Prepared for:
VtANR
Waterbury, Vt

Prepared by:
AECOM
Chelmsford, MA

Water Resource Services Inc.
Wilbraham, MA

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September 2011

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Prepared By: Ken Wagner, WRS and Don Kretchmer, AECOM

Reviewed By Aaron Hopkins, AECOM

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1.0 Background

Ticklenaked Pond in Ryegate, VT suffers from algal blooms and related water quality impairments. The lake is 14.5 meters deep at the deepest hole (46 ft), and has a mean depth of 4.9 meters (16 ft). The lake volume is approximately 1.1M m^3 (864 acre-ft) with a watershed of 1,444 acres. Data have been collected by both volunteers and staff from the Vermont Agency of Natural Resources (VTANR) that allow assessment of external and internal nutrient loads. In response to algal blooms, a total phosphorus Total Maximum Daily Load (TMDL) analysis was conducted by the VTANR (VTANR 2009). As the first phase of implementation of the TMDL, several watershed phosphorus control projects have been conducted. These projects have centered on the agricultural sources of phosphorus and have been implemented in the past several years.

The primary decision to be made in the management of Ticklenaked Pond revolves around the desire to inactivate the internal phosphorus (P) reserves in light of the level of ongoing P loading from the watershed. AECOM and WRS were retained to provide a more definitive assessment based on existing data and some additional sediment evaluation. This document represents an effort to summarize that assessment based on all available data and modeling efforts.

1.1 Approach

There are several central questions that drive the analysis presented in this report:

1. What is the internal P load to Ticklenaked Pond?
2. What is the external P load to Ticklenaked Pond?
3. With a range of possible changes in external loading, including none at all, what is the expected impact and duration of benefit from decreasing the internal load?
4. What level of aluminum treatment is necessary to counteract the internal P load?

The approach to each question is as follows:

1. Internal load: We examined previous efforts to estimate internal loading, including two calculation modes from actual data, estimation from area, duration of release, and reasonable literature values for rate of P release from anoxic sediment. We also considered the output of multiple models.
2. External load: We examined the actual data and multiple models applied to estimate external loading. The Wisconsin Lake Modeling Suite (WiLMS) and incorporated empirical equations were central to this effort, backed up by application of the Lake Loading Response Model (LLRM). Ultimately, we used the LLRM results to set the loads being considered for treatment effectiveness and longevity. LLRM was then used to evaluate the influence of several load reduction scenarios on in-lake phosphorus concentrations.
3. Level and duration of benefit from treatment: We applied a spreadsheet that incorporates data or estimates for features of the external and internal loads and cycling within the pond, allows adjustment based on management actions applied, and calculates an average annual load

condition going forward for 25 years. The annual load can be compared to any desired threshold for loading or equated to an in-lake P concentration.

4. Aluminum dose: We applied a spreadsheet that incorporates data for available sediment P and sediment features over any target treatment area to an assumed sediment depth, then calculates the total available sediment P that would be targeted for inactivation. The spreadsheet then accepts assumptions about Al:P ratio and forms of Al to be applied to generate a dose as kg Al or gallons of alum and aluminate (both are used to keep the pH in balance), and estimates a cost for the chemicals to perform the treatment. We divided the lake into portions that would receive the same dose, fine tuning the treatment based on available sediment P values.

2.0 Loading Analysis

2.1 External Load

Conditions in Ticklenaked Pond are ultimately defined by its watershed (Figure 1), although with enough historic loading, the internal load can become a dominant source of P. VTANR personnel have estimated the external load by several methods including from actual data and from the WiLMS model, which itself incorporates multiple empirical equations for load estimation. Multiple tributaries feed the pond, but one (Scotch Burn, with two branches) is dominant. Atmospheric inputs, while expected to be minor, should also be accounted for when estimating the potential load. Direct septic system input, calculable by assumption for systems near the lake, can also be identified and is included in the external load. Application of the LLRM by AECOM personnel provides a platform similar to WiLMS, but can be used to further subdivide the watershed into functional units and may shed more light on loading sources and locations.

Considering all the available data and modeling to date, but relying on the results of LLRM, the external P load to Ticklenaked Pond appears to be about 118.5 kg/yr. The assigned breakdown of this load is 110.6 kg P/yr for tributary inputs, 5.6 kg P/yr from the atmosphere, and 2.3 kg P/yr from nearby septic systems. This is lower than some available estimates, but reflects application of BMPs over the last decade and an apparent decline in the in-lake TP concentration since 2006. A distribution of loads by source is presented in Table 1 while relevant input parameters for the current conditions scenario and results of the simulation and comparison to data from 2006 through 2010 are summarized in Table 2.

Table 1: Current TP Loading to Ticklenaked Pond as Simulated by LLRM

TP INPUTS	Modeled Current TP Loading (kg/yr)	% of Total Load
Atmospheric	5.6	4
Internal	35.5	23
Waterfowl	0.0	0
Septic Systems	2.3	1
Scotch West	26.8[1]	0
Upper Scotch	57.1[1]	0
Lower Scotch	91.4	59
Tick 6	4.0	3
Tick 4	2.2	1
Tick Direct	8.4	5
Tick 3	0.8	1
Tick 2	2.5	2
Tick 5	1.3	1
Watershed Total	110.6	72
Total	**153.9**	**100**

[1]Scotch West and Upper Scotch loads are shown for information only. The total load from the Lower Scotch subwatershed includes loads from Scotch West, Upper Scotch and Lower Scotch to the lake.

Table 2: Results of LLRM for Current Conditions in Ticklenaked Pond

IN-LAKE MODELS FOR PREDICTING CONCENTRATIONS: Current Conditions													
THE TERMS					***THE MODELS***					***PREDICTED CHL AND WATER CLARITY***			
	PHOSPHORUS					***PHOSPHORUS***	**PRED.**	**PERMIS.**	**CRITICAL**				
							CONC.	**CONC.**	**CONC.**				2006-2010
SYMBOL	**PARAMETER**	**UNITS**	**DERIVATION**	**VALUE**	**NAME**	**FORMULA**	**(ppb)**	**(ppb)**	**(ppb)**	**MODEL**	**Value**	**Mean**	**Measured**
TP	Lake Total Phosphorus Conc.	ppb	From in-lake models	To Be Predicted	Mass Balance	TP=L/(Z(F))*1000	49						
KG	Phosphorus Load to Lake	kg/yr	From export model	154	(Maximum Conc.)					**Mean Chlorophyll (ug/L)**			
L	Phosphorus Load to Lake	g P/m2/yr	KG*1000/A	0.692	Kirchner-Dillon 1975	TP=L(1-Rp)/(Z(F))*1000	31	17	34	Carlson 1977	13.2		
TPin	Influent (Inflow) Total Phosphorus	ppb	From export model	49	(K-D)					Dillon and Rigler 1974	11.1		
TPout	Effluent (Outlet) Total Phosphorus	ppb	From data, if available	32	Vollenweider 1975	TP=L/(Z(S+F))*1000	40	22	43	Jones and Bachmann 1976	12.8		
I	Inflow	m3/yr	From export model	3136191	(V)					Oglesby and Schaffner 1978	15.5		
A	Lake Area	m2	From data	222600	Larsen-Mercier 1976	TP=L(1-Rlm)/(Z(F))*1000	31	17	34	Modified Vollenweider 1982	15.6	13.6	11.0
V	Lake Volume	m3	From data	1,081,418	(L-M)					**Peak Chlorophyll (ug/L)**			
Z	Mean Depth	m	Volume/area	4.858	Jones-Bachmann 1976	TP=0.84(L)/(Z(0.65+F))*1000	34	18	37	Modified Vollenweider (TP) 1982	48.7		
F	Flushing Rate	flushings/yr	Inflow/volume	2.900	(J-B)					Vollenweider (CHL) 1982	41.5		
S	Suspended Fraction	no units	Effluent TP/Influent TP	0.653	Reckhow General (1977)	TP=L/(11.6+1.2(Z(F)))*1000	24	13	26	Modified Jones, Rast and Lee 1979	46.6	45.6	32.1
Qs	Areal Water Load	m/yr	Z(F)	14.089	(Rg)					**Secchi Transparency (M)**			
Vs	Settling Velocity	m	Z(S)	3.173						Oglesby and Schaffner 1978 **(Avg)**	1.6		1.9
Rp	Retention Coefficient (settling rate)	no units	((Vs+13.2)/2)/(((Vs+13.2)/2)+Qs)	0.368	Average of Model Values		32	17	35	Modified Vollenweider 1982 **(Max)**	3.7		3.0
Rlm	Retention Coefficient (flushing rate)	no units	1/(1+F^0.5)	0.370	(without mass balance)								
					Measured Value	2006-2010 mean	32.4			**Bloom Probability**			
					(mean, median, other)	2006-2010 median	29.0			Probability of Chl >10 ug/L **(% of time)**	64.5%		
						2006-2010 Std Dev	11.7			Probability of Chl >15 ug/L **(% of time)**	33.0%		
					From Vollenweider 1968					Probability of Chl >20 ug/L **(% of time)**	15.5%		
					Permissible Load (g/m2/yr)	Lp=10^(0.501503(log(Z(F))-1.0018)	0.38			Probability of Chl >30 ug/L **(% of time)**	3.4%		
					Critical Load (g/m2/yr)	Lc=2(Cp)	0.75			Probability of Chl >40 ug/L **(% of time)**	0.8%		
					Permissible Load (kg/yr)		83.5						
					Critical Load (kg/yr)		167.1						

The total external P load varies annually as a function of weather pattern and source variation, so some consideration of a range of external loads is warranted in treatment longevity assessment.

