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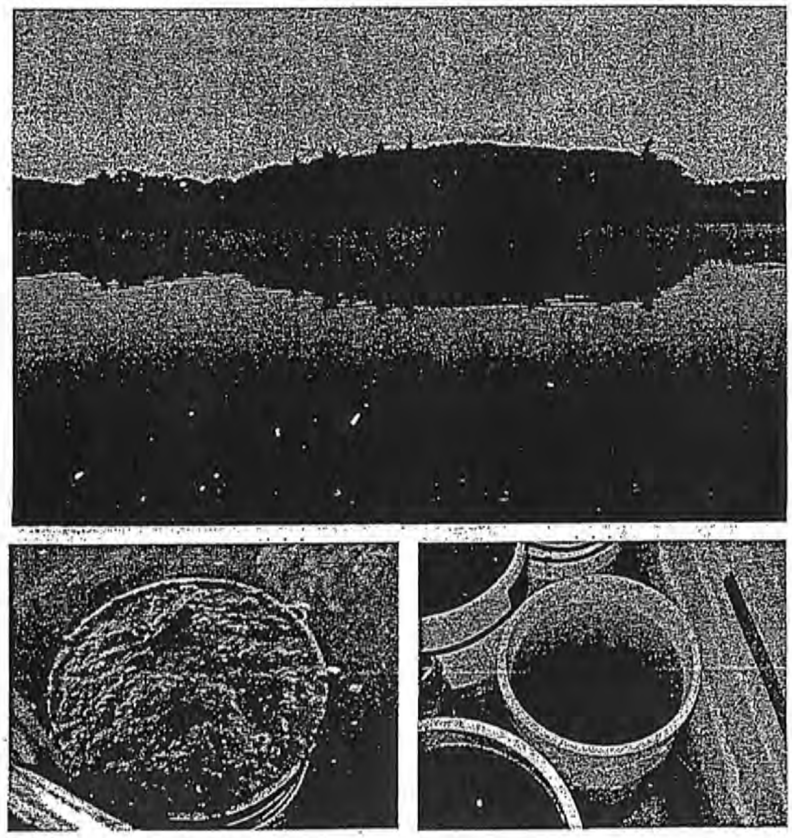
Supplemental Nutrient Loading Evaluation of Hop Brook



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1.0 INTRODUCTION

Four impoundments of Hop Brook (Hager Pond, Grist Millpond, Carding Millpond and Stearns Millpond) exhibit signs of advanced eutrophication, including excessive growths of algae. Inputs to the brook and its impoundments include the discharge from the Marlborough East Waste Water Treatment Facility (MEWWTF) and a variety of non-point sources, with phosphorus and nitrogen inputs posing the greatest concern. Phosphorus is believed to control productivity in this system, although water velocity minimizes algae and plant biomass in much of the brook, and light restrictions imposed by extensive surficial algal mats limit further growths in the impoundments by late summer. A permit for continued operation of the MEWWTF has been under development by USEPA and MADEP, with considerable public input, for several years, and field investigations and modeling (ENSR 2000) have been conducted to support this effort. Based on the available data, it appears that reduced phosphorus loading from the MEWWTF is essential to improving aquatic conditions in the Hop Brook impoundments, but that loading from other sources may have to be addressed before detectable improvement is attained.

Of particular concern is the potential role of internal recycling of phosphorus within the impoundments. More specifically, phosphorus that has been incorporated into surficial bottom sediments as iron precipitates can be released back into the water column under low oxygen conditions. Formation of iron precipitates is the most common form of sedimented phosphorus in most lakes in this region, and low oxygen conditions are likely to occur overnight and at times of elevated decay in systems where productivity is high. Yet while the potential for internal phosphorus recycling in the Hop Brook impoundments is very high, such recycling appeared low in field investigations. Low releases of phosphorus from sediment may be a function of more permanent binding of phosphorus or continuously adequate oxygen, neither of which seems likely in this system. However, equilibrium chemistry dictates that phosphorus release may be reduced or curtailed when the phosphorus content of the overlying water is already high. Studies summarized in a pending paper by Reddy et al. (in review) suggest that sediment phosphorus release may be depressed at overlying water phosphorus concentrations >100 ug/L, while concentrations in Hop Brook are higher. This raises a critical management question; if the MEWWTF discharge concentration of phosphorus is reduced, will internal recycling of phosphorus in the Hop Brook impoundments increase, thereby negating the benefits of reduced discharge phosphorus concentration?

This investigation is primarily focused on evaluating the role of internal phosphorus loading from the sediments of the Hop Brook impoundments under expected future loading scenarios for the MEWWTF. This effort encompasses the measurement of oxygen profiles within the impoundments over a daily cycle, assessment of the pool of available phosphorus in the surficial sediments of each impoundment, evaluation of actual release under lowered phosphorus levels in the overlying water, and modeling of the likely future condition of the impoundments under various plausible management scenarios.

2.0 METHODS

2.1 Diurnal Dissolved Oxygen

Dissolved oxygen and temperature profiles were collected from a boat at one location (deep portion) at each of the four ponds four times daily over the course of the day on 26 August 2003 (Figures 1-4). Measurements were made at one-foot increments from the water surface to the water column/sediment interface once before dawn, once in mid-morning, once in early afternoon, and once around dusk.

A YSI meter equipped with dissolved oxygen and temperature probes was used to determine concentrations and temperature. The YSI meter was calibrated on the day of measurement before and after sampling. A second calibrated YSI meter was available on-site in the event the first meter did not perform properly (i.e., did not hold calibration).

2.2 Sediment Fractionation

Sediment samples from each of the four Hop Brook impoundments (Hager Pond, Grist Millpond, Carding Millpond and Stearns Millpond) were collected on 26 August 2003 and analyzed for sediment phosphorus fractions as discussed in the Supplemental Quality Assurance Project Plan (QAPP) (Appendix A). A brief description of the method used to collect and analyze the sediment samples for phosphorus sediment fractions is presented here.

Sediment samples from three locations in each of the four Hop Brook impoundments (Figures 1-4) were collected using an Eckman Dredge. Upon collection, sediment color and texture were recorded. The top half-inch to one inch of sediment was removed, homogenized, placed in glass jars, and shipped to Spectrum Analytical for extraction.

The sediment phosphorus extraction procedure determined the amount of loosely sorbed phosphorus by extraction with an ammonium chloride solution. Iron-bound phosphorus was determined by extraction with a bicarbonate/dithionate solution. Sediments were also analyzed for total phosphorus, total iron and percent solids.

