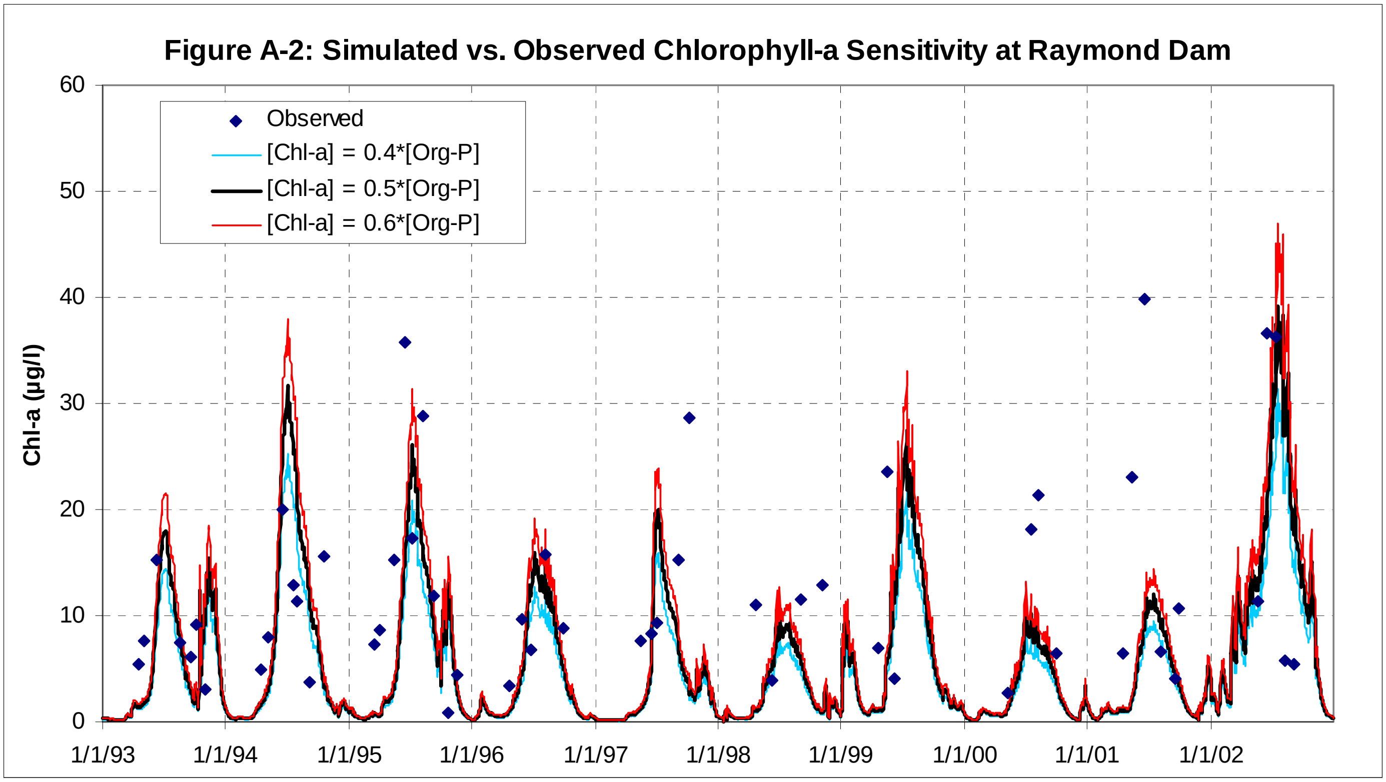


Figure A-2: Simulated vs. Observed Chlorophyll-a Sensitivity at Raymond Dam
Observed
[Chl-a] = 0.4*[Org-P]
[Chl-a] = 0.5*[Org-P]
[Chl-a] = 0.6*[Org-P]
Chl-a (µg/l)
0
10
20
30
40
50
60
1/1/93
1/1/94
1/1/95
1/1/96
1/1/97
1/1/98
1/1/99
1/1/00
1/1/01
1/1/02