The estimated external load is not all “effective” load, however, as some particulate P will settle to the bottom of the pond before it provides any available P for algal uptake. A portion of that deposited P may be recycled after decay or as other processes act upon it, but the associated load will be part of the internal load, creating a “double counting” situation if the total external load and internal load are added in any calculation. Just how much of the external load is “effective” load is subject to some speculation, and should be bracketed in further calculations.

2.2 Internal Load

The average of multiple methods of internal loading estimation is about 42 kg/yr. Estimates range from about 20 to 80 kg/yr, but most center on the range of 35 to 50 kg/yr, and variability between years could certainly span that range. An alternative approach is offered by the sediment analysis conducted in February of 2011. Results of this testing are presented in Table 3.

Table 3: Sediment Testing Results for Ticklenaked Pond, February 2011

Station	Total Phosphorus as P (mg/kg dry)	Percent Solids (%)	Specific Gravity	Moisture (%)	Iron Bound Phosphorus as P (mg/kg dry)	Loosely sorbed Phosphorus as P (mg/kg dry)
Tick - 1	2010	16.2	0.773	91.0	196	BRL[1]
Tick - 2	2810	16.1	0.443	93.4	529	BRL[1]
Tick – 3	2280	11.8	0.498	93.2	347	BRL[1]
Tick – 4	2310	12.0	0.531	94.3	336	BRL[1]
Tick – 5	2440	9.8	0.496	95.2	365	BRL[1]
Tick – 6	1990	9.5	0.795	95.7	299	BRL[1]
Tick – 7	1820	34.2	0.844	85.3	147	BRL[1]
Tick – 8	1700	13.8	0.895	94.3	236	BRL[1]
Tick – 8 (dupe)	1840	11.9	0.794	95.3	303	BRL[1]

1BRL – Below Reporting Limit

The results of the sediment testing are translated into an internal P reserve through several assumptions:

1. Average available sediment P concentration was 306 mg/kg and was entirely a function of iron-bound P (Fe-P), as loosely sorbed P is below detection for each sample. This is a common occurrence in New England pond sediment samples
2. The depth of sediment participating in P release is 10 cm; this value is usually set at 4 to 10 cm, so we have estimated on the high end of the expected range.
3. The percent of solid material is properly reflected by 100% minus the percent moisture as measured in the samples. Note that the percent solids measures given by the lab are for partly dried samples and relate to lab calculations of P content, not raw percent solids in the sediment samples.

4. The specific gravity of the sediment, in dry form, would be about 1.5. Specific gravity from the lab is for wet sediment and is <1.0 in most cases, which is not relevant to this calculation.

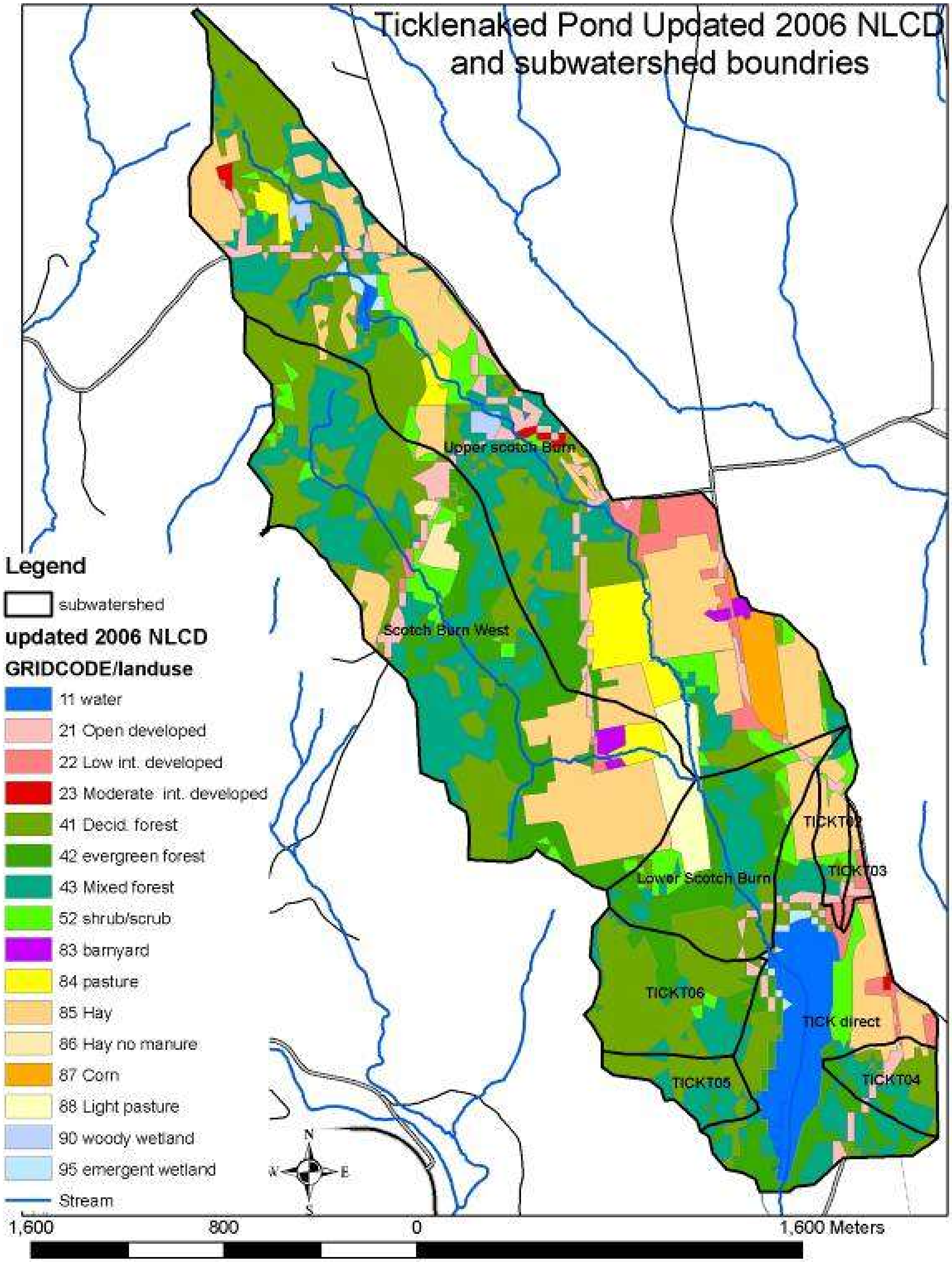


Figure 1: Ticklenaked Pond Watershed

The quantity of available sediment P over each square meter of contributing pond bottom is calculated as the product of the concentration (as mg/kg), a contributing sediment depth of 10 cm, the in-situ percent solids (100-% moisture), a water weight of 1000 kg/m^2, and a sediment specific gravity of 1.5. The results for sediment samples average 2.91 g/m^2. Rounding to 3 g/m^2 and multiplying by the anticipated contributory area of 7 hectares (70,000 m^2, representing the anoxic zone), the total available sediment reserves amount to 210 kg for Ticklenaked Pond. This excludes any available sediment P outside the 7 ha anoxic area and any other forms of sediment P that might eventually become available. The estimate can be adjusted for other sources of P when justified, but this approach is fairly standard for northeastern lake assessments.

However, the data for available sediment P suggest that there are considerable reserves in areas where the water does not become anoxic, leaving open the possibility that the contributory area is >7 ha, with significant P reserves over at least 12.3 ha. Yet release of that sediment P is greatly depressed by the presence of oxygen (which keeps P bound to iron and insoluble), so the contribution of the additional 5.3 ha is uncertain and likely to be low. For this analysis, we will work with the 7 ha anoxic zone for consistency, but consideration of a greater area of treatment is warranted.

Not all of the 210 kg of available sediment P in the targeted area will become available in any year. In our experience, the portion of available sediment P that is released and makes it into the epilimnion where it becomes part of the effective P load to a lake is normally between 10 and 30%, with most varies between 10 and 20% (Mattson et al 2004, BEC 1993, ENSR 2001, ENSR 2008, AECOM 2009). In shallow lakes a larger percentage may become available by virtue of mixing, if anoxia is strong enough to allow release, but for stratified systems lower effective releases prevail. Under the circumstances in Ticklenaked Pond it would be reasonable to estimate a 10 to 20% transfer per year, which equates to 21 to 42 kg/yr.

Considering all of the available estimates for internal load, a value of 35.5 kg/yr was applied in the model, based on 7 ha of contributing area releasing an average of 5.63 mg/m^2/day for 90 days. A similar loading estimate was made by using real data from early summer and early fall to calculate the accumulation of phosphorus in the hypolimnion. One could work with a range for internal load, which is likely to be variable over time, and treatment longevity assessment should take this into consideration. In particular, the anoxia noted in most springs after ice out suggests that internal loading may occur over a longer period of time, although this could reduce the rate of release during summer. Based on what we know of this system, the internal load is not likely to be much lower than 30 kg/yr, and may be substantially higher.

2.3 Total Load to Ticklenaked Pond

Adding the estimated average external load of 118.5 kg/yr and the estimated internal load of 35.5 kg/yr, the total load to the lake is 154 kg/yr, although not all of that may be completely and immediately available to algae for growth. LLRM applies multiple empirical models that take lake features and settling rates into consideration, and derives average total phosphorus (TP), chlorophyll (CHL) and Secchi disk transparency (SDT) values (Table 3). Based on data available from VT ANR, the in-lake mean or median TP concentration was between 29 and 35 ug/L over the last 5 years. Chlorophyll ranged from 8 to 25 ug/L, with means or medians between 11 and 16 ug/L. Water clarity, measured by Secchi disk, averaged about 1.9 m. From LLRM, the average epilimnetic TP concentration is predicted to be 32 ug/L, average CHL is projected at 13.6 ug/L, and SDT is expected to average 1.6 m. This level of agreement was considered sufficient to deem the model to be representative of current conditions in Ticklenaked Pond.