Figure 1 - Hager Pond Sample Locations

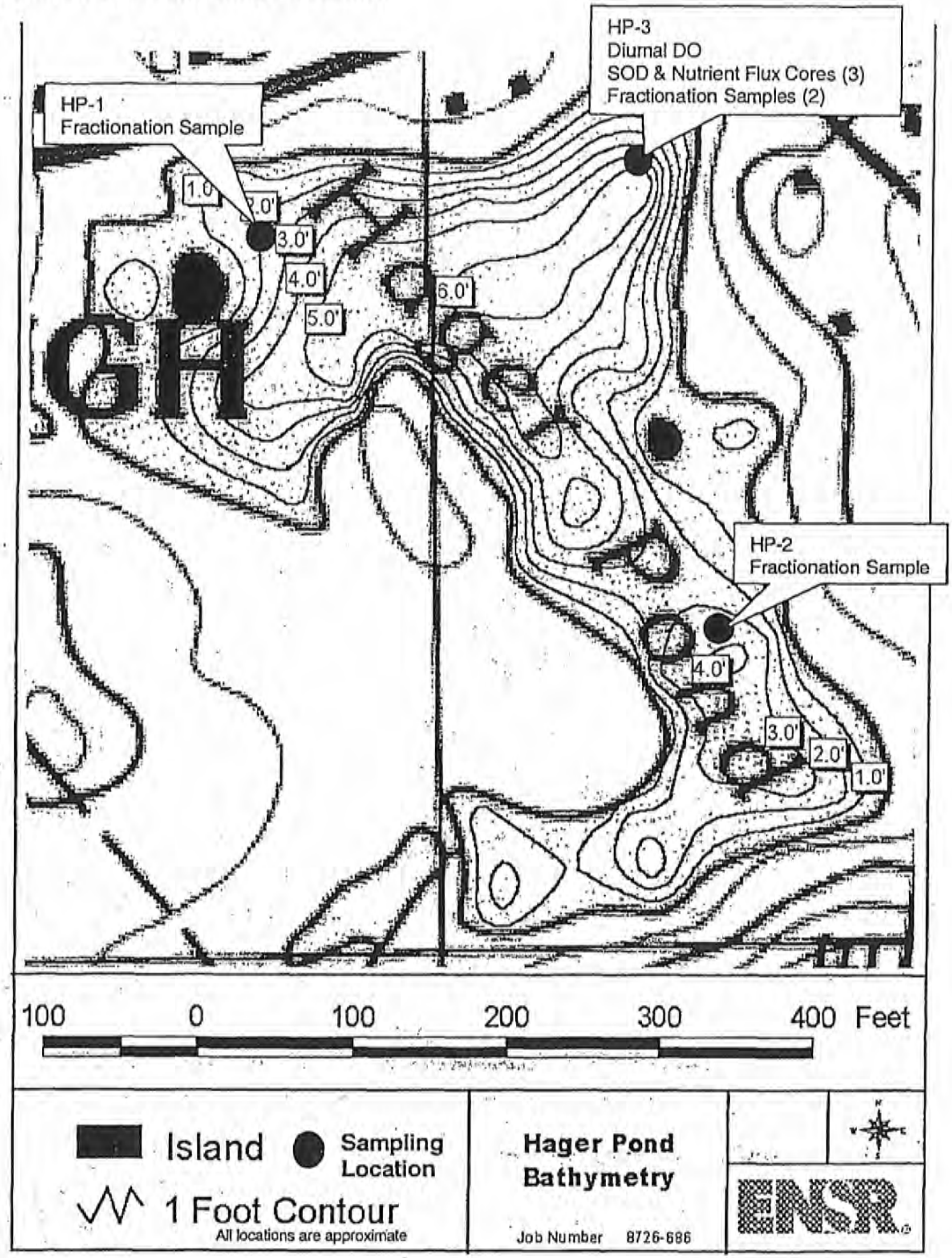


Figure 2 - Grist Millpond Sample Locations

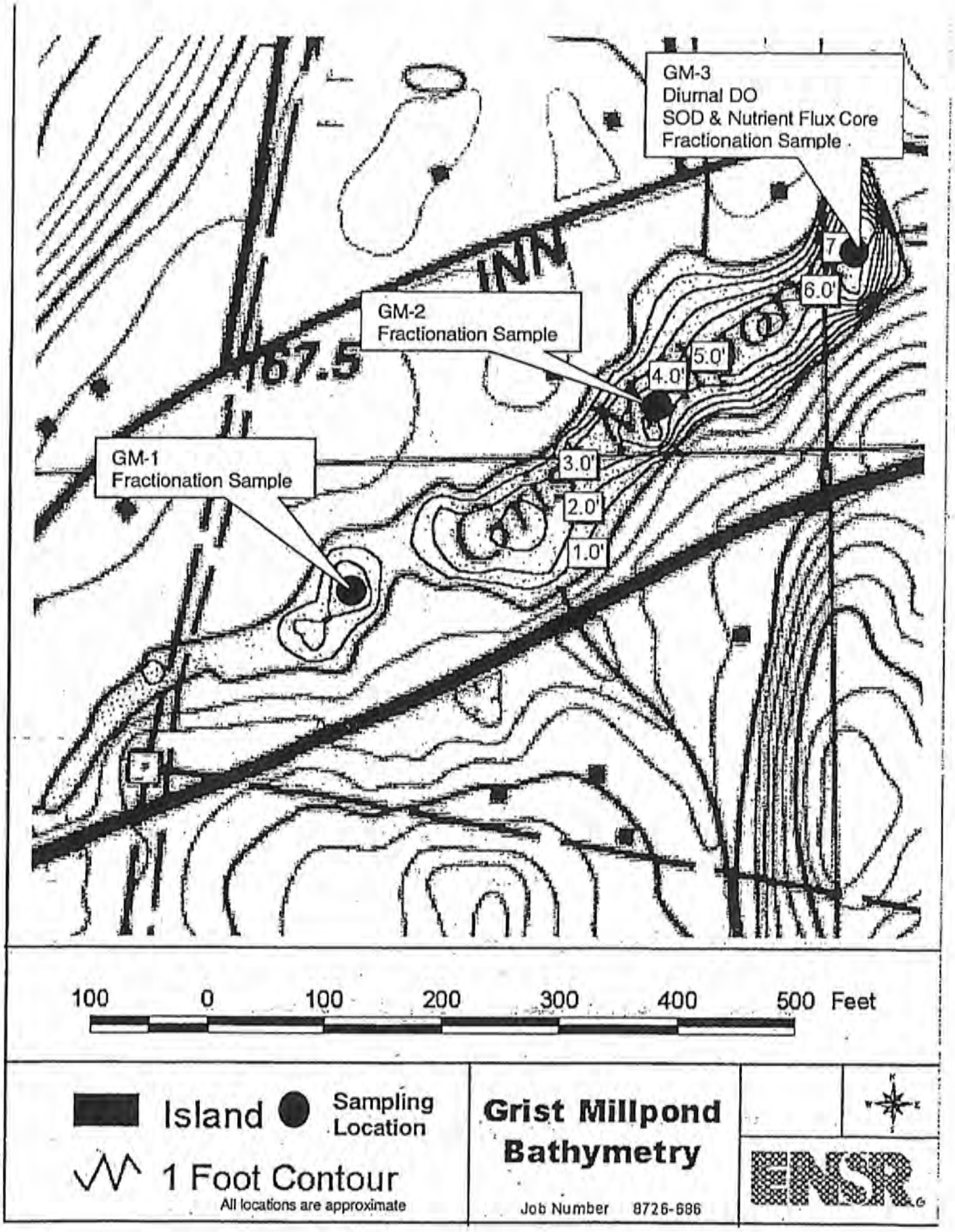


Figure 3 - Carding Millpond Sample Locations

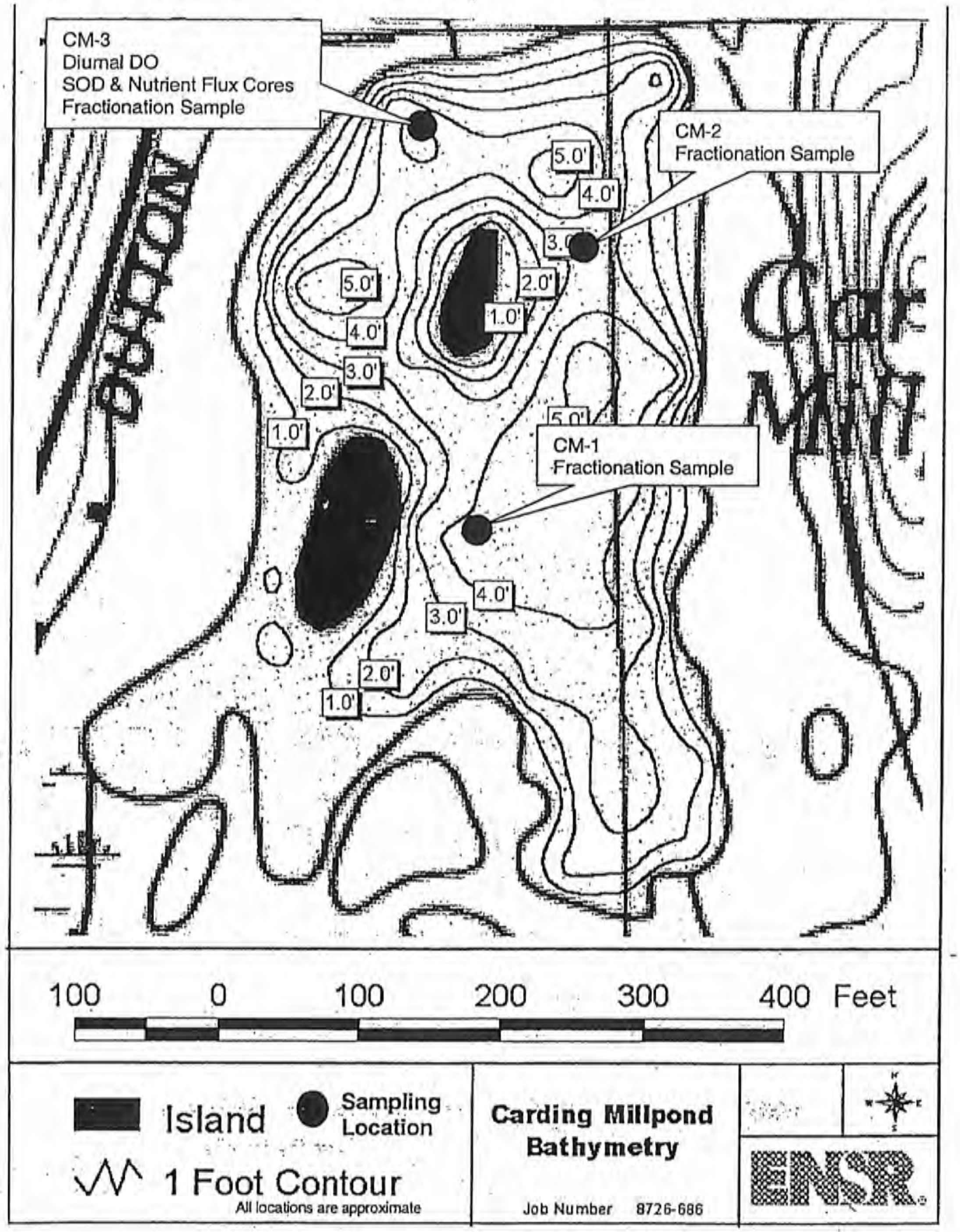
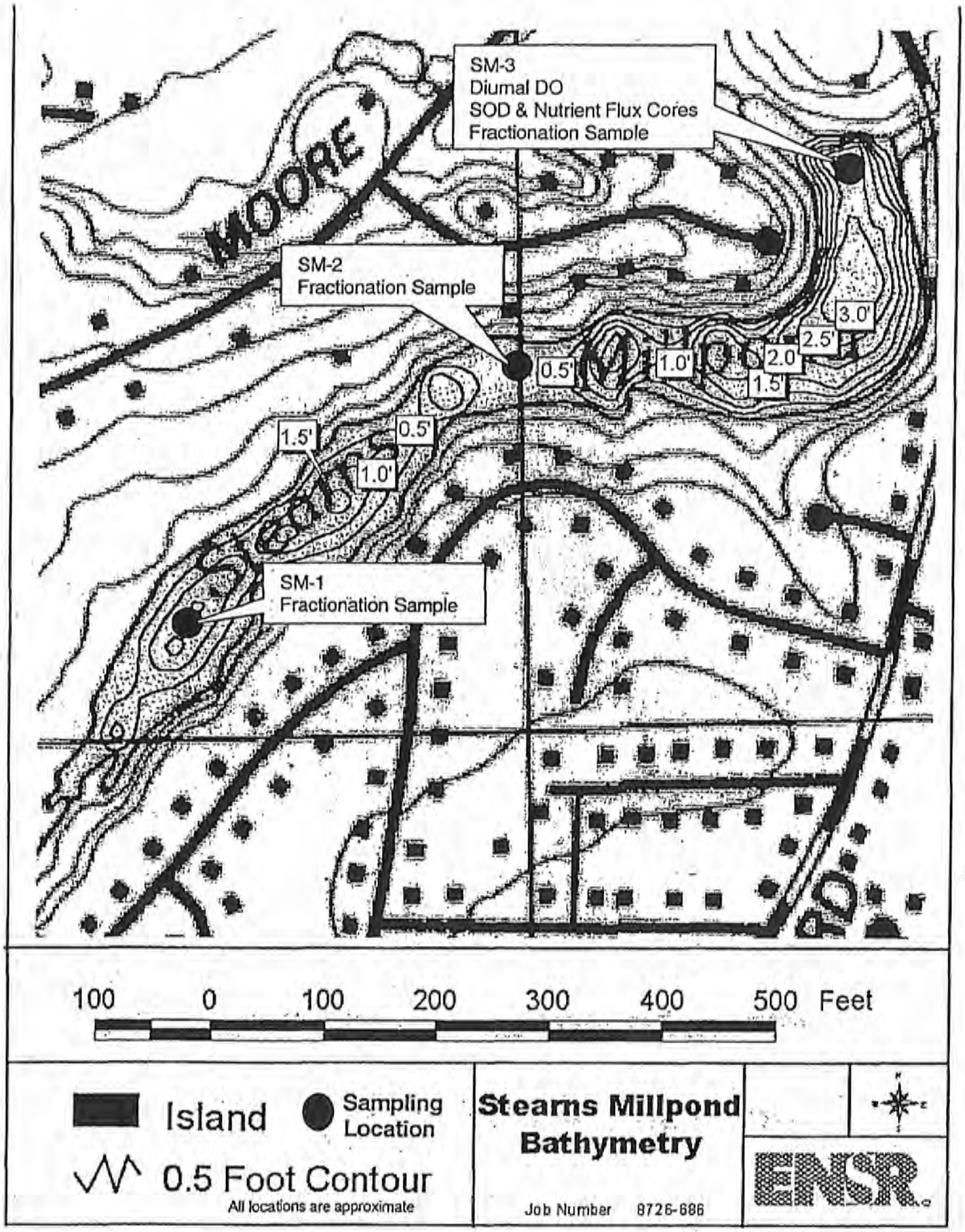


Figure 4 - Carding Millpond sample locations



2.3 Sediment Oxygen Demand and Nutrient Flux

Sediment nutrient flux and sediment oxygen demand (SOD) were determined for the four Hop Brook impoundments during incubations spanning 20 October 2003 to 27 October 2003. Incubations were completed as discussed in the supplemental QAPP (Appendix A) with the following exceptions:

- The distilled water used to fill the core headspace was found to have extremely low dissolved oxygen (DO) (<30% saturated), therefore the headspace was aerated prior to collection of the DO time series. After the cores were aerated, DO values changed little over a one hour period. Due to time constraints the cores were allowed to incubate overnight, and DO was determined in the morning. Oxygen flux was estimated from the initial DO data points taken on the first evening and the DO on the second day. All the cores were still exhibiting DO values greater than 2 mg/L on the second day, so it is reasonable to apply these data. Two of the cores on the third day were still oxic; these data were also used in calculating SOD estimates.
- Volume of the core headspace was determined at the end of the incubation by siphoning off the headspace water into a graduated cylinder instead of using a ruler to estimate volume. The siphon method was determined to be more accurate.

A brief description of the method used to determine SOD and nutrient flux is presented here. Further information can be found in the supplemental QAPP (Appendix A).

At each site an 8-inch diameter core was collected from a boat. Cores were collected from the four Hop Brook impoundments (Figures 1-4 and Table 1). A triplicate sample consisting of three distinct cores was collected from Hager Pond. The cores were filled to approximately half their depth with sediment and half with site water. A baffle was placed in the headspace of each core so that during transportation the headspace would not disturb the sediment/water interface. Cores were transported to the laboratory in a vertical position.

Once samples arrived at the laboratory, cores were placed in a water bath set at approximately 23°C. Physical features of the sediment were described. The headspace water was removed and replaced with distilled water. A stirring apparatus was placed in each core and the top was sealed to prevent atmospheric interaction. Measurement of changes in DO concentration and nutrient concentration over time provided data needed to determine the SOD and nutrient flux of each core. Nutrient samples were collected for nitrate/nitrite (NO_3/NO_2-N), ammonia (NH_3-N) and orthophosphate (PO_4-P), allowing nutrient flux to be determined for these analytes. During the incubation period the cores were allowed to become anoxic.

SOD was determined as follows:

SOD:

$$\frac{\text{Slope}^1\ (\text{mg L}^{-1}\ \text{hr}^{-1}) * \text{Volume (L)} * 24\ \text{hrs day}^{-1}}{\text{Area (m}^2) * 1000\ \text{mg g}^{-1}} = \text{g O}_2/\text{m}^2\ \text{day}$$

[1] Refers to the slope of the regression of changes in O_2 concentration over time.

Sediment nutrient flux:

$$\frac{\text{Slope}^1\ (\text{mg L}^{-1}\ \text{hr}^{-1}) * \text{Volume (L)} * 24\ \text{hrs day}^{-1}}{\text{Area (m}^2)} = \text{mg/m}^2\ \text{day}$$

[1] Refers to the slope of the regression of changes in nutrient concentration over time.

SOD, the uptake of oxygen by the sediments, is generally reported as a positive value. Nutrient flux is generally described as a positive value, if the sediments are releasing nutrients. These opposing descriptions of sediment-water column interactions can be confusing. In this report the following convention will be used: positive SOD will denote no observable SOD and positive nutrient flux will represent a nutrient release from the sediment into the water column. Negative SOD or nutrient flux will indicate uptake from the water column by the sediments.