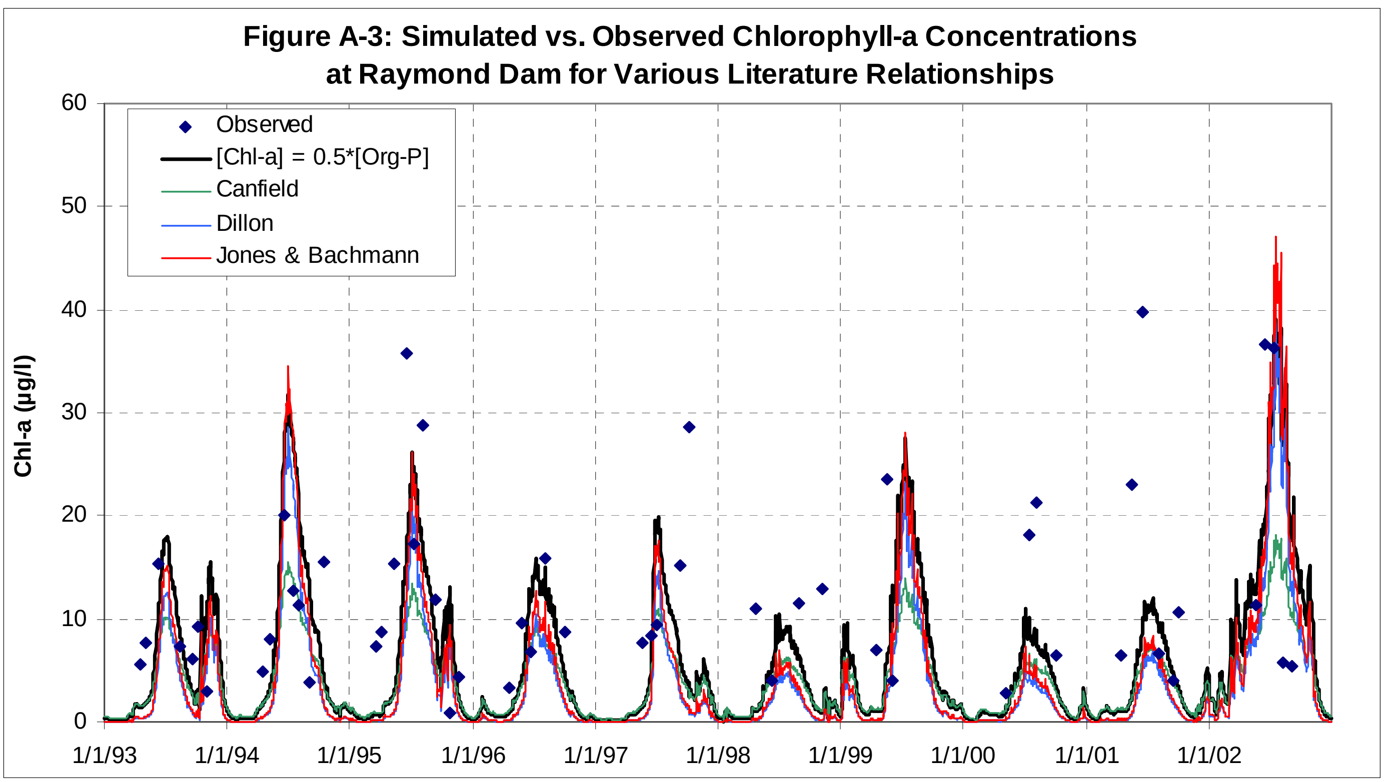


Figure A-3: Simulated vs. Observed Chlorophyll-a Concentrations
at Raymond Dam for Various Literature Relationships
Observed
[Chl-a] = 0.5*[Org-P]
Canfield
Dillon
Jones & Bachmann
Chl-a (µg/l)
0
10
20
30
40
50
60
1/1/93
1/1/94
1/1/95
1/1/96
1/1/97
1/1/98
1/1/99
1/1/00
1/1/01
1/1/02

Table A-2: Observed Chlorophyll a Data for the Wanaque Reservoir at Raymond Dam (NJDWSC)

Date	Obs. Conc (µg/l).	Date	Obs. Conc (µg/l).
4/19/1993	5.5	5/19/1997	7.6
5/3/1993	7.7	6/16/1997	8.3
6/9/1993	15.3	7/1/1997	9.4
8/16/1993	7.4	9/8/1997	15.2
9/20/1993	6.1	10/6/1997	28.6
10/6/1993	9.2	4/21/1998	11.0
11/3/1993	3.0	6/8/1998	4.0
4/18/1994	4.9	9/1/1998	11.5
5/9/1994	8.0	11/9/1998	12.8
6/20/1994	20.0	4/19/1999	6.9
7/19/1994	12.8	5/17/1999	23.6
8/1/1994	11.4	6/7/1999	4.1
9/6/1994	3.8	5/8/2000	2.8
10/18/1994	15.6	7/17/2000	18.2
3/20/1995	7.3	8/7/2000	21.4
4/3/1995	8.7	10/2/2000	6.5
5/15/1995	15.3	4/16/2001	6.4
6/19/1995	35.7	5/14/2001	23.1
7/10/1995	17.3	6/18/2001	39.8
8/7/1995	28.8	8/6/2001	6.6
9/11/1995	11.8	9/18/2001	4.1
10/24/1995	0.9	10/1/2001	10.7
11/20/1995	4.4	5/20/2002	11.4
4/22/1996	3.4	6/17/2002	36.6
5/28/1996	9.6	7/15/2002	36.3
6/24/1996	6.8	8/12/2002	5.8
8/5/1996	15.8	9/3/2002	5.5
10/1/1996	8.8		