The calibrated LLRM model was used to evaluate a number of alternative loading scenarios and the probable lake response to these loadings. The results of these scenarios are summarized in Table 4. Several of the scenarios are worth highlighting.

Natural background was defined as background TP loading from non-anthropogenic sources. Hence, land uses in the watershed were set to their assumed "natural" state of forests and wetlands without internal loading or septic inputs. This estimate is useful as it sets a realistic lower bound of TP loading (52 kg-P/yr) and in-lake concentrations (10 ug/L) possible for Ticklenaked Pond. Loadings and target concentrations below these levels are very unlikely to be achieved.

A number of scenarios were examined which reduced agricultural loading in the watershed by various percentages both with and without reduction in internal loading. It is apparent that there are a number of scenarios that can reduce TP loads and in-lake TP concentrations to the TMDL in-lake target concentration of 24 ug/l. In order to attain that in-lake concentration, with a 10% margin of safety, the total load to Ticklenaked Pond must be reduced to 94 kg-P/yr (VTANR 2009). It is clear that there are no realistic external load reduction scenarios that can reach that target without addressing the internal load as well. Similarly, reduction of the internal load alone is insufficient to meet the TMDL target. A combination of internal load reduction, preceded by external load reduction, provides the best opportunity for meeting the TMDL target. It should be emphasized that the concentrations and loads to be expected after internal load treatment are only relevant for the first year after treatment. Changes in concentrations and loads in years after treatment are explored in much more detail in subsequent sections of this report.

Table 4: Loading Scenarios for Ticklenaked Pond as Predicted by LLRM

Scenario	Total load (kg-P/yr)	Percent Watershed Load Reduction from Current (%)	Predicted in-lake concentration (ug/l)	Scenario Notes
Natural background	52	58	10	All land use returned to forest, no septic or internal loads.
Current conditions	154	0	32	Calibrated to data from 2006-2010. Internal load (35.5 kg/yr) calculated from differences in hypolimnetic concentrations of P over growing season.
Current conditions, 90% internal load removed	122	0	25	Current conditions and 90% of internal load removed.
10% agric. load reduction	148	5	31	All agric. loads reduced by 10%
10% agric. load reduction, 90% internal	117	5	24	All agric. loads reduced by 10% and 90% of internal load removed.

Scenario	Total load (kg-P/yr)	Percent Watershed Load Reduction from Current (%)	Predicted in-lake concentration (ug/l)	Scenario Notes
load removed				
20% agric. load reduction	143	10	30	All agric. loads reduced by 20%
20% agric. load reduction, 90% internal load removed	111	10	23	All agric. loads reduced by 20% and 90% of internal load removed.
Barnyard load removed	149	4	31	Barnyard export coefficient (3.0 kg/ha/yr) changed to average of other agric. uses (0.55 kg/ha/yr).
Barnyard load removed, 90% internal load removed	118	4	24	Barnyard export coefficient (3.0 kg/ha/yr) changed to average of other agric. uses (0.55 kg/ha/yr) and 90% of internal load removed.
25% of external load removed	124	27	26	Assumes no change in septic or atmospheric loads, all reductions from watershed
25% of external load removed, 90% internal load removed	92	27	19	Assumes no change in septic or atmospheric loads, all reductions from watershed, 90% of internal load removed
33% of external load removed	115	35	24	Assumes no change in septic or atmospheric loads, all reductions from watershed
33% of external load removed, 90% internal load removed	83	35	17	Assumes no change in septic or atmospheric loads, all reductions from watershed, 90% of internal load removed
45% of external load removed	101	48	21	Assumes no change in septic or atmospheric loads, all reductions from watershed
45% of external load removed, 90% internal load removed	69	48	14	Assumes no change in septic or atmospheric loads, all reductions from watershed, 90% of internal load removed

3.0 Level and Duration of Benefit from Management

3.1 Results of Load Reductions

This is the key issue in the case of Ticklenaked Pond. Will the reduction in the internal load achievable by sediment P inactivation provide enough of a load reduction to appreciably improve the condition of the pond? If pond condition is improved by sediment P inactivation how long will it last? Assuming that the analysis of current loading is reliable and representative, it can be used in another analysis to evaluate the level of improvement and the pattern of change over time in annual increments. The key variables and the decision process for value selection can be summarized as follows:

- External load – The annual load of P that enters the lake, determined by processes discussed previously, set at 118.5 kg/yr for Ticklenaked Pond under current conditions.
- Fraction of external load available – The portion of the external load that is immediately available for use; the effective external load. Potentially between 10 and 90% of the total external load, and usually between 50 and 75%, this value is set at 75% in this case to start and will be varied to evaluate sensitivity of results to this variable.
- Effective external load – The product of the external load and fraction of that load that is available, calculated at 89 kg/yr for current conditions in Ticklenaked Pond.
- Internal reserves – The amount of P in the sediment readily available for transfer under the right conditions; set as the iron-bound P concentrations over 10 cm of sediment depth over an area of 7 ha in Ticklenaked Pond under current conditions, which calculates as 210 kg of P. Sediment data indicate that reserves extend into shallower water, but it is not clear that oxygen conditions allow substantial release in these areas.
- Pre-treatment fraction of internal reserves available – Current fraction of internal reserves that is actually released and makes it into the upper water layer, making it part of the effective P load. Usually between 10 and 30%, set at 17% for Ticklenaked Pond because this yields an internal load of 35.5 kg/yr, the value applied in LLRM.
- Internal load – The amount of available sediment P that becomes part of the total effective P load to the lake. Estimated at 35.5 kg/yr for Ticklenaked Pond, consistent with estimates from other methods of calculation or measurement. This value may vary among years, however, with changes in weather and external load variation. Some assessment of needs based on a reasonable range of internal loading values is warranted.
- Fraction of total load that settles to sediment – The portion of the annual effective load that settles to the sediment, as opposed to being flushed through the system. Set at 37% as the average of values from multiple calculation methods incorporated into LLRM based on flushing, input and output P concentrations, and empirical equations.
- Portion of internal load inactivated – The portion of the internal load eliminated by treatment. Set at 0% reduction for current conditions in Ticklenaked Pond and 90% after Al treatment. It is reasonable to assume that 90% of the internal load can be inactivated by treatment, but external loading can replace that load over time.

- Post-treatment fraction of internal reserves available – The amount of P available from the sediment after treatment, set as the same percentage (17%) of internal reserves as before treatment of Ticklenaked Pond. As long as the sources of P to the pond remain the same, this value should not change appreciably.
- Non-refractory portion of load that settles to sediment – The portion of the sedimented annual P load that is not refractory and could be recycled as readily available sediment P the next year. This must be at least the fraction represented by the ratio of available P to total P from sediment testing (14% in this case) plus any fraction of organic matter that may eventually become available, which can be substantial. Given a large organic fraction, this value is set at 63%, resulting in a near steady state condition for P loading under current conditions. This is another variable with substantial uncertainty that should be investigated in a sensitivity analysis.

The resulting 25 year pattern of P loading to Ticklenaked Pond, with no further management, suggests elevated but fairly stable loading (Table 5). Loading is less than the calculated critical load, above which algal blooms would be expected to be frequent, but far in excess of the permissible load, below which algal blooms should be rare. However, the internal load is likely to be maximal in the summer, so on a seasonal basis the critical loading limit is approached or exceeded during summer months indicating that algal blooms are expected during a substantial portion of the summer. This is consistent with observations for Ticklenaked Pond, and while this simple model may not adequately represent the range and frequency of conditions in the pond, it is considered to be a reasonable representation of overall condition, based on the available data.

If an aluminum treatment is performed and results in a practically attainable but maximal reduction of the internal load of 90%, the total P load to the pond in the year of treatment declines to 122.1 kg/yr, with an effective load of 92.4 kg/yr (Table 6), much closer to the permissible load than the critical load but still above the permissible load. Some reduction in the frequency and severity of algal blooms would be expected, but that relief would not last. The summer improvement may be disproportionately higher than the model suggests, since the reduced internal load is expected to be largely a summer phenomenon. Yet there is some indication that spring internal loading may be significant, and loading would increase as the internal reserves are replaced by watershed inputs, asymptotically approaching the current loading level over the next 25 years and not substantially lower than the pretreatment level after about 7 years. Performing just an aluminum treatment with no additional reduction in the external load will result in less improvement than may be desired and a return to current conditions over the following decade, based on the assumptions inherent in the analysis. These will be tested in more detail later.

If the aluminum treatment is performed and the external load is reduced by 25% (Table 7), the total P load would be reduced to 94.5 kg/yr, with an effective load of 71.7 kg/yr. This is well below the permissible level, and would be expected to increase to just beyond the permissible limit (about 114 kg/yr as total load, 83.5 kg/yr as effective load) in the fifth year after treatment. The load continues to increase, asymptotically approaching a new equilibrium load of about 118 kg/yr total load (effective load of 95 kg/yr), well below the critical loading threshold but substantially above the permissible load. This should provide some lasting improvement in pond condition, but the load would stabilize at a level that would still support algal blooms.

With both aluminum treatment and a 33% reduction in the external load (Table 8), the P load is reduced to a total load of 85.6 kg/yr and an effective load of 65.1 kg/yr, well below the permissible level. The load rises gradually over time, remaining below the permissible level for 14 years, and asymptotically approaching a new equilibrium level of about 106 kg/yr as total load and 86 kg/yr as effective load, slightly greater than the calculated corresponding permissible loading limits. A 45% reduction in external loading, about the most that can be expected with full implementation of BMPs, would permanently reduce the load to below the permissible level (Table 9), but as some BMPs have already been implemented, this level of reduction may not be achievable.