Table 1 - Samples Collected From Each Hop Brook Impoundment

Pond	Site ID	Sediment Fractionation Sample	Diurnal DO Measurement	Nutrient Flux and SOD Measurement
Hager Pond	HP-1	X		
	HP-2	X		
	HP-3	X	X	X
Grist Millpond	GP-1	X		
	GP-2	X		
	GP-3	X	X	X
Carding Millpond	CM-1	X		
	CM-2	X		
	CM-3	X	X	X
Stearns Millpond	SM-1	X		
	SM-2	X		
	SM-3	X	X	X

2.4 Modeling of Possible Future Conditions in Impoundments

QUAL2E was applied to Hop Brook and its impoundments in 2000 and again for this report. This is a one dimensional model that utilizes physical, chemical and biological input for a stream reach to predict water quality conditions and algal productivity and biomass. It is not as sophisticated as two- or three-dimensional models, but requires less data and is well suited to smaller stream systems, such as Hop Brook. The presence of impoundments creates complications that can be addressed in the model, but some aspects of the aquatic system (e.g., rooted plants, algal mats, denitrification) are not explicitly modeled. Consequently, some interpretation of results is necessary with these limitations in mind.

The original model for Hop Brook applied terms for denitrification that appear to match the actual measures now available. This is not surprising, as the model was adjusted to account for actual loss of nitrate in the downstream direction. The more recent lab incubations of sediment cores from impoundments simply verified that denitrification was occurring as expected.

The original model also incorporated sediment release of phosphorus at a rate of 3 mg/m^2-day, a rate near the high end of the oxic sediment range. This rate was chosen because available data suggested only limited anoxia and minimal release of phosphorus from sediment was necessary to account for observed concentrations. Overlying water contained enough phosphorus to minimize sediment releases as a function of equilibrium chemistry. However, with the planned lowering of the phosphorus concentration in MEWWTF effluent, the model was adjusted to account for that lowered point source load and for lab-measured phosphorus flux from the sediment under conditions of lower overlying water phosphorus levels. Because the flux in the impoundments could vary over time in response to anoxia, overlying water phosphorus level, and available sediment phosphorus reserves, a range of flux values were applied.

As the assumptions of the QUAL2E model may not hold true under all expected conditions in this system, the spreadsheet model that links watershed inputs and in-lake processes to predict average in-lake conditions was again applied to the Hop Brook system for comparison to QUAL2E results. This model, ShedMod, was developed by Ken Wagner of ENSR as a screening and teaching tool for evaluating lake response to watershed or in-lake management actions. This model was applied in the 2000 Hop Brook evaluation, and was modified for this assessment through adjustment of the internal loading rate (phosphorus flux from sediments) and reduction of MEWWTF inputs to 0.2 or 0.1 mg/L at a flow of just over 3 mgd. Additionally, as the summer period is of primary concern in the impoundments, the model was run for just the 100-day period beginning in mid-June and extending to late September. This period typically experiences 100% of the internal load, 27.4% of the watershed load, and 16.5% of the annual flow. This scenario creates a worst case situation, but one that properly represents the time of year when conditions most interfere with desired and designated uses of the Hop Brook impoundments.

2.5 Modeling of Theoretical Pre-Settlement Conditions in Impoundments

The ShedMod spreadsheet model can be used to estimate the conditions that would exist in the Hop Brook impoundments in the absence of human pollution sources. This analysis is theoretical in that the impoundments would not exist except for human actions, and a certain amount of inputs would be expected in association with those actions. However, by setting all land uses to forest or wetland in the model, and setting internal loads and other inputs to the lowest probable natural level, an estimate of the minimum load to be experienced by these impoundments can be derived.

3.0 RESULTS

3.1 Diurnal Dissolved Oxygen

The results of the diurnal dissolved oxygen (DO) survey are presented in Table 2 and Figure 5. The membrane of the DO meter was damaged after the third round of sampling at Carding Millpond. A second DO meter was used for the remaining measurements. The membrane was replaced on the initial meter before the final round. The meter values were comparable after membrane replacement. Figure 5 contains original meter readings with the exception of Hager Pond and Stearns Millpond during the third round where the back-up meter readings are graphed.

It was expected that the lowest DO concentrations would be detected during the first round of measurements based on typical diurnal cycles. This was not the case in three of the four impoundments. The lowest DO was found during the first round of sampling in Carding Millpond. The lowest DO concentrations were detected in the remaining three impoundments during the second round of sampling; this could have resulted from substantial cloud between the first two readings, delaying significant photosynthetic release of oxygen by algae and rooted plants in the impoundments. By mid-afternoon, skies were clear with bright sun, yielding supersaturated conditions in three of the four impoundments. The water column of Carding Millpond was functionally anoxic throughout the day. This impoundment is completely covered by *Trapa natans* (water chestnut). It is likely that this non-native macrophyte shades water column photosynthetic plants and algae, resulting in low DO and re-aeration potential from atmospheric interaction. *Trapa natans* is not a significant source of water column oxygen since much of the photosynthetic portion of the plant is at the water surface and oxygen is released into the air.

Table 2 - Dissolved Oxygen Values throughout the Diurnal Survey on August 26, 2003.

Sunrise: 6:03 AM Sunset: 7:29 PM

Hager Pond

Measurements taken with faulty membrane (4:46 PM); Second reading using back-up YSI 95 (4:46 PM); Second reading using back-up YSI 95 (8:40 PM)

5:35 AM				11:05 AM				4:46 PM							8:40 PM						
Depth (ft)	Temp (C)	DO (mg/L)	% Sat	Depth (ft)	Temp (C)	DO (mg/L)	% Sat	Depth (ft)	Temp (C)	Temp (C)	DO (mg/L)	DO (mg/L)	% Sat	% Sat	Depth (ft)	Temp (C)	Temp (C)	DO (mg/L)	DO (mg/L)	% Sat	% Sat
0	22.76	7.22	89.4	0	23.36	7.50	88.6	0	26.91	27.4	0.38	19.66	4.6	249.3	0	26.00	26.8	18.99	20.23	235.7	252.8
1	22.79	8.78	103.3	1	22.98	6.09	71.1	1	26.91	27.4	0.13	19.51	1.7	244.2	1	26.08	26.8	18.62	20.41	231.7	253.8
2	22.78	10.39	121.5	2	22.67	5.71	66.7	2	24.14	24.7	0.10	19.19	1.2	231.1	2	25.81	26.2	19.54	20.09	239.0	247.2
3	22.24	8.95	101.8	3	21.99	3.45	42.7	3	22.50	23.4	0.08	14.80	0.9	172.3	3	22.59	23.4	14.68	13.78	168.1	159.9
4	21.75	0.38	4.1	4	22.05	0.83	8.5	4	22.03	22.7	0.06	9.64	0.6	112	4	22.10	23	3.31	5.41	37.3	65.9
				5	21.81	0.38	4.3	5	21.91	22.6	0.03	0.58	0.3	6.8	5	22.14	23	1.12	0.47	12.7	5.6

Grist Millpond

Second reading using back-up YSI 95 (3:10 PM); Second reading using back-up YSI 95 (7:15 PM)

5:55 AM				10:40 AM				3:10 PM							7:15 PM						
Depth (ft)	Temp (C)	DO (mg/L)	% Sat	Depth (ft)	Temp (C)	DO (mg/L)	% Sat	Depth (ft)	Temp (C)	Temp (C)	DO (mg/L)	DO (mg/L)	% Sat	% Sat	Depth (ft)	Temp (C)	Temp (C)	DO (mg/L)	DO (mg/L)	% Sat	% Sat
0	22.1	9.22	105.8	0	22.66	6.37	73.1	0	25.81	26.4	10.64	12.56	130.7	157.2	0	24.51	26.4	13.40	14.22	161.0	174.9
1	22.05	9.53	109.3	1	22.35	5.87	68.0	1	24.71	24.9	8.46	11.72	102.0	142.3	1	22.92	25.1	15.75	15.28	187.1	185.0
2	21.88	8.36	94.8	2	22.03	5.45	62.5	2	22.98	23.7	7.74	11.12	90.3	133.0	2	23.29	24.2	14.88	14.79	174.2	173.9
3	21.82	7.62	86.2	3	21.75	4.84	54.1	3	22.68	23.3	6.67	12.80	77.4	150.5	3	22.85	23.6	12.04	12.36	141.2	148.2
4	21.86	7.94	87.3	4	21.71	2.85	32.4	4	22.22	22.9	5.53	10.44	61.5	122.0	4	22.05	23.0	7.69	8.59	89.1	100.2
5	21.84	0.14	1.5	5	21.78	0.2	2.4	5	22.18	22.9	0.27	0.62	3.1	7.1	5	21.96	22.7	0.21	0.47	2.5	5.3

Table 2 (continued) - Dissolved Oxygen Values throughout the Diurnal Survey on August 26, 2003.

Carding Millpond

								Second reading using back-up YSI 95							Second reading using back-up YSI 95						
6:45 AM				10:15 AM				3:43 PM							7:45 PM						
Depth (ft)	Temp (C)	DO (mg/L)	% Sat	Depth (ft)	Temp (C)	DO (mg/L)	% Sat	Depth (ft)	Temp (C)	Temp (C)	DO (mg/L)	DO (mg/L)	% Sat	% Sat	Depth (ft)	Temp (C)	Temp (C)	DO (mg/L)	DO (mg/L)	% Sat	% Sat
0	19.88	0.1	1.2	0	20.36	0.49	5.1	0	21.72	21.3	0.07	0.66	0.7	7.5	0	20.08	21.6	0.27	0.74	2.8	8.2
1	19.88	0.08	0.9	1	19.93	0.31	3.3	1	20.15	20.8	0.05	0.64	0.6	7.1	1	20.06	20.7	0.22	0.54	2.4	5.9
2	19.71	0.06	0.6	2	19.64	0.17	1.8	2	19.83	20.6	0.02	0.64	0.2	7.0	2	19.70	20.4	0.18	0.51	2.0	5.7
3	19.52	0.05	0.5	3	19.51	0.10	1.2	3	19.62	20.3	0.01	0.63	0.1	7.0	3	19.53	20.3	0.16	0.51	1.7	5.6
4	19.51	0.05	0.7	4	19.41	0.07	0.6	4	19.49	20.2	0.00	0.65	0.0	7.1	4	19.5	20.2	0.14	0.52	1.5	5.7
				4.4	19.41	0.06	0.6														

Stearns Millpond

								Second reading using back-up YSI 95							Second reading using back-up YSI 95						
6:20 AM				11:45 AM				4:05 PM							8:10 PM						
Depth (ft)	Temp (C)	DO (mg/L)	% Sat	Depth (ft)	Temp (C)	DO (mg/L)	% Sat	Depth (ft)	Temp (C)	Temp (C)	DO (mg/L)	DO (mg/L)	% Sat	% Sat	Depth (ft)	Temp (C)	Temp (C)	DO (mg/L)	DO (mg/L)	% Sat	% Sat
0	20.65	7.39	80.7	0	23.42	3.51	41.0	0	25.6	26.3	1.85	12.59	21.5	159.0	0	24.20	24.9	13.88	14.11	165.9	170.1
1	20.69	6.50	72.6	1	21.7	4.41	49.1	1	23.46	24.4	1.24	14.78	14.7	169.0	1	23.61	24.7	14.67	14.50	174.3	176.6
2	20.72	5.75	64.1	2	21.33	4.20	47.8	2	22.95	23.7	0.82	18.6	9.6	218.0	2	22.75	23.9	15.22	15.51	177.1	183.7
3	20.83	3.25	36.3	3	21.21	0.54	6.0	3	22.15	23.2	0.03	2.0	0.3	1.0	3	22.57	23.3	4.06	2.07	46.8	24.1

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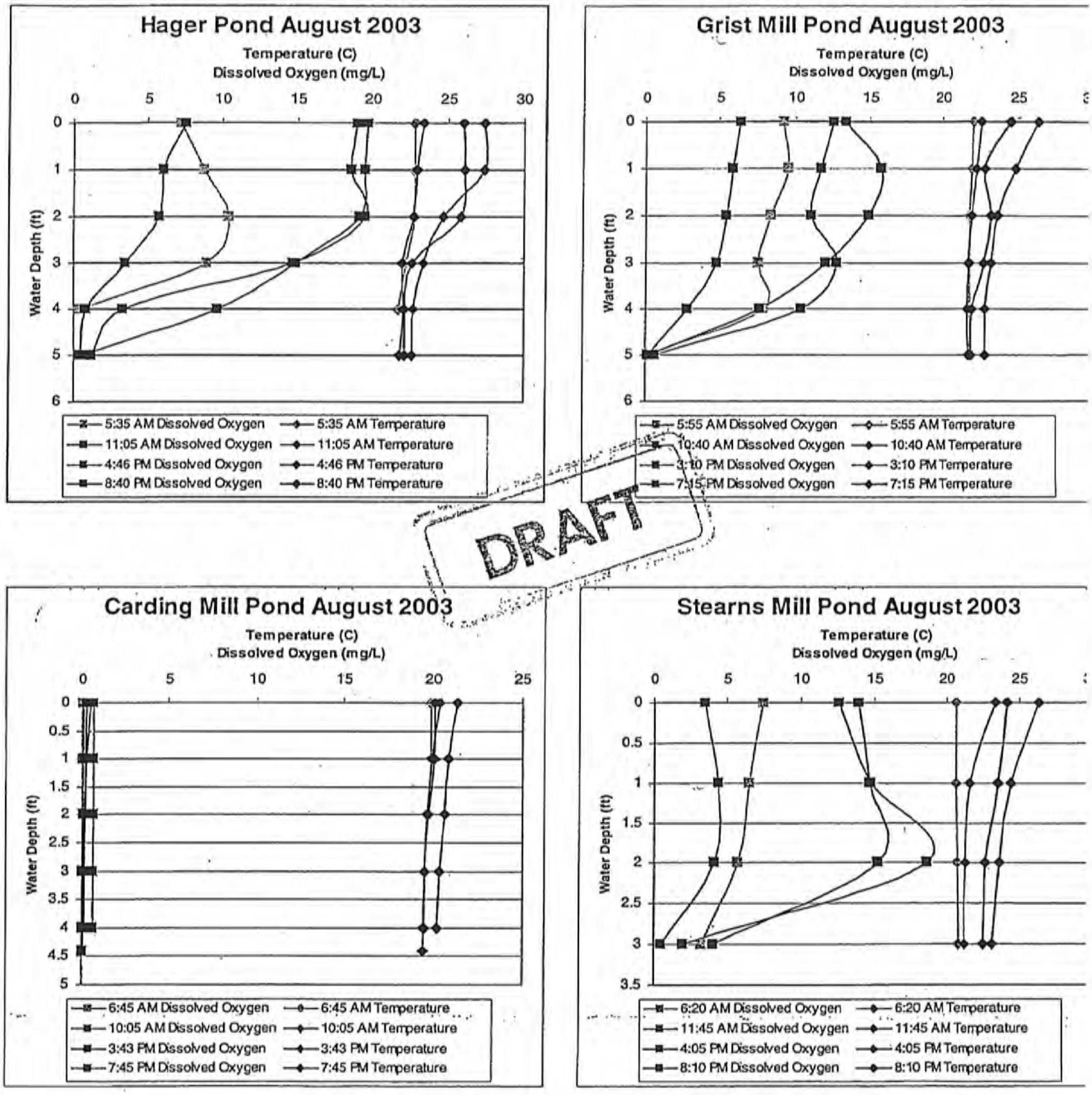
Figure 5. Temperature/Dissolved Oxygen Profiles on August 26, 2003.



3.2 Sediment Chemistry

Results for sediment chemistry are reported in mg/kg of dry sediment. Sediment iron concentration ranged from 3,520 to 64,950 mg/kg (Table 3). Iron was highest in Hager Pond. Total sediment phosphorus ranged from 272 to 20,100 mg/kg. Highest total phosphorus values were associated with Hager Pond. Percent solids values ranged from 6.90 to 68.3 % solids, with sites at Gristmill Pond having the highest percent solids values and the only values >10%. Site GM-1 and GM-2 consisted of sand and a mixture of sand, silt and plant material, respectively. Sandy sediments have a greater solids percentage than silty sediments. Loosely sorbed and iron-bound phosphorus ranged from 0.64 to 41.6 mg/kg and 13.3 to 2,725 mg/kg, respectively. Values for loosely sorbed phosphorus varied substantially within the same pond. Values for iron-bound phosphorus were lowest at the sandy sites in Grist Millpond (GM-1 and GM-2) and highest in Hager Pond.

Loosely sorbed phosphorus provides an estimate of the amount of phosphorus immediately available for biological uptake through sediment-water column exchange if a diffusion gradient exists. Comparison of data reported for the Hop Brook impoundments (Table 3) to reported literature values (Table 4) indicates that loosely sorbed phosphorus levels in the impoundments are low compared to many other lakes. Loosely sorbed phosphorus is quite low in comparison with other forms of phosphorus, which is fairly typical. Iron-bound phosphorus levels, when compared to literature reported values, range from low in the case of the sandy sites in Grist Millpond to high as reported in Hager Pond. However, iron-bound phosphorus is rarely more than 20% of the total phosphorus value in the Hop Brook impoundments. The total phosphorus assay includes all forms of phosphorus in the sediment, including organic and inorganic mineral forms. Total phosphorus data from the Hop Brook impoundments reveal values that are high relative to many other lakes, sometimes an order of magnitude higher than literature reported values. Much of this phosphorus is bound in organic or non-iron inorganic compounds that are largely resistant to release of phosphorus.

Sediment chemistry is often affected by the percent solids value. Sandy sites generally have lower iron and phosphorus values, and will exert lower SOD as well. Sites GM-1 and GM-2 both contain more sand than the other sampled sites (with GM-1 having much more sand than GM-2), and have lower sediment phosphorus and iron values. Site GM-3 was more similar to the sediments in the other sampled ponds. The sites in Hager Pond exhibit the highest iron, total phosphorus and iron-bound phosphorus levels, but were not appreciably different than Carding Millpond or Stearns Millpond in terms of solids content.

Table 3 - Sediment Chemistry Results For Hop Brook Impoundments

Site	Iron	Total Phosphorus	% Solids	Loosely Sorbed Phosphorus	Iron-bound Phosphorus	Sediment Description
Units	mg/kg dry weight	mg/kg dry weight	%	mg/kg dry weight	mg/kg dry weight	
HP-1	60,900	17,500	9.90	3.3[1]	910	Dark brown/black muck with black mottling
HP-2	42,400	7,980	6.90	19.9	1,280	Dark brown/black muck with black mottling
HP-3	64,950	20,100	6.90	26.4	2,725	Dark brown/black muck with black mottling
GM-1	3,520	272	68.3	0.64	13.3	Sand
GM-2	13,700	1,950	18.6	4.2	123	Mix of sand, silt, algae and plant material
GM-3	32,000	6,010	9.30	19.9	1,285	Loose silt, much plant material
CM-1	37,100	3,320	7.00	5.9	435	Loose material, silt
CM-2	33,200	4,790	8.40	25.3	290	Loose material, silt
CM-3	36,900	4,970	8.30	41.6	214	Loose material, silt
SM-1	27,700	2,770	9.10	3.8[1]	346	Loose silt
SM-2	22,500	2,870	8.50	4.8	457	Loose silt with plant and leaf litter
SM-3	27,100	1,900	7.60	6.1[1]	266	Loose silt with plant and leaf litter
Average of all ponds	**33,498**	**6,203**	**14.1**	**13.5**	**695**	
Range	**3,520 - 64,950**	**272 - 20,100**	**6.60 - 68.3**	**0.64 - 41.6**	**13.3 - 2,725**	

[1] Sample is below the detection limit (BDL); value reported is the detection limit.

Table 4 - Literature Reported Sediment Chemistry Results

Location	Loosely Sorbed P (mg P/kg)	Iron and Al bound P (mg P/kg)	Ca bound P (mg P/kg)	Total P (mg P/kg)	Fe (mg Fe/g)	Notes[1,3]
64 Lakes in Ontario Canada, CT, VT, PA & NY	0-872	233-5879	75-737	1342-5075	21.4 – 111.3	Alkalinity 0.10-2.87 meq/L
Lk. Arreso, Denmark	320	470	240	2650		Shallow, eutrophic and unstratified
Lk. Fina, Sweden	32	2640 Fe bound- P only		4000	44.5	Shallow lake
Lk. Vallentuna, Sweden	34	90		1600	28.1	
Long Pond, MA	0.97-1.53	24.5-172				
Otis Reservoir, MA	3.02-5.60	26.0-34.0				
Lk. Vallentunasjon	138	257	315	1810		Previously sewage loaded lake
Lk. Sodea-Bergundasjon, Sweden	253	4017	707	6490		Rich in Iron and humics
Lk. Erken	15	137	461	1230		Mesotrophic lake with calcareous soils in watershed
Lk. Stora Hastevatten	10	60	19	950		Acidified oligotrophic lake
Lk. Blakaren, Sweeden	10% of TP					Calcareous lake
Lk. Balaton, Hungary	5-10% of TP		Ca mineral and residual P[2] composed 80% of TP			Calcareous Lake
Lk. Brielle, Netherlands	7-20% of TP					Calcareous Lake
Lks. Wingra, Monona, Delevan and Geneva (USA)	1-12% of TP		Ca mineral and residual P[2] composed 79-88% of TP			Calcareous Lake
Lake Waco, TX	<0.2	12 to 54		220 - 660		Calcareous Lake Sediments
Range	0 to 872	12 to 5879	19 to 737	220 to 6790	21.4 to 111.3	

[1] All results per dry sediment weight

[2] Residual Phosphorus = organic and inert phosphorus

[3] Table from ENSR 2003

3.3 Sediment Oxygen Demand

Sediments within collected cores consisted of fine brown colored material (Table 5). Plant materials as well as small animals were observed in several of the cores. Sediment oxygen demand (SOD) values determined in the lab ranged from -1.2 to -0.8 g O_2/m^2 day, indicating sediment uptake of dissolved oxygen from the water column at all sites (Table 6). Average SOD in a typical eutrophic lake ranges from approximately -1.4 to -0.5 g O_2/m^2 day (Hutchinson, 1957). The range of SOD recorded in the Hop Brook impoundments are well within the range of literature reported values (Table 7) and would be considered moderate overall.

Table 5 - Sediment Description of Cores Collected in Hop Brook Impoundments

Core	Description of Sediment
Hager Pond Rep1	Mostly uniform fine grained material, brown. A few small pieces of plant litter.
Hager Pond Rep2	Uniform file grained material, brown.
Hager Pond Rep3	Uniform fine grained material, brown, some small pieces of plant material.
Grist Millpond	Fine grained, uniform brown color.
Carding Millpond	Water chestnut fragments, plant litter (stems, roots and leaves) on the surface, fine grained material, dark brown like Sterns Millpond
Sterns Millpond	Some plants on surface, darker brown than other cores, a lot of leaf and stem litter on surface, some small invertebrates seen swimming in headspace, fine grained material.

Table 6 - Nutrient Flux and Sediment Oxygen Demand (SOD) Results for Hop Brook Impoundments

Site	NH_4-N Flux mg NH_4-N / m^2 day	PO_4-P Flux mg PO_4-P / m^2 day	NO_3/NO_2-N Flux mg NO_3/NO_2-N / m^2 day	SOD g O_2 / m^2 day
Hager Pond Rep1	8.1	6.7	-74.2	-0.8
Hager Pond Rep2	22.9	4.9	-75.0	-1.0
Hager Pond Rep3	34.6	13.2	-67.3	-1.1
Grist Millpond	63.2	13.2	-51.1	-1.2
Carding Millpond	55.5	9.3	-34.9	-0.8
Sterns Millpond	66.9	8.3	-41.1	-1.1
Range	8.1 to 66.9	4.9 to 13.2	-75.0 to -34.9	-1.2 to -0.8

Notes:
Negative flux indicates sediment uptake; positive flux indicates sediment release.
Incubations completed at approximately 23º Celsius.