The pattern of effects of potential management on the phosphorus load to Ticklenaked Pond can be visualized as a series of curves created by bars in a graph (Figure 2). Each curve asymptotically approaches an equilibrium annual total load which can be compared with the desirable loading threshold represented as the Vollenweider permissible load. The actual loading pattern would not be nearly so smooth, and the permissible load does not represent a perfect boundary, but the overall impression is clear. Aluminum treatment alone is not expected to provide sufficient or lasting improvement in the condition of Ticklenaked Pond. In addition to inactivation of the current internal load, reduction in the external load of about 25% appears necessary to achieve desirable and lasting improvement within the pond. A 33% external load reduction would provide a margin of safety, but may not be necessary, given the relative importance of internal loading to summer conditions, the possibility that the internal load represents a larger fraction of the total load than estimated so far, and the expected lower availability of external inputs driven by storm water runoff.

3.2 Sensitivity Analysis

Consideration of the sensitivity of the response of Ticklenaked Pond to variability in the parameters that control processing of the phosphorus load focuses on variation in the fraction of the external load that is immediately available for algal uptake, the fraction of the sediment P reserves that become the internal load each summer, the fraction of the annual load sedimented within the lake, and the non-refractory portion of the sedimented P load. These are all estimates that may be subject to substantial variation. In considering that variability, it is more relevant to consider effective load instead of total load, since we are varying assumptions that affect what portion of the load is directly involved in algal blooms. Both total and effective loads have been provided in Tables 2-6, but we will focus on the effective load here for comparing the impact of assumptions on load estimates.

The 90% internal load reduction and 25% external load + 90% internal load reduction scenarios are of greatest interest, as these represent the range of likely actions that could be achieved for this pond and watershed. Adjusting assumptions to favor greater importance of internal loading to the maximum conceivable extent (more of the P reserves becoming available, more external load sedimented, and more of the sedimented load in non-refractory forms), the trajectories of post-treatment conditions for these two scenarios are presented in Tables 10 and 11. Slightly better initial conditions are achieved under these revised assumptions for internal load reduction alone, but the long term equilibrium loading level is slightly higher than under the original assumptions. For the 25% external load reduction + 90% internal load reduction, one additional year is gained below the permissible level, but the long term equilibrium load is slightly higher than under the original assumptions. This is largely a function of more of the external load feeding the internal load, which is a consequence of assuming that more of the external load is unavailable when it reaches the lake, but can be processed over time to generate internal load. Overall, the results are not strikingly different than under the original assumptions.

Adjusting assumptions to favor the importance of external loading and downplaying the internal load to the greatest justifiable extent (increasing the portion of the external load that is available, decreasing the sedimented fraction, decreasing the portion of internal reserves that are released from the sediment, and increasing the refractory portion of the sedimented load), the initial post-treatment load for internal load reduction alone is about 14% higher than under the original assumptions, but the long term equilibrium load is very similar among the two alternatives (Table 12). For the scenario involving 25% external load reduction + 90% internal load reduction, the initial post-treatment loading is about 18% higher than under the original assumptions and the long term equilibrium is again very close to that under the original assumptions (Table 13).

The range of expected results (Figure 3) indicates that management conclusions drawn under the range of possible assumptions are not appreciably different; some additional watershed loading reduction is needed beyond internal load reduction to get large and lasting benefits in Ticklenaked Pond.

4.0 Incorporating the TMDL into Inactivation Longevity Modeling

4.1 TMDL Target

The Total Maximum Daily Load derived for Ticklenaked Pond by the VT ANR translates into an annual total phosphorus load of 104 kg/yr. This load assumes an external load of 94 kg/yr and a margin of safety of 10 kg/yr, allowing for some uncertainty in the watershed load and some possible internal loading even after an inactivation treatment. This load is expected to result in an in-lake TP concentration of between 24 and 25 ug/L. While such a TP concentration is likely to support algal blooms at times, it would represent an improvement over current bloom frequency and a condition that could support designated uses.

4.2 Longevity Scenarios Linked to the TMDL

Adjusting previous result and longevity model runs to the TMDL requires setting the external load at 104 kg/yr and eliminating the internal load. Total elimination of the internal load is not realistic, and in fact that load may increase in response to lesser external loading as a function of greater concentration gradient between upper and lower water layers. This could keep the effective load near the current effective load for some time, ameliorating any benefit from reduced external loading. Ultimately, however, the internal load would decline in response to reduced external loading, and the total and effective loads would asymptotically approach some new equilibrium at a lower level than currently experienced.

If an inactivation treatment is performed, the internal load would be greatly reduced in a single burst, and would increase at slower than current trends. With a reduced concentration gradient within the lake, and lesser active reserves to contribute to internal loading, the actual availability of internally recycled phosphorus is likely to decline, although it is very difficult to quantitatively predictthe magnitude of reduction. For modeling purposes, some bracketing of this expected reduction in availability is appropriate. Below we examine 4 scenarios relating to the TMDL:

- Scenario 0: Current conditions as perceived from available data.
- Scenario 1: Achievement of the TMDL target as an external load with no inactivation of internal load, leading to some compensation of reduced external load by increased internal load.
- Scenario 2A: Achievement of the TMDL plus inactivation of internal load with availability based on current conditions.
- Scenario 2A: Achievement of the TMDL plus inactivation of internal load with availability set as low as seems plausible.

Table 5: Predicted Pattern of P Loading to Ticklenaked Pond under Continued Current Conditions

Scenario 0 - current conditions																												
																			Below permissible									
Ext. Load			118.5	kg/yr	From LLRM model, represents 110.6 kg/yr tribs, 5.6 kg/yr atmos, 2.3 kg/yr direct septic											Permissible load = 83.5 kg/yr			Between permissible and critical									
Fraction Ext. Load Avail:			0.75		Assumes a portion is refractory particulates, possibly processed as internal load, but avoiding double counting											Critical load = 167 kg/yr			Above critical									
Effective Ext. Load			89	kg/yr																								
Int. Reserves			210	kg	Calc from measured avail sed P, 10 cm active depth, 7 ha contributory area																							
Pre-trtmnt Fraction of ASP Avail:			0.17		Typical fraction that becomes effective internal load, yields match for model value derived from multiple sources																							
Int. Load			35.5	kg/yr																								
Fraction Load Sedimented:			0.37		Average from LLRM model calculations																							
Int. Load Inactivated			0.00		No treatment																							
Post-trtmnt Fraction of ASP			0.17		No change in release rate for uninactivated P assumed																							
Non-refractory Portion of Sed Load			0.63		Balances load for near steady state																							
		In-Lake																										
		Pre-trtmt	Trtmt Yr	Year 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Ext. Load	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5
Effective Ext. Load	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88
Int. Reserves	210.00	210.00	210.40	210.75	211.06	211.33	211.56	211.76	211.94	212.09	212.23	212.34	212.44	212.53	212.61	212.68	212.73	212.79	212.83	212.87	212.90	212.93	212.96	212.98	213.00	213.01	213.03	213.04
Int. Load	35.50	35.50	35.56	35.62	35.67	35.71	35.75	35.79	35.82	35.84	35.87	35.89	35.90	35.92	35.93	35.94	35.95	35.96	35.97	35.97	35.98	35.99	35.99	35.99	36.00	36.00	36.00	36.00
Total Load	154.00	154.00	154.06	154.12	154.17	154.21	154.25	154.29	154.32	154.34	154.37	154.39	154.40	154.42	154.43	154.44	154.45	154.46	154.47	154.47	154.48	154.49	154.49	154.49	154.50	154.50	154.50	154.50
Total Effective Load	124.38	124.38	124.43	124.49	124.54	124.59	124.63	124.66	124.69	124.72	124.74	124.76	124.78	124.79	124.81	124.82	124.83	124.84	124.84	124.85	124.86	124.86	124.86	124.87	124.87	124.87	124.88	124.88
Sedimented Load		56.98	57.00	57.02	57.04	57.06	57.07	57.09	57.10	57.11	57.12	57.12	57.13	57.13	57.14	57.14	57.15	57.15	57.15	57.16	57.16	57.16	57.16	57.16	57.16	57.16	57.17	57.17

Table 6: Predicted Pattern of P Loading to Ticklenaked Pond with a 90% EffectiveAaluminum Treatment and Current External Loading