Table 7 - Literature Reported Sediment Oxygen Demand (SOD) Results[2]

Location	Sediment Description	SOD[1] (g O_2/m^2 day)
Lakes and Streams in Europe	Unknown Sediment type Sediment Incubation temp. 0-18°C	-0.31 to -2.6
Lower Green Bay, Wisconsin	Unknown Sediment type Sediment incubation temp. 12°C	-1.90 to -1.65
Assabet River, MA	Muck Sediment incubation temp. 10-25°C	-1 to –2.4
Onondaga Lake, NY	Hyper-eutrophic lake	-1.68
Lk. Shagawa, Minnesota	Soft water lake, eutrophic	-0.12 to -0.22
Browns Lake, MS	Silt and Clay	-1.12
Literature Review	Unknown Sediment Type (6 sites reported)	-.0007 to -2.9
Lake Waco, TX	Calcareous silt Sediment Incubation temp. 14-16°C	-1.75 to -0.73
Rathburn Lk., Iowa	Sand	-0.46
Range		-0.0007 to -2.9

[1] Negative SOD indicates sediment uptake

[2] Table from ENSR 2003

3.4 Nutrient Flux

Flux of NH_4-N ranged from 8.1 to 66.9 mg NH_3-N/m^2-day, NO_3/NO_2-N from -75.0 to -34.9 mg NO_3/NO_2-N/m^2 day, and PO_4-P ranged from 4.9 to 13.2 mg PO_4-P/m^2-day (Table 6). Positive flux of NH_3-N and PO_4-P indicates release of these nutrients from the sediments into the water column. Both these rates are similar to release rates found in the Assabet River (ENSR 2001), and the phosphorus fluxes are within the range reported in the literature (e.g., Nurnberg, 1984; 1988) for lakes experiencing anoxia. These phosphorus release rates would be high, however, for most oxic lakes.

Negative NO_3/NO_2-N flux indicates sediment uptake of NO_3/NO_2-N. Uptake of NO_3/NO_2-N results from microbial denitrification within the sediments. Microbial denitrification utilizes NO_3 as an electron acceptor producing inert gaseous nitrogen (N_2), effectively removing NO_3 from the system. At the sites of greatest denitrification, ammonia flux is lowest, so nitrate loss is not due to any conversion of nitrate to ammonia. The observed range of denitrification in the Hop Brook impoundments is similar to that measured in the Assabet River (ENSR, 2001), and is consistent with observed decreases in NO_3 measured in Hop Brook in the downstream direction from the MEWWTF in the previous ENSR investigation (ENSR 2000).

PO_4-P nutrient flux does not appear to be related to sediment total phosphorus or iron concentrations, as flux rates are similar between impoundments, even though total phosphorus and iron values are highest in Hager Pond. The loosely sorbed and iron-bound phosphorus data are extremely variable within a given impoundment, therefore there is no clear relationship between these values and PO_4-P flux. Although readily available phosphorus values are low relative to total phosphorus reserves in surficial sediments, there is a very large reservoir of potentially available phosphorus that could be transferred into the water column, and that transfer is accelerated by anoxic conditions.

As an example of possible phosphorus release from the sediment in the Hop Brook impoundments, calculation of the number of days it would take PO_4-P flux to increase impoundment PO_4-P concentration from 0 to 1 mg/L yields a range of 37 to 156 days (Table 8). This assumes that no flushing of the impoundments occurs, there are no additional inputs of phosphorus, and equilibrium chemistry does not reduce flux rates. None of these assumptions is completely reliable, but the potential for elevated phosphorus concentrations as a function of internal loading alone is evident.

If all the loosely sorbed and iron-bound phosphorus found within the sediment in the Hop Brook impoundments was released as orthophosphate at the flux rate determined during this study, it would take 127 to 700 days. This assumes no additional contribution of phosphorus to the sediments or conversion of other phosphorus forms to available forms, which are not reliable assumptions, but the duration of release is obviously quite substantial, spanning the growing season. Release of all iron-bound and loosely sorbed phosphorus at once would increase pond PO_4-P concentrations from 1.7 to 10.2 mg/L, underscoring the magnitude of the currently available phosphorus reserves in the sediment.

Table 8 - Physical Characteristics of Hop Brook Impoundments and Phosphorus Release Calculations

DRAFT

Characteristic	Units	Hager Pond	Grist Millpond	Carding Millpond	Stearns Millpond
Volume*	Acre-ft	77.2	38.9	96.6	21.1
Surface Area	Acres	31.0	17.5	41.4	20.4
Average Depth	Ft	2.5	2.2	2.3	1.0
Maximum Depth	Ft	7.5	8.5	6.0	3.5
Period of time it would take for pond to increase 1 mg/L PO_4-P[1]	Days	58 to 156	51	75	37
Increase in impoundment PO_4-P if all loosely sorbed and iron-bound P releases at once[1]	mg/L	7.6	10.2	1.7	4.4
Period of time it would take for all loosely sorbed and iron-bound P to release at pond flux rate measured	Days	700	544	127	163

*Aug 1999, extremely dry year, water levels probably at least 1 ft higher under normal conditions

[1] Calculation assumes that there are no additional sources of PO_4-P to impoundment and no water exchange in impoundment

3.5 Modeling Possible Future Phosphorus Levels

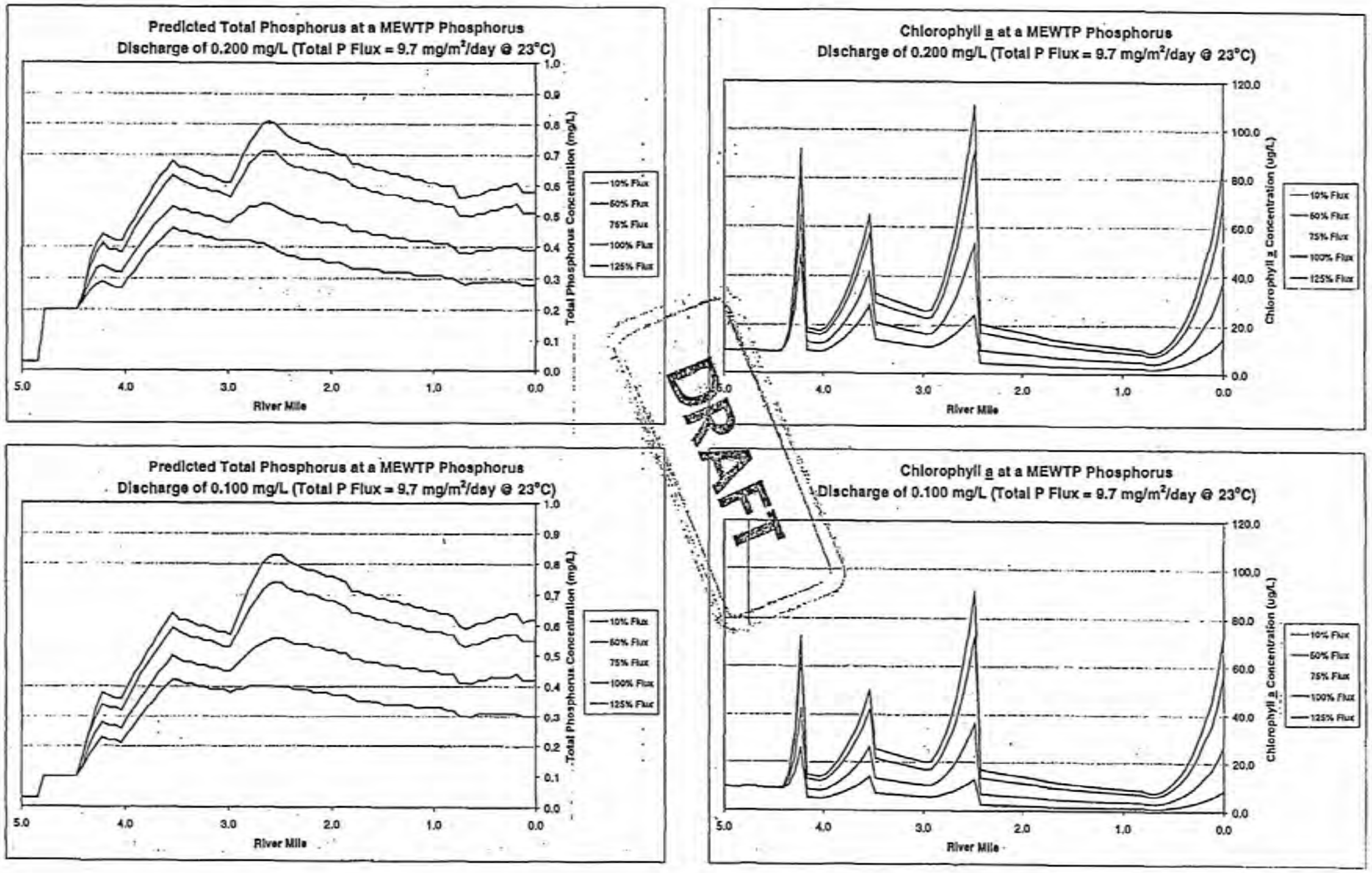
With the current regulatory effort to reduce phosphorus from WWTF effluents in New England and a new permit for the MEWWTF in the issuance process, it is certain that the loading of phosphorus from the MEWWTF to Hop Brook and its impoundments will be lowered. Limits of 0.1 or 0.2 mg/L have been discussed, and the draft permit has a 0.1 mg/L limit at this time. We also modeled discharges of 0.05 mg/L (the lowest limit practically implemented to date) and 0.0 mg/L (eliminating the phosphorus load but not the water load, a useful theoretical construct but hardly practical). From the previous ENSR (2000) investigation, it is clear that other watershed sources represent a threat to water quality in general and phosphorus levels specifically, with reduced productivity and algal biomass problem abatement not predicted without action beyond the new MEWWTF effluent limit. Additionally, with a large reserve of available phosphorus in the surficial sediments of all four Hop Brook impoundments, the potential for elevated internal loading to compensate for reduced external loading is high.

With the new information provided by the field investigation detailed in this report, QUAL2E was applied to the Hop Brook system with a reduced MEWWTF input and an increased internal loading component (Figure 6). It is apparent that the projected internal load (averaging 9.7 mg/m^2-day) compensates for the loss of external load, yielding very high phosphorus concentrations in all four impoundments. However, the model is not sophisticated enough to address limitation of sediment phosphorus release as the concentration in the overlying water increases, and the concentration continues to increase in the downstream direction to levels that are not likely to actually occur. The salient point from the model is that levels of phosphorus as high as found under current discharge limits might be expected after increased restriction of the MEWWTF. Increased internal loading could offset decreased external loading, yielding minimal change in algal biomass and overall system productivity.

The potential variability in the internal load was explored with QUAL2E by setting the sediment phosphorus flux at a range of values, as high as 125% of the measured average to as low as 10% of that average. The effect on phosphorus levels in the impoundments is striking, with as much as a twofold range of final phosphorus concentrations resulting. In all cases, the phosphorus level is higher than desirable, even with no phosphorus input from the MEWWTF. However, the failure of the model to react to rising internal loading is a shortcoming that limits the utility of the actual values derived from the model. The important result is that internal loading can yield excessive phosphorus levels and that the plausible range of loading results in about a twofold change in phosphorus level in the impoundments.

The chlorophyll a predictions from the QUAL2E model also have some inherent limitations related to the way the model operates, but provide a believable pattern of values over space in the target system. Values spike in the impoundments as a function of residence time and response to available nutrients.

Figure 6a. Phosphorus and Chlorophyll Concentrations Predicted for the Hop Brook Impoundments Under Selected Input Conditions Using QUAL2E.