Scenario 1 - No external reduction, 90% int red																												
Ext. Load			118.5	kg/yr	From LLRM model, represents 110.6 kg/yr tribs, 5.6 kg/yr atmos, 2.3 kg/yr direct septic																							
Fraction Ext. Load Avail:			0.75		Assumes a portion is refractory particulates, possibly processed as internal load, but avoiding double counting																							
Effective Ext. Load			89	kg/yr																								
Int. Reserves			210	kg	Calc from measured avail sed P, 10 cm active depth, 7 ha contributory area																							
Pre-trtmnt Fraction of ASP:			0.17		Typical fraction that becomes effective internal load, yields match for model value derived from multiple sources																							
Int. Load			35.5	kg/yr																								
Fraction Load Sedimented:			0.37		Average from LLRM model calculations																							
Int. Load Inactivated			0.90		90% reduction from aluminum treatment																							
Post-trtmnt Fraction of ASP			0.17		No change in release rate for uninactivated P assumed																							
Non-refractory Portion of Sed Load			0.63		Balances load for near steady state																							
		In-Lake																										
		Pre-trtmt	Trtmt Yr	Year 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Ext. Load	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5
Effective Ext. Load	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88	88.88
Int. Reserves	210.00	210.00	21.04	45.94	67.60	86.46	102.88	117.17	129.61	140.43	149.85	158.05	165.19	171.40	176.81	181.52	185.61	189.18	192.28	194.98	197.34	199.38	201.16	202.71	204.06	205.24	206.26	207.15
Int. Load	35.50	35.50	3.56	7.76	11.43	14.61	17.39	19.80	21.90	23.73	25.32	26.71	27.92	28.97	29.88	30.68	31.37	31.97	32.50	32.95	33.35	33.70	34.00	34.26	34.49	34.69	34.86	35.01
Total Load	154.00	154.00	122.06	126.26	129.93	133.11	135.89	138.30	140.40	142.23	143.82	145.21	146.42	147.47	148.38	149.18	149.87	150.47	151.00	151.45	151.85	152.20	152.50	152.76	152.99	153.19	153.36	153.51
Total Effective Load	124.38	124.38	92.43	96.64	100.30	103.49	106.26	108.68	110.78	112.61	114.20	115.59	116.79	117.84	118.76	119.55	120.24	120.85	121.37	121.83	122.22	122.57	122.87	123.13	123.36	123.56	123.73	123.88
Sedimented Load		56.98	45.16	46.72	48.07	49.25	50.28	51.17	51.95	52.63	53.22	53.73	54.17	54.56	54.90	55.20	55.45	55.67	55.87	56.04	56.18	56.31	56.42	56.52	56.61	56.68	56.74	56.80

Table 7: Predicted Pattern of P Loading to Ticklenaked Pond with a 90% Effective Aluminum Treatment and 25% Reduction in External Loading

Scenario 2 - 25% ext red, 90% int red			
Ext. Load	90.9	kg/yr	25% reduction in surficial watershed load (no change in atmos or septic loads)
Fraction Ext. Load Avail:	0.75		Assumes a portion is refractory particulates, possibly processed as internal load, but avoiding double counting
Effective Ext. Load	68	kg/yr	
Int. Reserves	210	kg	Calc from measured avail sed P, 10 cm active depth, 7 ha contributory area
Pre-trtmnt Fraction of ASP:	0.17		Typical fraction that becomes effective internal load, yields match for model value derived from multiple sources
Int. Load	35.5	kg/yr	
Fraction Load Sedimented:	0.37		Average from LLRM model calculations
Int. Load Inactivated	0.90		90% reduction from aluminum treatment
Post-trtmnt Fraction of ASP	0.17		No change in release rate for uninactivated P assumed
Non-refractory Portion of Sed Load	0.63		No change assumed for new inputs

		In-Lake Pre-trtmt	Trtmt Yr	Year 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Ext. Load	118.5	118.5	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9
Effective Ext. Load	88.88	88.88	68.18	68.18	68.18	68.18	68.18	68.18	68.18	68.18	68.18	68.18	68.18	68.18	68.18	68.18	68.18	68.18	68.18	68.18	68.18	68.18	68.18	68.18	68.18	68.18	68.18	68.18
Int. Reserves	210.00	210.00	21.04	39.50	55.57	69.56	81.73	92.33	101.55	109.58	116.56	122.65	127.94	132.55	136.56	140.05	143.08	145.73	148.03	150.03	151.78	153.29	154.62	155.76	156.77	157.64	158.39	159.05
Int. Load	35.50	35.50	3.56	6.68	9.39	11.76	13.81	15.60	17.16	18.52	19.70	20.73	21.62	22.40	23.08	23.67	24.18	24.63	25.02	25.36	25.65	25.91	26.13	26.32	26.49	26.64	26.77	26.88
Total Load	154.00	154.00	94.46	97.58	100.29	102.66	104.71	106.50	108.06	109.42	110.60	111.63	112.52	113.30	113.98	114.57	115.08	115.53	115.92	116.26	116.55	116.81	117.03	117.22	117.39	117.54	117.67	117.78
Total Effective Load	124.38	124.38	71.73	74.85	77.57	79.93	81.99	83.78	85.34	86.69	87.87	88.90	89.80	90.58	91.25	91.84	92.36	92.80	93.19	93.53	93.83	94.08	94.30	94.50	94.67	94.82	94.94	95.06
Sedimented Load		56.98	34.95	36.10	37.11	37.98	38.74	39.41	39.98	40.48	40.92	41.30	41.63	41.92	42.17	42.39	42.58	42.75	42.89	43.01	43.12	43.22	43.30	43.37	43.44	43.49	43.54	43.58

Table 8: Predicted Pattern of P Loading to Ticklenaked Pond with a 90% Effective Aluminum Treatment and 33% Reduction in External Loading

Scenario 3 - 33% ext red, 90% int red			
Ext. Load	82	kg/yr	33% reduction in surficial watershed load (no change in atmos or septic loads)
Fraction Ext. Load Avail:	0.75		Assumes a portion is refractory particulates, possibly processed as internal load, but avoiding double counting
Effective Ext. Load	62	kg/yr	
Int. Reserves	210	kg	Calc from measured avail sed P, 10 cm active depth, 7 ha contributory area
Pre-trtmnt Fraction of ASP:	0.17		Typical fraction that becomes effective internal load, yields match for model value derived from multiple sources
Int. Load	35.5	kg/yr	
Fraction Load Sedimented:	0.37		Average from LLRM model calculations
Int. Load Inactivated	0.90		90% reduction from aluminum treatment
Post-trtmnt Fraction of ASP	0.17		No change in release rate for uninactivated P assumed
Non-refractory Portion of Sed Load	0.63		No change assumed for new inputs

		In-Lake Pre-trtmt	Trtmt Yr	Year 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Ext. Load	118.5	118.5	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82
Effective Ext. Load	88.88	88.88	61.50	61.50	61.50	61.50	61.50	61.50	61.50	61.50	61.50	61.50	61.50	61.50	61.50	61.50	61.50	61.50	61.50	61.50	61.50	61.50	61.50	61.50	61.50	61.50	61.50	61.50
Int. Reserves	210.00	210.00	21.04	37.43	51.69	64.11	74.91	84.32	92.50	99.63	105.83	111.23	115.93	120.02	123.58	126.67	129.37	131.72	133.76	135.54	137.09	138.43	139.61	140.63	141.51	142.29	142.96	143.55
Int. Load	35.50	35.50	3.56	6.33	8.74	10.83	12.66	14.25	15.63	16.84	17.89	18.80	19.59	20.28	20.88	21.41	21.86	22.26	22.61	22.91	23.17	23.40	23.59	23.77	23.92	24.05	24.16	24.26
Total Load	154.00	154.00	85.56	88.33	90.74	92.83	94.66	96.25	97.63	98.84	99.89	100.80	101.59	102.28	102.88	103.41	103.86	104.26	104.61	104.91	105.17	105.40	105.59	105.77	105.92	106.05	106.16	106.26
Total Effective Load	124.38	124.38	65.06	67.83	70.24	72.33	74.16	75.75	77.13	78.34	79.39	80.30	81.09	81.78	82.38	82.91	83.36	83.76	84.11	84.41	84.67	84.90	85.09	85.27	85.42	85.55	85.66	85.76
Sedimented Load		56.98	31.66	32.68	33.57	34.35	35.02	35.61	36.12	36.57	36.96	37.30	37.59	37.84	38.07	38.26	38.43	38.58	38.70	38.82	38.91	39.00	39.07	39.13	39.19	39.24	39.28	39.32

Table 9: Predicted Pattern of P Loading to Ticklenaked Pond with a 90% Effective Aluminum Treatment and 45% Reduction in External Loading

Scenario 4 - 45% ext red, 90% int red																											
Ext. Load			68.7	kg/yr	45% reduction in surficial watershed load (no change in atmos or septic loads)																						
Fraction Ext. Load Avail:			0.75		Assumes a portion is refractory particulates, possibly processed as internal load, but avoiding double counting																						
Effective Ext. Load			52	kg/yr																							
Int. Reserves			210	kg	Calc from measured avail sed P, 10 cm active depth, 7 ha contributory area																						
Pre-trtmnt Fraction of ASP:			0.17		Typical fraction that becomes effective internal load, yields match for model value derived from multiple sources																						
Int. Load			35.5	kg/yr																							
Fraction Load Sedimented:			0.37		Average from LLRM model calculations																						
Int. Load Inactivated			0.90		90% reduction from aluminum treatment																						
Post-trtmnt Fraction of ASP			0.17		No change in release rate for uninactivated P assumed																						
Non-refractory Portion of Sed Load			0.63		No change assumed for new inputs																						
		In-Lake																									
		Pre-trtmt	Trtmt Yr	Year 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Ext. Load	118.5	118.5	68.7	68.7	68.7	68.7	68.7	68.7	68.7	68.7	68.7	68.7	68.7	68.7	68.7	68.7	68.7	68.7	68.7	68.7	68.7	68.7	68.7	68.7	68.7	68.7	68.7	68.7
Effective Ext. Load	88.88	88.88	51.53	51.53	51.53	51.53	51.53	51.53	51.53	51.53	51.53	51.53	51.53	51.53	51.53	51.53	51.53	51.53	51.53	51.53	51.53	51.53	51.53	51.53	51.53	51.53	51.53	51.53
Int. Reserves	210.00	210.00	21.04	34.33	45.89	55.96	64.72	72.35	78.98	84.76	89.79	94.17	97.98	101.29	104.18	106.69	108.88	110.78	112.43	113.88	115.13	116.22	117.17	118.00	118.72	119.35	119.89	120.37
Int. Load	35.50	35.50	3.56	5.80	7.76	9.46	10.94	12.23	13.35	14.32	15.17	15.91	16.56	17.12	17.61	18.03	18.40	18.72	19.00	19.25	19.46	19.64	19.80	19.94	20.06	20.17	20.26	20.34
Total Load	154.00	154.00	72.26	74.50	76.46	78.16	79.64	80.93	82.05	83.02	83.87	84.61	85.26	85.82	86.31	86.73	87.10	87.42	87.70	87.95	88.16	88.34	88.50	88.64	88.76	88.87	88.96	89.04
Total Effective Load	124.38	124.38	55.08	57.33	59.28	60.98	62.46	63.75	64.87	65.85	66.70	67.44	68.08	68.64	69.13	69.56	69.92	70.25	70.53	70.77	70.98	71.17	71.33	71.47	71.59	71.69	71.79	71.87
Sedimented Load		56.98	26.73	27.57	28.29	28.92	29.47	29.94	30.36	30.72	31.03	31.31	31.55	31.75	31.93	32.09	32.23	32.35	32.45	32.54	32.62	32.69	32.75	32.80	32.84	32.88	32.92	32.95

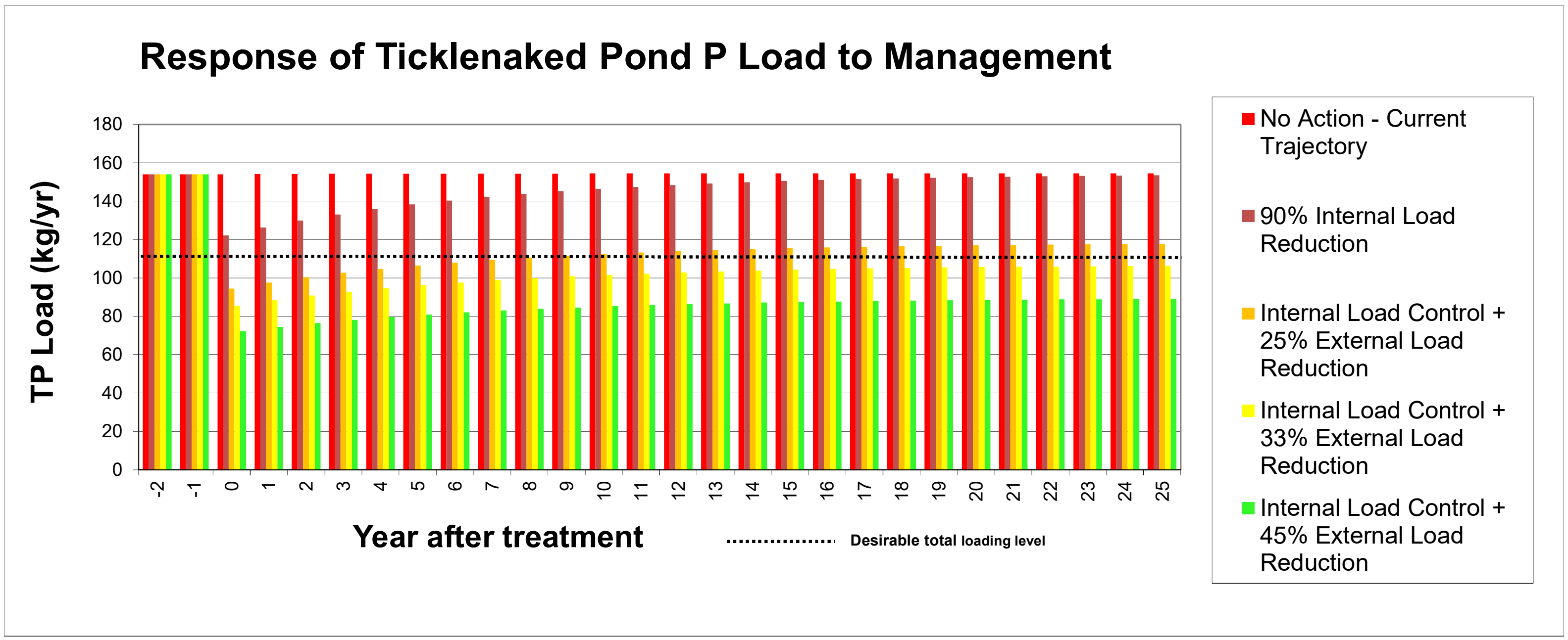


Figure 2: Response of Ticklenaked Pond Phosphorous Load to Management Options

Table 10: Predicted Pattern of P Loading to Ticklenaked Pond with 90% Effective Aluminum Treatment and Current External Loading, Under Alternative Assumptions that Increase the Importance of Internal Loading

Scenario 1 - No external reduction, 90% int red																												
Ext. Load			118.5	kg/yr	From LLRM model, represents 110.6 kg/yr tribs, 5.6 kg/yr atmos, 2.3 kg/yr direct septic																							
Fraction Ext. Load Avail:			0.50		Decreased fraction available																							
Effective Ext. Load			59	kg/yr																								
Int. Reserves			210	kg	Calc from measured avail sed P, 10 cm active depth, 7 ha contributory area																							
Pre-trtmnt Fraction of ASP:			0.30		Increased importance of internal load																							
Int. Load			63	kg/yr																								
Fraction Load Sedimented:			0.50		If more of external load is unavailable, more sedimentation must occur																							
Int. Load Inactivated			0.90		90% reduction from aluminum treatment																							
Post-trtmnt Fraction of ASP			0.30		No change in release rate for uninactivated P assumed																							
Non-refractory Portion of Sed Load			0.75		Increased importance of internal load																							
		In-Lake																										
		Pre-trtmt	Trtmt Yr	Year 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Ext. Load	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5
Effective Ext. Load	59.25	59.25	59.25	59.25	59.25	59.25	59.25	59.25	59.25	59.25	59.25	59.25	59.25	59.25	59.25	59.25	59.25	59.25	59.25	59.25	59.25	59.25	59.25	59.25	59.25	59.25	59.25	59.25
Int. Reserves	210.00	210.00	21.51	61.91	94.74	121.41	143.09	160.70	175.00	186.63	196.07	203.75	209.98	215.05	219.16	222.51	225.22	227.43	229.23	230.68	231.87	232.83	233.61	234.25	234.76	235.18	235.52	235.80
Int. Load	63.00	63.00	6.45	18.57	28.42	36.42	42.93	48.21	52.50	55.99	58.82	61.12	62.99	64.51	65.75	66.75	67.57	68.23	68.77	69.21	69.56	69.85	70.08	70.27	70.43	70.55	70.66	70.74
Total Load	181.50	181.50	124.95	137.07	146.92	154.92	161.43	166.71	171.00	174.49	177.32	179.62	181.49	183.01	184.25	185.25	186.07	186.73	187.27	187.71	188.06	188.35	188.58	188.77	188.93	189.05	189.16	189.24
Total Effective Load	122.25	122.25	65.70	77.82	87.67	95.67	102.18	107.46	111.75	115.24	118.07	120.37	122.24	123.76	125.00	126.00	126.82	127.48	128.02	128.46	128.81	129.10	129.33	129.52	129.68	129.80	129.91	129.99
Sedimented Load		90.75	62.48	68.54	73.46	77.46	80.71	83.35	85.50	87.24	88.66	89.81	90.75	91.51	92.12	92.63	93.03	93.36	93.63	93.85	94.03	94.17	94.29	94.39	94.46	94.53	94.58	94.62

Table 11: Predicted Pattern of P Loading in Ticklenaked Pond with a 90% Effective Aluminum Treatment and 25% Reduction in External Loading, Under Alternative Assumptions that Increase the Importance of Internal Loading

Scenario 2 - 25% ext red, 90% int red																												
Ext. Load			90.9	kg/yr	From LLRM model, represents 110.6 kg/yr tribs, 5.6 kg/yr atmos, 2.3 kg/yr direct septic																							
Fraction Ext. Load Avail:			0.50		Decreased fraction available																							
Effective Ext. Load			45	kg/yr																								
Int. Reserves			210	kg	Calc from measured avail sed P, 10 cm active depth, 7 ha contributory area																							
Pre-trtmnt Fraction of ASP:			0.30		Increased importance of internal load																							
Int. Load			63	kg/yr																								
Fraction Load Sedimented:			0.50		If more of external load is unavailable, more sedimentation must occur																							
Int. Load Inactivated			0.90		90% reduction from aluminum treatment																							
Post-trtmnt Fraction of ASP			0.30		No change in release rate for uninactivated P assumed																							
Non-refractory Portion of Sed Load			0.75		Increased importance of internal load																							
		In-Lake																										
		Pre-trtmt	Trtmt Yr	Year 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Ext. Load	118.5	118.5	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9
Effective Ext. Load	59.25	59.25	45.45	45.45	45.45	45.45	45.45	45.45	45.45	45.45	45.45	45.45	45.45	45.45	45.45	45.45	45.45	45.45	45.45	45.45	45.45	45.45	45.45	45.45	45.45	45.45	45.45	45.45
Int. Reserves	210.00	210.00	21.51	51.56	75.98	95.82	111.94	125.04	135.68	144.33	151.36	157.06	161.70	165.47	168.53	171.02	173.04	174.68	176.02	177.10	177.98	178.70	179.28	179.75	180.14	180.45	180.70	180.91
Int. Load	63.00	63.00	6.45	15.47	22.79	28.75	33.58	37.51	40.71	43.30	45.41	47.12	48.51	49.64	50.56	51.31	51.91	52.41	52.81	53.13	53.39	53.61	53.78	53.93	54.04	54.13	54.21	54.27
Total Load	181.50	181.50	97.35	106.37	113.69	119.65	124.48	128.41	131.61	134.20	136.31	138.02	139.41	140.54	141.46	142.21	142.81	143.31	143.71	144.03	144.29	144.51	144.68	144.83	144.94	145.03	145.11	145.17
Total Effective Load	122.25	122.25	51.90	60.92	68.24	74.20	79.03	82.96	86.16	88.75	90.86	92.57	93.96	95.09	96.01	96.76	97.36	97.86	98.26	98.58	98.84	99.06	99.23	99.38	99.49	99.58	99.66	99.72
Sedimented Load		90.75	48.68	53.18	56.85	59.82	62.24	64.21	65.80	67.10	68.15	69.01	69.71	70.27	70.73	71.10	71.41	71.65	71.85	72.02	72.15	72.25	72.34	72.41	72.47	72.52	72.56	72.59