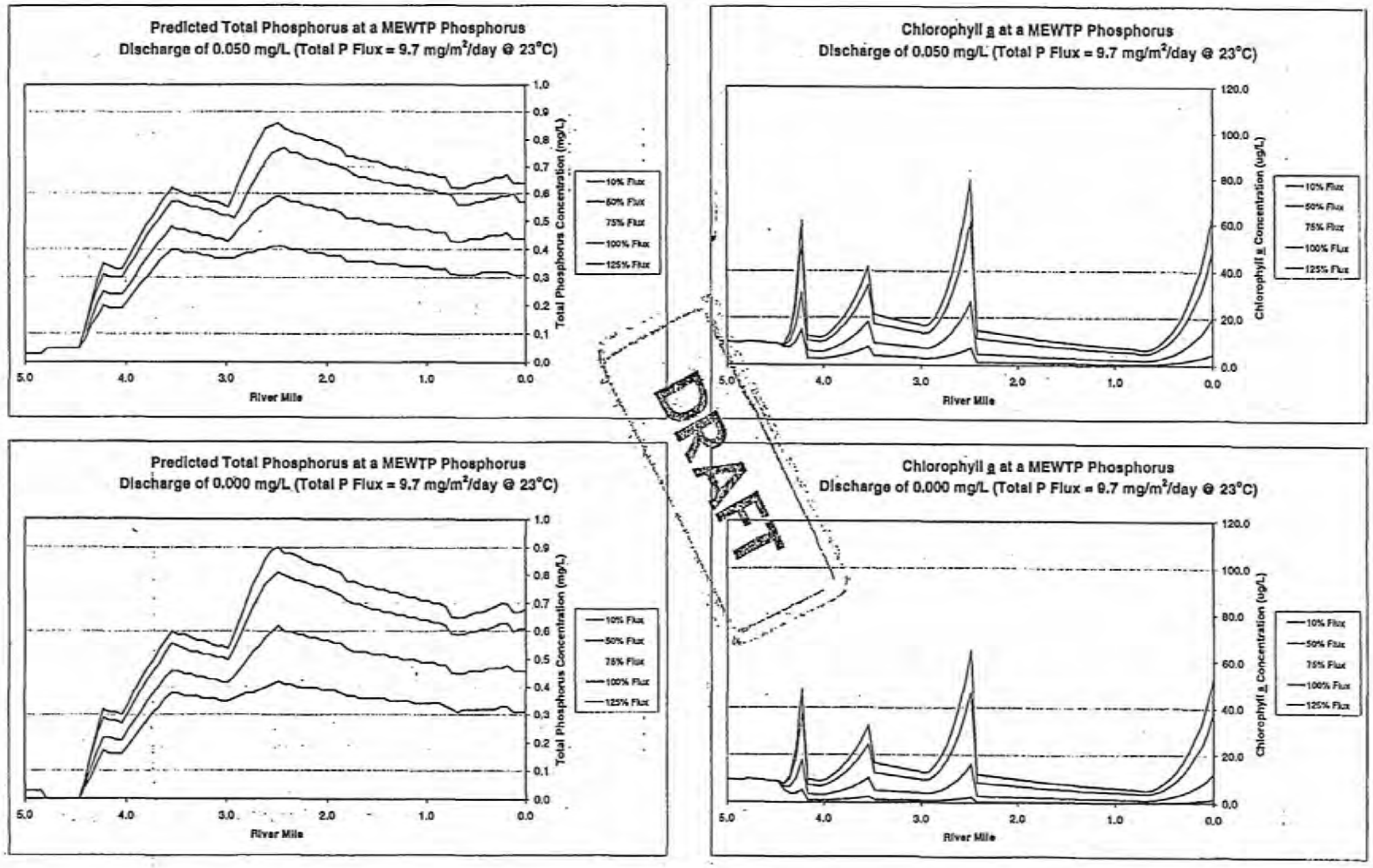
Predicted Total Phosphorus at a MEWTP Phosphorus Discharge of 0.200 mg/L (Total P Flux = 9.7 mg/m²/day @ 23°C)

Chlorophyll a at a MEWTP Phosphorus Discharge of 0.200 mg/L (Total P Flux = 9.7 mg/m²/day @ 23°C)

Predicted Total Phosphorus at a MEWTP Phosphorus Discharge of 0.100 mg/L (Total P Flux = 9.7 mg/m²/day @ 23°C)

Chlorophyll a at a MEWTP Phosphorus Discharge of 0.100 mg/L (Total P Flux = 9.7 mg/m²/day @ 23°C)

Figure 6b. Phosphorus and Chlorophyll Concentrations Predicted for the Hop Brook Impoundments Under Selected Input Conditions Using QUAL2E.



Predicted Total Phosphorus at a MEWTP Phosphorus Discharge of 0.050 mg/L (Total P Flux = 9.7 mg/m²/day @ 23°C)

Chlorophyll a at a MEWTP Phosphorus Discharge of 0.050 mg/L (Total P Flux = 9.7 mg/m²/day @ 23°C)

Predicted Total Phosphorus at a MEWTP Phosphorus Discharge of 0.000 mg/L (Total P Flux = 9.7 mg/m²/day @ 23°C)

Chlorophyll a at a MEWTP Phosphorus Discharge of 0.000 mg/L (Total P Flux = 9.7 mg/m²/day @ 23°C)

Values are much lower in the flowing portion of stream between the impoundments. The four peaks observed in the chlorophyll graphs in Figure 6 correspond to the impoundments, and the pattern is similar among the graphs. Even with no phosphorus in the discharge from the MEWWTF, other external loads and the project internal load (at the 100% level) combine to provide peaks in excess of 20 ug/L. The generally accepted nuisance level for algae is around 20 ug/L, although values as high as 50 ug/L may not be too objectionable in some cases. With the currently proposed MEWWTF limit of 0.1 mg/L for phosphorus and a sediment release rate of 9.7 mg/m^2-day, the expected chlorophyll level will range from 50 to 90 ug/L.

Given the limitations of the model, the chlorophyll values are probably underestimates. While the flux rate for phosphorus passing into the overlying water will decline with increasing phosphorus levels in that overlying water, uptake by algal mats will not decline, and may even be accelerated under the lower input conditions induced by more stringent MEWWTF limits. If algae are present as mats instead of diffuse, microscopic growths, chlorophyll will be concentrated in a much thinner layer than the entire water column; the average volumetric chlorophyll prediction may be roughly correct, but the resultant appearance of the impoundments may not be improved. Reducing the MEWWTF input of phosphorus without control of internal loading is just as likely to induce algal mat formation as current conditions.

If the flux of phosphorus from bottom sediments is lowered to 10% of the rate expected from lab measurements from actual cores, the reduction in chlorophyll is striking. Although the decline for Hager Pond is roughly proportional to the predicted change in phosphorus level, the decrease for the other three impoundments is fivefold to ninefold, compared to a twofold phosphorus decrease. Hager Pond would still experience elevated algal biomass, but the other three ponds would exhibit much reduced algal levels. Again, this may be an overestimate of the benefits of internal loading control, simply because of model limitations, but the direction of change is clear and the expected magnitude is substantial.

The linked watershed-lake spreadsheet model provides an alternative means for evaluating potential changes in the condition of the impoundments in response to reduced loading from the MEWWTF and altered internal loading (Table 9). In this model, inputs are mixed in each impoundment and responses are predicted from empirical equations for phosphorus, chlorophyll and Secchi transparency. Inputs are processed in Hager Pond, then passed on to Grist Millpond along with any additional watershed inputs from that downstream area. Grist Millpond processes the load and passes it on to Carding Millpond, which in turn supplies a load to Stearns Millpond, each with successive additions of watershed loads and each with an internal load determined by the measured flux rate and the pond area. The time step is 100-day period spanning summer, and loads have been adjusted to that period.

Scenarios include the current conditions, reductions in effluent phosphorus levels for the MEWWTF to 0.2 or 0.1 mg/L, and internal loading of 2 mg/m^2-day (current estimate), 9.7 mg/m^2-day (lab estimate of potential load), and 1 mg/m^2-day (anticipated load with proper controls). An additional important

Table 9 – Phosphorus, Chlorophyll and Secchi Transparency in the Hop Brook Impoundments Under Selected Input Conditions Using ShedMod

Pond	Current (WWTF @ 420 ug/L)	WWTF @ 200 ug/L Sed Rel @ 2.0 mg/m2/d	WWTF @ 100 ug/L Sed Rel @ 2.0 mg/m2/d	WWTF @ 200 ug/L, Sed Rel @ 9.7 mg/m2/d	WWTF @ 100 ug/L, Sed Rel @ 9.7 mg/m2/d	WWTF @ 100 ug/L Sed Rel @ 1.0 mg/m2/d	WWTF @ 100 ug/L, Sed Rel @ 9.7 mg/m2/d, WS Load 50% available	WWTF @ 100 ug/L, Sed Rel @ 1.0 mg/m2/d, WS Load 50% available
	Predicted Summer Average Phosphorus Concentration (ug/L)							
Hager	348	195	125	276	206	115	194	103
Grist	277	165	115	205	154	110	101	57
Carding	239	157	120	251	213	108	163	60
Stearns	160	129	114	156	141	111	88	57
	Predicted Summer Average Chlorophyll-a Concentration (ug/L)							
Hager	280	132	75	207	141	68	131	59
Grist	208	107	67	141	98	64	58	28
Carding	172	100	71	183	148	62	105	30
Stearns	103	78	67	99	88	64	48	28
	Predicted Summer Maximum Chlorophyll a Concentration (ug/L)							
Hager	857	411	238	639	440	214	408	188
Grist	640	335	214	438	307	202	183	92
Carding	531	314	226	566	459	199	330	97
Stearns	323	246	212	312	276	204	154	92
	Predicted Summer Average Secchi Transparency (m)							
Hager	0.26	0.41	0.57	0.31	0.39	0.61	0.41	0.66
Grist	0.31	0.46	0.61	0.39	0.49	0.63	0.67	1.04
Carding	0.35	0.48	0.59	0.34	0.38	0.64	0.47	1.01
Stearns	0.47	0.56	0.61	0.48	0.52	0.63	0.75	1.04

modification relates to the availability of the non-MEWWTF portion of the watershed load, much of which will be particulate in nature and not readily available for algal uptake. This particulate load will largely be incorporated into the sediment, the effect of which is part of the internal load. Based on the data collected in the 2000 investigation, it is estimated that about half of the non-MEWWTF external load will be processed in this manner. Including the whole watershed load and the increased internal load would therefore overestimate effective inputs. Consequently, the non-MEWWTF load has been reduced by 50% for each impoundment in association with the proposed 0.1 mg/L effluent limitation for two additional scenarios, one with the full lab-measured internal load and one representing an internal load reduced my active management (inactivation or dredging).

While no scenario results in chlorophyll and Secchi transparency values that would be considered highly desirable, major improvement is observed with reductions in MEWWTF and internal loading (Table 9). It is expected that reduced MEWWTF inputs will foster increased internal loading, so further restricting the MEWWTF effluent phosphorus level will not by itself yield a substantial improvement in expected conditions, even assuming that only half of the non-MEWWTF watershed load is biologically available. Phosphorus values for scenarios not involving low internal loading routinely exceed 100 ug/L, a level at which productivity problems are almost certain in an impoundment. Yet with control over internal loading, predicted phosphorus values approach the 100 ug/L mark assuming full availability of external loads. Under the assumption of half of the non-MEWWTF watershed load being available, a MEWWTF effluent limit of 0.1 mg/L and control of internal loading to a level of 1.0 mg/m^2-day yields values of 57 to 60 ug/L in three of the impoundments. Only Hager Pond, closest to the MEWWTF and heavily influenced by its discharge, has a predicted phosphorus level slightly over 100 ug/L.

Only the final scenario, with the MEWWTF effluent phosphorus limit at 0.1 mg/L, the internal load at 1.0 mg/m^2-day, and assuming only half of the non-MEWWTF watershed load is biologically available, yields chlorophyll concentrations and Secchi transparencies that could be considered acceptable for habitat and aesthetic uses. Values are still high for contact recreation or consumptive uses. The MEWWTF is still a dominant influence, especially during periods of low flow, but that influence is moderated to a significant degree.

These scenarios suggest no alteration of nitrogen loading, as no major changes to external or internal nitrogen loading are anticipated. Depending upon how the internal phosphorus load is addressed, a change in nitrogen loading could occur, but a major decrease is not expected. This is generally a positive factor, as reduced N:P ratios favor cyanobacteria that would be especially undesirable in these impoundments. A reduction in phosphorus with no reduction in N:P ratios would be the best way to minimize algal mats and planktonic blooms.

3.6 Modeling of Theoretical Pre-Settlement Conditions in Impoundments

Setting land uses to forest or wetland in accordance with topography from maps, setting the internal loading rate at 1.0 mg/m^2-day, and leaving atmospheric and wildlife loads as they are in the current model, the "natural" loads to the four Hop Brook impoundments are derived, with the associated in-lake phosphorus concentrations, chlorophyll levels, and Secchi transparencies (Table 10). Phosphorus levels are not high, but are not low either. The relatively large contributory watersheds for these small impoundments results in moderate loading of phosphorus, even from natural land uses. Resulting mean and maximum summer chlorophyll levels are also moderate, but far below the levels currently experienced by the impoundments. Water clarity is also moderate, with Secchi transparencies of 1.5 to 2.0 m. In these impoundments, this means that light would penetrate to most of the bottom, fostering rooted plant growth beyond what is supported currently.

This analysis does suggest that low fertility conditions would not be expected in the Hop Brook impoundments, even in the absence of human-induced inputs. Of course, the impoundments were formed by human intervention, but this analysis indicates the theoretical minimum level of fertility they could experience. Natural processes will seek to fill in those impounded areas, so relatively rapid increases in productivity might be expected over a period of decades to a century.

Table 10 – Phosphorus, Chlorophyll and Secchi Transparency in the Hop Brook Impoundments Under Conditions of Minimal Human Influence Using ShedMod

Pond	Pred. P (ug/L)	Mean Chl (ug/L)	Max Chl (ug/L)	Mean SDT (m)
Hager	35	15.3	50.8	1.5
Grist	26	10.8	36.2	1.9
Carding	35	15.5	51.5	1.5
Stearns	25	10.0	33.8	2.0

4.0 MANAGEMENT IMPLICATIONS

From the available data and analyses, the following observations relevant to the management of the Hop Brook system can be offered:

1. Low dissolved oxygen was observed at the bottom of all four impoundments, throughout the water column of Carding Millpond. Previous studies indicated no strong anoxia immediately below or between impoundments, but did not document the oxygen demand within those impoundments. Sediment oxygen demand, as determined from lab measurements with incubated sediment cores, were typical of shallow, eutrophic ponds at 800 to 1200 mg/m^2-day. Re-aeration from the atmosphere is sufficient to keep most of the water column oxic, except in Carding Millpond, where dense surficial plant cover restricts that re-aeration. In all four impoundments, however, anoxia occurs near the sediment-water interface.
2. Release of nutrients results from the microbial decomposition of organic matter found within sediments and/or chemical redox reactions. Anoxia-mediated phosphorus releases, which include redox reactions and anaerobic decomposition, produce higher values than oxic decomposition, mainly as a function of phosphorus binding by iron, calcium, or aluminum under oxic conditions. Typical phosphorus release from oxic sediments is 0-3 mg/m2-day, while releases from anoxic sediments can exceed 15 mg/m2-day. The potential for phosphorus release will be highest where the concentration of iron-bound phosphorus is high in anoxic sediments.
3. High available phosphorus was measured in organic sediments, with iron-bound phosphorus as a substantial fraction (typically >10%). Such organic sediments were dominant in all the ponds except Grist Millpond, but were present there as well. The growth of algal mats that initiate at the sediment-water interface will be stimulated by the combination of organic, nutrient-rich sediments and low oxygen. This situation is likely to be the cause of the primary production pathway observed in these impoundments. Lower loading from the watershed may lower production, but the role of internal production requires attention in any successful management program.
4. The MEWWTF discharges just upstream of Hager Pond. Physical, chemical and biological processes act on the elevated phosphorus in this pond, causing increased settling of organic material and leading to higher total phosphorus and iron-bound phosphorus levels in the Hager Pond sediments. The role of the MEWWTF discharge diminishes in the downstream direction, but is still substantial even in Stearns Millpond. Control of internal loading will have more influence at greater distance from the MEWWTF.
5. Denitrification is responsible for the observed decline of nitrate in the downstream direction from the MEWWTF. Elevated nitrogen affects the type of algae that is present, while phosphorus controls the quantity of algae where light is adequate. Reducing both nitrogen and phosphorus is desirable in the Hop Brook impoundments, but reduction of nitrogen without a commensurate reduction in phosphorus could result in highly undesirable cyanobacteria blooms. A reduction in phosphorus without a reduction in nitrogen is unlikely to have negative consequences for algal growth.

6. Modeling by two separate approaches indicates that conditions in the Hop Brook impoundments are not likely to be markedly improved by reductions in the phosphorus concentration in the discharge from the MEWWTF alone. The highly available nature of the large MEWWTF inputs suggests that no improvement is to be expected unless the MEWWTF effluent phosphorus level is lowered, but this is unlikely to be sufficient by itself. While research and pilot testing for very low effluent limits (<0.02 mg/L) continues, feasible limits on the order of 0.05 to 0.2 mg/L applied in the models do not suggest an adequate reduction in phosphorus in the Hop Brook impoundments. At the proposed 0.1 mg/L limit, the concentration in Hager Pond immediately downstream remains elevated from the MEWWTF discharge. In the three downstream impoundments, and to some extent in Hager Pond, increased internal recycling is expected to compensate for the reduction in MEWWTF inputs, maintaining undesirably high levels of phosphorus.
7. Working with assumptions of a MEWWTF discharge phosphorus concentration of 0.1 mg/L, a controlled internal load of 1.0 mg/m^2-day, and an availability factor for other inputs of 50%, summer phosphorus levels in Grist Millpond, Carding Millpond and Stearns Millpond on the order of 60 ug/L are expected. The phosphorus level in Hager Pond would remain close to that in the MEWWTF discharge. Resulting algal biomass and water clarity in all but Hager Pond should be markedly improved over current conditions and may be sufficient to support uses related to habitat and aesthetic appeal without further management.

5.0 MANAGEMENT OPTIONS

5.1 General Management Options

There are three basic levels of management effort that could be applied to the Hop Brook impoundments:

1. No action – Allowing human and natural impacts to continue to impair the uses of these impoundments. This is not a valid option under the provisions of the Clean Water Act.
2. Eliminate the impoundments – Removal of dams has become an option worthy of consideration in many river systems. Usually this option is exercised where obsolete dams provide minimal benefits but block desirable fish passage or otherwise interfere with river ecology. Actual data for the Hop Brook system indicates that productivity problems are minimized in the riverine portions of Hop Brook. This is consistent with experience in other stream systems with impoundments. However, the Hop Brook impoundments are considered by many to serve useful purposes, and it is not clear that blocked fish passage is a major issue in this case. Removal of the dams and establishment of riverine conditions might be considered by all interested parties in an appropriate forum, but is not an option that can be recommended in this investigation.
3. Reduce pollutant loading to meet designated uses - Reduce the load of phosphorus, and other pollutants as well, as necessary to meet designated uses of the Hop Brook impoundments. This involves efforts directed at multiple sources, as field assessment, laboratory testing and modeling have demonstrated that control of no one source is likely to be adequate to achieve the desired conditions. Clearly the MEWWTF inputs must be reduced and internal loading must be suppressed. Additional efforts may be necessary, focusing on storm water inputs from urbanized areas. Key methods of achieving these objectives will comprise the remainder of this evaluation.

5.2 Reduction of MEWWTF phosphorus load

Reduction of MEWWTF phosphorus load is mandated by the new NPDES permit, currently in the review and comment phase, but expected to result in an average effluent phosphorus level of 0.1 mg/L. This degree of phosphorus removal will require treatment beyond the now common addition of alum or polymers in association with primary and/or secondary clarification steps. Typically, some form of filtration is applied as well as settling to achieve such low levels of phosphorus. Dissolved air flotation can also achieve the target level, some biological removal systems have been shown to be capable of this level of removal, although variability tends to be higher for biological treatment processes than either physical or chemical approaches. The precise method is left to the treatment engineers and the management of the system is left to the operators. It is sufficient for this analysis to note that a target effluent level of 0.1 mg/L is feasible and is likely to be required.

5.3 Suppression of internal loading

Suppression of internal loading of phosphorus can be accomplished by three distinct methods: aeration, inactivation, and removal. Aeration of a shallow lake would involve diffused air or mechanical mixers that thoroughly mix the lake and foster increased atmospheric oxygen transfer to the water by virtue of any gradient between the atmosphere and the water, the latter being subject to oxygen demand and lower oxygen content than the air. Mixing has some benefits in impoundments like those associated with Hop Brook, but requires visible equipment and long-term operation and maintenance costs. Shallowness of the system will reduce efficiency as well. It should only be necessary to aerate between May and September, but it will be necessary to aerate during that period every year; the need for aeration does not decline in the vast majority of cases. Some additional information on aeration is presented in Appendix B, but this approach is not the preferable alternative for the Hop Brook impoundments.

Inactivation of surficial sediment phosphorus has become a more common technique over the last decade, with application of aluminum compounds as the most common approach. Iron and calcium have also been applied, but are less effective in acidic and low oxygen conditions, as might be expected in the Hop Brook impoundments. Aluminum in the form of aluminum sulfate, or alum, would serve to bind phosphorus in the upper layer (typically about 4 cm) of bottom sediment in each impoundment. The dose can be calculated from information on available phosphorus concentration and density of solids in those upper 4 cm of bottom sediment, assuming a dose of ten times the amount of phosphorus that must be inactivated (Table 11). In some cases the dose has been set as high as 100 times the available phosphorus level to offset residual binding by iron or calcium, but we have found a tenfold ratio of aluminum to phosphorus to be adequate in New England lakes. Addition of a buffer would probably be necessary to avoid adverse effects on pH and sensitive biota, as the alum dose would be high and the alkalinity of the Hop Brook system is low. It may also be necessary to add the alum in stages, as the concentration induced by adding the whole dose at once is quite high.

Table 11 – Aluminum Dose Necessary to Inactivate Surficial Sediment Phosphorus in the Hop Brook Impoundments

Pond	Mean Available P (mg/kg)	Mean % Solids	Available P in upper 4 cm of 1 m2 (g)	Alum Dose (10X Avail. P) (g)	Volume of Alum (gal/m2)	Area to be Treated (m2)	Volume of Alum Needed (gal)	Mean Depth (m)	Volume Treated (m3)	Aluminum Conc. (mg/L)
Hager	1655	7.9	7.8	78	0.351	126259	44317	0.755	95326	103
Grist	482	32.7	9.5	95	0.428	70981	30380	0.677	48054	140
Carding	337	7.9	1.6	16	0.072	167745	12078	0.711	119267	22
Stearns	361	8.4	1.8	18	0.081	82833	6709	0.315	26092	57

There are many considerations involved in nutrient inactivation, particularly for an alum treatment, but such treatment can be very effective in curtailing internal phosphorus loading. Additional information about phosphorus inactivation is included in Appendix B. The primary risk is transient toxicity to aquatic fauna from high levels of reactive aluminum. Maintaining a pH between 6 and 7.5 minimizes this risk, but where doses are large, adding the alum over several sequential treatments spread over several weeks or more may also be advisable. Doses that create an initial, albeit temporary, aluminum concentration in excess of 10 mg/L should be considered for sequential addition. All estimated doses for the Hop Brook impoundments are well in excess of that target.

The cost of alum treatment is a function of chemicals to meet the calculated dose and the labor to apply it. A round figure of $1000/acre, or $2500/hectare, is provided as a general guideline (Wagner, 2001). However, the dose in this case is higher than usual, given high levels of available phosphorus in the surficial sediments, and costs may be higher simply as a function of greater chemical needs. With bulk loads of alum at about $0.70/gallon, chemical costs would range from $5000 for Stearns Millpond to $31,000 for Hager Pond. However, buffering will be necessary, and the use of sodium aluminate at half the dose of alum at a cost of $2.70/gal yields a chemical cost range for the impoundments of $8700 to $58,000. With added permitting, labor and monitoring costs, treatment of the impoundments of Hop Brook might be expected to cost between $20,000 to $90,000 for individual impoundments. An approximate cost for all four impoundments is $210,000.

The third option for managing internal loading is sediment removal, or dredging. Dredging can be accomplished by conventional excavation under wet or dry conditions, or by hydraulic means. There are a great many considerations that must be addressed when planning and implementing a dredging project; these are outlined in Appendix B and discussed at length in the 2004 Generic Environmental Impact Report on Lake Management in Massachusetts (Mattson et al., 2004). While dredging is a complicated environmental operation with potentially unavoidable temporary impacts, it also has the greatest potential for restoring an impoundment to its original condition. Removal of accumulated nutrient-rich sediments from the Hop Brook impoundments offers the opportunity of minimizing internal loading and rooted plant growths, both issues for these waterbodies.

Given the conditions present in these ponds, hydraulic dredging is possible but may not produce as "clean" a final bottom condition as desired. Conventional wet excavation could cause large downstream suspended solids loads and associated turbidity, with corresponding impacts on aquatic life that would be unacceptable under current regulatory mandates. While a more detailed assessment of dredging options is warranted, a dry dredging operation would seem preferable for these impoundments. This would entail draining the impoundments for a period of months, probably sequentially and not at once, with routing of flows through each in a confined manner. Considerable alteration of outlet structures may be necessary for this option to be applied. Such outlet modification has not been investigated in this study and would carry a substantial cost (>$100,000 per outlet would not be unusual).

If dredging is to occur in any of the impoundments, the two key considerations are sediment quality and sediment quantity, both of which were investigated in the ENSR 2000 study of this system. Sediments in Hager Pond and Grist Millpond did not exceed any Massachusetts Contingency Plan standards (relating to hazardous waste classification), but exceeded the 90th percentile for background soil values. This means that there would be some restriction on disposal of these sediments, but nothing so extreme as to cast doubt on the feasibility of dredging. For Carding and Steams Millponds, sediments were suitable for a range of disposal options, not exceeding any applicable standard. Sediment quantities varied from a low of 15,700 cubic yards (cy) in Grist Millpond to a high of 63,100 cy in Carding Millpond, as shown in Table 6-2 in the ENSR 2000 report and reprinted here for convenience as Table 12. It would be desirable to remove all soft sediment from each impoundment to truly restore the impoundments to their original condition, limiting internal loading and substrate suitability for rooted plant growth or algal mat formation. Partial dredging options might be considered, but are likely to greatly reduce the benefits of dredging in these impoundments.