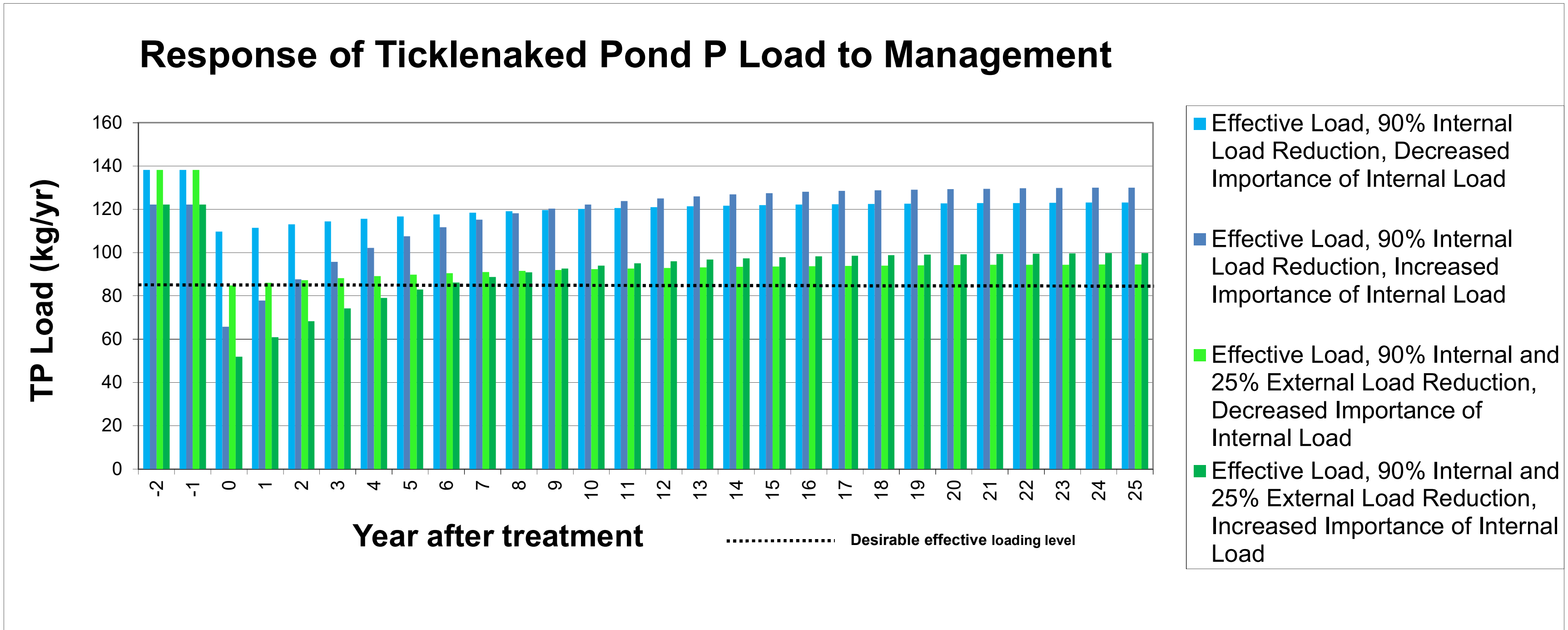
Table 12: Predicted Pattern of P Loading to Ticklenaked Pond with a 90% Effective Aluminum Treatment and Current External Loading, Under Alternative Assumptions that Decrease the Importance of Internal Loading

Scenario 1 - No external reduction, 90% int red																												
Ext. Load			118.5	kg/yr	From LLRM model, represents 110.6 kg/yr tribs, 5.6 kg/yr atmos, 2.3 kg/yr direct septic																							
Fraction Ext. Load Avail:			0.90		Increased fraction available																							
Effective Ext. Load			107	kg/yr																								
Int. Reserves			210	kg	Calc from measured avail sed P, 10 cm active depth, 7 ha contributory area																							
Pre-trtmnt Fraction of ASP:			0.15		Decreased importance of internal load																							
Int. Load			31.5	kg/yr																								
Fraction Load Sedimented:			0.25		If less of external load is unavailable, less sedimentation is likely																							
Int. Load Inactivated			0.90		90% reduction from aluminum treatment																							
Post-trtmnt Fraction of ASP			0.15		No change in release rate for uninactivated P assumed																							
Non-refractory Portion of Sed Load			0.50		Decreased importance of internal load																							
		In-Lake																										
		Pre-trtmt	Trtmt Yr	Year 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Ext. Load	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5	118.5
Effective Ext. Load	106.65	106.65	106.65	106.65	106.65	106.65	106.65	106.65	106.65	106.65	106.65	106.65	106.65	106.65	106.65	106.65	106.65	106.65	106.65	106.65	106.65	106.65	106.65	106.65	106.65	106.65	106.65	106.65
Int. Reserves	210.00	210.00	19.73	31.95	42.57	51.79	59.81	66.77	72.82	78.07	82.64	86.61	90.05	93.04	95.64	97.90	99.87	101.57	103.05	104.34	105.46	106.43	107.27	108.01	108.64	109.20	109.68	110.09
Int. Load	31.50	31.50	2.96	4.79	6.39	7.77	8.97	10.02	10.92	11.71	12.40	12.99	13.51	13.96	14.35	14.69	14.98	15.24	15.46	15.65	15.82	15.96	16.09	16.20	16.30	16.38	16.45	16.51
Total Load	150.00	150.00	121.46	123.29	124.89	126.27	127.47	128.52	129.42	130.21	130.90	131.49	132.01	132.46	132.85	133.19	133.48	133.74	133.96	134.15	134.32	134.46	134.59	134.70	134.80	134.88	134.95	135.01
Total Effective Load	138.15	138.15	109.61	111.44	113.04	114.42	115.62	116.67	117.57	118.36	119.05	119.64	120.16	120.61	121.00	121.34	121.63	121.89	122.11	122.30	122.47	122.61	122.74	122.85	122.95	123.03	123.10	123.16
Sedimented Load		37.50	30.36	30.82	31.22	31.57	31.87	32.13	32.36	32.55	32.72	32.87	33.00	33.11	33.21	33.30	33.37	33.43	33.49	33.54	33.58	33.62	33.65	33.68	33.70	33.72	33.74	33.75

Table 13: Predicted Pattern of P Loading to Ticklenaked Pond with a 90% Effective Aluminum Treatment and 25% Reduction in External Loading, Under Alternative Assumptions that Decrease the Importance of Internal Loading

Scenario 2 - 25% ext red, 90% int red																												
Ext. Load			90.9	kg/yr	From LLRM model, represents 110.6 kg/yr tribs, 5.6 kg/yr atmos, 2.3 kg/yr direct septic																							
Fraction Ext. Load Avail:			0.90		Increased fraction available																							
Effective Ext. Load			82	kg/yr																								
Int. Reserves			210	kg	Calc from measured avail sed P, 10 cm active depth, 7 ha contributory area																							
Pre-trtmnt Fraction of ASP:			0.15		Decreased importance of internal load																							
Int. Load			31.5	kg/yr																								
Fraction Load Sedimented:			0.25		If less of external load is unavailable, less sedimentation is likely																							
Int. Load Inactivated			0.90		90% reduction from aluminum treatment																							
Post-trtmnt Fraction of ASP			0.15		No change in release rate for uninactivated P assumed																							
Non-refractory Portion of Sed Load			0.50		Decreased importance of internal load																							
		In-Lake																										
		Pre-trtmt	Trtmt Yr	Year 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Ext. Load	118.5	118.5	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9	90.9
Effective Ext. Load	106.65	106.65	81.81	81.81	81.81	81.81	81.81	81.81	81.81	81.81	81.81	81.81	81.81	81.81	81.81	81.81	81.81	81.81	81.81	81.81	81.81	81.81	81.81	81.81	81.81	81.81	81.81	81.81
Int. Reserves	210.00	210.00	19.73	28.50	36.12	42.74	48.49	53.49	57.83	61.61	64.88	67.73	70.20	72.35	74.22	75.84	77.25	78.47	79.53	80.46	81.26	81.96	82.56	83.09	83.55	83.94	84.29	84.59
Int. Load	31.50	31.50	2.96	4.27	5.42	6.41	7.27	8.02	8.68	9.24	9.73	10.16	10.53	10.85	11.13	11.38	11.59	11.77	11.93	12.07	12.19	12.29	12.38	12.46	12.53	12.59	12.64	12.69
Total Load	150.00	150.00	93.86	95.17	96.32	97.31	98.17	98.92	99.58	100.14	100.63	101.06	101.43	101.75	102.03	102.28	102.49	102.67	102.83	102.97	103.09	103.19	103.28	103.36	103.43	103.49	103.54	103.59
Total Effective Load	138.15	138.15	84.77	86.08	87.23	88.22	89.08	89.83	90.49	91.05	91.54	91.97	92.34	92.66	92.94	93.19	93.40	93.58	93.74	93.88	94.00	94.10	94.19	94.27	94.34	94.40	94.45	94.50
Sedimented Load		37.50	23.46	23.79	24.08	24.33	24.54	24.73	24.89	25.04	25.16	25.26	25.36	25.44	25.51	25.57	25.62	25.67	25.71	25.74	25.77	25.80	25.82	25.84	25.86	25.87	25.89	25.90