Dredging costs vary mainly with method, sediment quality and quantity, and distance to disposal area. It is difficult to derive an accurate cost estimate from the available information, but based on the sediment quality, extreme disposal costs should be avoidable. Based on the estimated sediment quantity and an approximate range of $15 to $25 per cubic yard removed, dredging costs would range from a possible low of $235,500 for Grist Millpond to a possible high of 1,578,000 for Carding Millpond. Assuming an intermediate cost of $20/cy, the cost of removing all soft sediment from all four impoundments would be on the order of $3.4 million. With permitting and engineering needs, possible outlet structure modifications, and flow routing provisions, the overall project cost is likely to be on the order of $5 million.

Table 12 - Soft Sediment Volumes Calculated Using Contoured Sediment Thickness Data.

Pond	Average Thickness (feet)	Maximum Thickness (feet)	Volume (cubic-yards)
Hager Pond	1.1	4.4	55,700
Grist Millpond	0.6	3.0	15,700
Carding Millpond	0.9	3.2	63,100
Steams Millpond	1.0	5.3	33,100

5.4 Storm water management

Storm water management is a relevant topic in virtually every watershed in Massachusetts, and would be a necessary step in protecting the investment made in Hop Brook water quality through MEWWTF treatment enhancement and any restorative actions within the impoundments. This study has not focused on the specific management actions that should be taken in this watershed, but from field examination and data analysis, it is apparent that additional detention and possibly infiltration of storm water would be greatly beneficial to water quality in Hop Brook and its impoundments.

Minimizing the generation or discharge of pollutants is always the preferable course of action in managing a watershed, but is not always practical. Trapping pollutants before they reach sensitive waterways is usually necessary, and to this end detention systems are most appropriate. Where soils are suitable, infiltration of storm water is consistent with the current Massachusetts Storm Water Policy (MADEP, 1997), as long as certain basic water quality limits are met before the storm water is infiltrated. Creation of combined pond and wetland systems appears to provide the greatest trapping capacity for the widest range of pollutants, and can enhance phosphorus removal. However, research to date indicates that removal of more than about 60% of total phosphorus is unlikely in a passive detention system (i.e., not actively managed with chemical additions or adjustable flow controls) (Schueler et al., 1992; USEPA, 1999). Infiltration can provide greater removal, but is limited by depth to ground water and soil conditions in many areas. Engineering of filtration systems (whereby water is passed through an engineered medium) is possible and may be necessary to maintain greater removal rates, but at much greater expense.

With the advent of Phase II of the NPDES program for storm water, which mandates plans and control programs for municipalities within metropolitan areas (including Marlborough and Sudbury), progress should be made on limiting storm water inputs to Hop Brook in coming years. This progress is likely to be slow, however, in light of funding limitations. If more rapid progress is to be made, it will require a concerted effort on the part of local, state and federal agencies working with existing and potential sources of pollution.

The ENSR 2000 report evaluated the potential water quality benefits of storm water management in association with more strict wastewater effluent limitations, but no control of internal loading was assumed in that analysis. Even at the lower internal load applied in the ENSR 2000 investigation, no combination of management efforts met the target range for phosphorus in the impoundments, although the combination of a discharge phosphorus limit of 0.1 mg/L and maximum practical storm water management came close. Likewise, the combination of a 0.1 mg/L effluent limitation and a 90% reduction in internal loading applied in this analysis results in conditions that approach an acceptable phosphorus level in all but Hager Pond, closest to the MEWWTF. This analysis also assumes that about half of the storm water inputs are not immediately available for biological uptake; implementation of storm water management actions focusing on short-term detention may act largely on that unavailable 50%, minimizing the immediate gain in available phosphorus control. However, as particulate phosphorus captured in the impoundments may be processed into available dissolved phosphorus, trapping particulates before they enter the lake can have long-term benefits. In contrast, infiltration or filtration would provide greater control over the available phosphorus fraction and more immediate benefits, but feasibility of infiltration or filtration systems is dependent on soil conditions or engineered systems with high maintenance requirements and increased cost.

If the model results for a MEWWTF discharge limit of 0.1 mg/L, a 90% reduction of internal phosphorus loading, and 50% availability for phosphorus in storm water are accepted, the resultant phosphorus concentrations in the four impoundments are 103 ug/L in Hager Pond and 57 to 60 ug/L in the other three impoundments. The three downstream ponds, Grist, Carding and Stearns, might reach the upper limit of the target range of 20 to 50 ug/L with reasonable storm water controls. In the model, after reduction of MEWWTF and internal loads, storm water represents 47% of the phosphorus load to Grist, 67% of the load to Carding, and 87% of the load to Stearns. The likely maximum storm water loading reduction of about 60% would yield concentrations of about 41, 36 and 27 ug/L in these impoundments, respectively, which is within the target range. Values for Carding and Stearns Millponds are very close to the predicted levels in the absence of human influence. However, some of the reduction in phosphorus level may be getting double counted; recall that the minimum load analysis (Table 9, right hand column) incorporated a 50% availability factor for storm water phosphorus. Storm water management will slow the build up of the internal load even if it does not provide the minimum predicted concentration.

Hager Pond is a different situation. Storm water inputs are not a major component of the load, and while management of those inputs is helpful, the MEWWTF inputs will still be more than the pond can handle without excessive productivity. There could be some improvement in conditions over the current summer situation, but at predicted phosphorus concentrations on the order of 100 ug/L, algal blooms are to be expected. Unless the MEWWTF load can be reduced even further, maintenance measures will be necessary to maintain designated uses of Hager Pond.

6.0 MANAGEMENT RECOMMENDATIONS

The impoundments of Hop Brook were created by the erection of dams on an otherwise unrestricted brook. Based on a reasonable projection of the conditions that would have been experienced by the impoundments in the absence of additional human influences, these waterbodies would have experienced moderate nutrient inputs and associated productivity, with increasing eutrophication over the many years since they were formed. However, this process has been greatly accelerated by the addition of treated wastewater effluent from the Marlborough East Waste Water Treatment Facility and runoff from developed or agricultural areas. Sections of Hop Brook with higher water velocities experience limited impairment, but the loads to the impoundments have resulted in excessive productivity and impairment of designated uses relating to habitat, aesthetics and recreation. Even with enhanced control of loading from the watershed, internal loading from sediment reserves that have accumulated over many years is sufficient to maintain the excessive productivity that impairs these waterbodies. If the Hop Brook impoundments are to support their designated uses, both external and internal loading must be substantially reduced.

As phosphorus controls productivity in this system, it is the logical choice of management focus. While the level of phosphorus that will support designated uses is not precisely known, nutrient standards are now under consideration by the USEPA and the supporting documentation (ENSR, 2003) provides some insights. Typical values for minimally impacted streams range from 20 to 50 ug/L (0.02 to 0.05 mg/L), although it should be noted that values greater than 20 ug/L are known to cause productivity problems in many lakes. Processing of inputs tends to reduce in-lake phosphorus levels by about half, so an input target of up to 50 ug/L would seem reasonable and consistent with the projected "pre-settlement" condition of the impoundments, had they existed. Likewise, phosphorus levels in excess of 100 ug/L (0.1 mg/L) are clearly associated with severe productivity problems in lakes, although many streams can handle such loads with limited impact. Improvement in the condition of the Hop Brook impoundments would be expected over the range of 100 down to 50 ug/L, such that some uses could be supported without actually achieving phosphorus concentrations lower than 50 ug/L in the impoundments. Achieving a phosphorus level of 20 ug/L would be very desirable, but is not consistent with the predicted minimum levels or 25 to 35 ug/L for these impoundments in the absence of human inlfuence, and some human influence is expected.

With the above information as a back-drop, the following summary observations and recommendations are offered:

1. The Hop Brook impoundments have the potential to support habitat and recreational uses that make them a valued part of the aquatic system and watershed community. As such, they are worthy of the attention and effort necessary to meet designated uses, at least for the great majority of time.

2. If a conscious goal-setting process negates this first observation, then the easiest means of minimizing productivity problems in Hop Brook is to remove the dams that maintain the impoundments and restore the system to an unrestricted, flowing stream.
3. If the value of the impoundments is not negated, existing regulations pertaining to existing waterbodies requires that actions be taken to enhance water quality and support designated uses. There is no doubt that uses of the Hop Brook impoundments are currently impaired by excessive productivity brought on be high loading of phosphorus and other contaminants from the watershed, and by continued recycling of those contaminants within the impoundments.
4. The level of phosphorus in the MEWWTF effluent must be reduced to a level that can be processed by the system with limited impact. The currently proposed 0.1 mg/L limit is the maximum that can be justified on these grounds alone, and is still too high for the immediately downstream Hager Pond. However, reduction in the MEWWTF effluent phosphorus concentration and load is not sufficient by itself to meet water quality goals associated with support of habitat and recreational uses of the impoundments.
5. Although substantial improvement in the condition of impoundments is not expected without a more restricted MEWWTF effluent phosphorus level, internal loading of phosphorus to the impoundments will compensate for expected reductions in the external load and maintain excessive productivity. For this reason, it is necessary to reduce the potential for internal recycling to sustain designated uses. This can be accomplished by three separate methods: aeration, phosphorus inactivation, or dredging.

6. Aeration of shallow impoundments is not likely to achieve the desired conditions and carries extended operation and maintenance costs that lower the benefit-cost ratio of this approach. Aeration is not recommended for these impoundments.
7. Phosphorus inactivation is possible through the addition of aluminum compounds, with a 2:1 volumetric ratio of aluminum sulfate to sodium aluminate projected to maintain a desirable pH, minimize toxicity, and reduce internal loading of phosphorus by at least 90% at an appropriate dose. That dose varies by impoundment, based on available phosphorus in the surficial sediments, with cost varying accordingly. To treat all four impoundments would cost about $210,000, which is much less that the cost of the third option, dredging. If successful, however, the increased water clarity induced by phosphorus inactivation is likely to foster extensive growths of rooted aquatic plants that could also impair designated uses.
8. Dredging would be the most truly restorative technique for the impoundments, removing nutrient reserves, many other accumulated contaminants and seed beds, and restoring depth and substrate features that characterized the impoundments at the time of their formation. Past investigation of impoundment sediment indicates limited quality-related disposal restriction for sediments from Hager Pond and Grist Millpond and no quality-related disposal restrictions for Carding Millpond and Stearns Millpond sediments. Quantities of soft sediment have been assessed, and are within the range of typical dredging projects in freshwater lakes. Dredging could occur by several methods, but draining the impoundments and controlling flow while "dry" dredging is conducted would be the preferred approach, allowing the most complete removal of sediments. Yet the cost of such an operation for all four impoundments approaches $5 million.

9. Phosphorus inactivation may have a greater benefit-cost ratio than dredging, despite having lesser benefits, and might be considered as an interim step with relatively little additional cost compared to the complete dredging option. Partial dredging, or incomplete sediment removal, may have some benefits, but is not expected to sustain the designated uses in a manner that would make such an option acceptable. The choice is therefore between phosphorus inactivation and complete dredging, with greater benefits and greater costs accruing to the dredging approach.
10. Storm water management is viewed as necessary to maintain designated uses. It is possible that the combination of MEWWTF effluent restrictions and internal load controls will achieve the desired conditions within the impoundments, as much of the storm water phosphorus load enters in a particulate form not readily available to algae or rooted plants. However, much of that phosphorus will eventually become available, and past inputs contribute to the current high potential for internal loading. To protect the investment that should be made in wastewater treatment and internal load reduction, long-term storm water management is essential. Infiltration or filtration systems would be preferred, as they have the highest phosphorus removal rate, but the feasibility and maintenance demands of these systems are not favorable in many cases. Detention systems are more practical under a greater variety of circumstances, although they allow more available phosphorus export than ideal for this system.

11. Hager Pond will require additional maintenance measures if it is to support designated uses. Options include periodic alum treatment or use of herbicides/algaecides. Alternatively, Hager Pond could be sacrificed as an open water impoundment and transformed into a wetland treatment system. This option was discussed in the ENSR 2000 report, and would involve altering the currently short-circuited flow and creating wetland cells through which inflow would pass sequentially. A functional wetland habitat could be created while providing additional treatment for the upstream portion of the watershed and the MEWWTF effluent, thereby further enhancing water quality for the downstream impoundments and prolonging the benefits from nutrient inactivation or dredging in those waterbodies.

7.0 REFERENCES

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Appendix A

Supplemental Quality Assurance Project Plan

for Hop Brook Investigations