Figure 3: Response of Ticklenaked Pond to Load Reduction Under a Range of Assumptions that Increase or Decrease the Importance of Internal Loading to Lake Conditions



The current conditions, corresponding to Scenario 0 above, are represented in Table 5. Tables 14, 15 and 16 represent Scenarios 1, 2A and 2B above, and all are summarized in Figure 4. The result of this refined analysis suggests that achievement of the TMDL would not initially result in an average in-lake TP concentration of 24-25 ug/L, but that the new equilibrium that would arise over a period of years would indeed meet that target. Inactivating the internal load upon achievement of the TMDL for external loading would greatly reduce the in-lake TP load initially, after which slowly increasing internal loading will raise the total load and in-lake TP level over years, asymptotically approaching about the same level as achievement of the TMDL without internal load control. This is entirely consistent with known lake processes; reductions in external loading will ultimately lead to lower in-lake TP levels, but it may take decades without action toward reducing internal loading (Scenario 1). Reductions in internal loading will provide immediate and substantial decreases in the in-lake TP, but these cannot be sustained if external loading continues to be a significant factor in overall loading (Scenario 2A). The significance of external loading is a function of both the magnitude of the load and the availability of that load; where the external load does not result in a highly available sedimented load that can then fuel internal loading, the new equilibrium for effective load and in-lake TP concentration may be considerably lower (Scenario 2B), but we have no simple way to predict the availability of future loading in response to decreased external load and inactivated internal load.

4.3 Water Quality Comparison

Another useful way to compare options involves considering the resulting conditions associated with each possible management option. Plugging the new loads into LLRM, we can predict the new in-lake TP concentration, chlorophyll level, and Secchi transparency under each management option (Table 17). While these values will change over time at rates that vary among scenarios, the initially expected conditions suggest that more than the internal load reduction alone is necessary to achieve a desirable state in the pond. There is a fairly major break between the 90% internal load reduction and either of the management scenarios with additional watershed load reduction in terms of resultant in-lake conditions. Models are better at predicting trends than exact values, but it appears that some additional watershed management is needed before a program of internal load reduction will provide adequate benefits.

The TMDL for Ticklenaked Pond calls for achieving an in-lake P concentration between 24 and 25 ug/L. Based on this analysis, the TMDL would be achieved in the long run with the 25% external load reduction and 90% internal load reduction approach. The models depend on assumptions that limit the reliability of single values, but it is apparent that some additional watershed management is needed beyond what is perceived to be the current loading level for the lake before a P inactivation treatment can be expected to meet the TMDL target for an extended period of years. If the current loading level is actually lower than appears to be the case from available data, there may be less to do before the TMDL is achieved. Changes in watershed loading, especially those linked to storm water events, can be difficult to detect without considerable data collection. Some estimation of where the external load stands now is warranted, and the decision to pursue internal load inactivation will be influenced by how close current loading is to the desired target level, based on reasonable perception of available data by decision makers.

Table 14: Predicted pattern of P loading to Ticklenaked Pond with achievement of TMDL target external loading, but with initial compensatory increase in internal loading

Scenario 1 - TMDL external loading conditions, some compensation of ext load reduction by int load increase																												
Scenario 1 - TMDL achieved, increased Int Load																												
Ext. Load			104	kg/yr	From TMDL - target for ext load is 94 kg/yr + 10 kg/yr MOS																							
Fraction Ext. Load Avail:			0.75		Assumes a portion is refractory particulates, possibly processed as internal load, but avoiding double counting																							
Effective Ext. Load			78	kg/yr	Product of external load and portion that is available																							
Int. Reserves			210	kg	Calc from measured avail sed P, 10 cm active depth, 7 ha contributory area																							
Pre-trtmnt Fraction of ASP Avail:			0.17		Plausible fraction that becomes effective internal load, yields match for model value derived as maximum expected internal load																							
Int. Load			35.5	kg/yr	Pre-TMDL load based on reserves and expected availability that matches available data																							
Fraction Load Sedimented:			0.37		Average from LLRM model calculations																							
Int. Load Inactivated			0.00		No treatment of internal load																							
Post-trtmnt Fraction of ASP			0.22		Increased int load as a function of increased concentration gradient resulting from reduced ext load - brings total load back to current (2011) level																							
Non-refractory Portion of Sed Load			0.63		Assumes no change in non-refractory portion from before TMDL loading was achieved (might increase slightly based on BMPs)																							
		In-Lake	TMDL	Post-TMDL load achievement																								
		Pre-trtmt	Achieved	Year 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Ext. Load	118	118	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104
Effective Ext. Load	88.50	88.50	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00
Int. Reserves	210.00	210.00	210.29	199.05	189.71	181.95	175.49	170.12	165.66	161.96	158.87	156.31	154.18	152.41	150.94	149.71	148.70	147.85	147.15	146.56	146.08	145.68	145.34	145.06	144.83	144.64	144.48	144.34
Int. Load	35.49	35.49	46.26	43.79	41.74	40.03	38.61	37.43	36.45	35.63	34.95	34.39	33.92	33.53	33.21	32.94	32.71	32.53	32.37	32.24	32.14	32.05	31.97	31.91	31.86	31.82	31.78	31.76
Total Load	153.49	153.49	150.26	147.79	145.74	144.03	142.61	141.43	140.45	139.63	138.95	138.39	137.92	137.53	137.21	136.94	136.71	136.53	136.37	136.24	136.14	136.05	135.97	135.91	135.86	135.82	135.78	135.76
Total Effective Load	123.99	123.99	124.26	121.79	119.74	118.03	116.61	115.43	114.45	113.63	112.95	112.39	111.92	111.53	111.21	110.94	110.71	110.53	110.37	110.24	110.14	110.05	109.97	109.91	109.86	109.82	109.78	109.76
Sedimented Load		56.79	55.60	54.68	53.92	53.29	52.76	52.33	51.97	51.66	51.41	51.20	51.03	50.89	50.77	50.67	50.58	50.52	50.46	50.41	50.37	50.34	50.31	50.29	50.27	50.25	50.24	50.23

Table 15: Predicted pattern of P loading to Ticklenaked Pond with achievement of TMDL target external loading and decrease in internal loading with post-treatment ASP availability similar to pre-treatment value

Scenario 2A - TMDL + 90% Int Load Red, mod ASP availability																												
Ext. Load			104	kg/yr	From TMDL - target for ext load is 94 kg/yr + 10 kg/yr MOS																							
Fraction Ext. Load Avail:			0.75		Assumes a portion is refractory particulates, possibly processed as internal load, but avoiding double counting																							
Effective Ext. Load			78	kg/yr	Product of external load and portion that is available																							
Int. Reserves			210	kg	Calc from measured avail sed P, 10 cm active depth, 7 ha contributory area																							
Pre-trtmnt Fraction of ASP:			0.22		Plausible fraction that becomes effective internal load, yields elevated internal load in response to high ASP, increased concentration gradient, continued low oxygen																							
Int. Load			46.2	kg/yr	Increased ASP availability based on post-TMDL load reaction of internal load																							
Fraction Load Sedimented:			0.37		Average from LLRM model calculations																							
Int. Load Inactivated			0.90		90% reduction of internal load																							
Post-trtmnt Fraction of ASP			0.17		Decreased int load availability to match modeled current conditions prior to TMDL achievement																							
Non-refractory Portion of Sed Load			0.65		Assumes no change in non-refractory portion from before TMDL loading was achieved (might increase slightly based on BMPs)																							
		In-Lake	All reduct.																									
		Pre-trtmt	Achieved	Year 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Ext. Load	118	118	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104
Effective Ext. Load	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00
Int. Reserves	210.00	210.00	20.33	42.72	62.21	79.19	93.98	106.86	118.07	127.84	136.35	143.75	150.20	155.82	160.72	164.98	168.69	171.92	174.73	177.19	179.32	181.18	182.80	184.21	185.44	186.51	187.44	188.25
Int. Load	46.20	46.20	3.46	7.26	10.58	13.46	15.98	18.17	20.07	21.73	23.18	24.44	25.53	26.49	27.32	28.05	28.68	29.23	29.70	30.12	30.48	30.80	31.08	31.32	31.52	31.71	31.86	32.00
Total Load	164.20	164.20	107.46	111.26	114.58	117.46	119.98	122.17	124.07	125.73	127.18	128.44	129.53	130.49	131.32	132.05	132.68	133.23	133.70	134.12	134.48	134.80	135.08	135.32	135.52	135.71	135.86	136.00
Total Effective Load	124.20	124.20	81.46	85.26	88.58	91.46	93.98	96.17	98.07	99.73	101.18	102.44	103.53	104.49	105.32	106.05	106.68	107.23	107.70	108.12	108.48	108.80	109.08	109.32	109.52	109.71	109.86	110.00
Sedimented Load		60.75	39.76	41.17	42.39	43.46	44.39	45.20	45.91	46.52	47.06	47.52	47.93	48.28	48.59	48.86	49.09	49.29	49.47	49.62	49.76	49.88	49.98	50.07	50.14	50.21	50.27	50.32

Table 16: Predicted pattern of P loading to Ticklenaked Pond with achievement of TMDL target external loading and decrease in internal loading with post-treatment ASP availability lower than pre-treatment value

Scenario 2B - TMDL + 90% Int Load Red, low ASP availability					
Ext. Load			104	kg/yr	From TMDL - target for ext load is 94 kg/yr + 10 kg/yr MOS
Fraction Ext. Load Avail:			0.75		Assumes a portion is refractory particulates, possibly processed as internal load, but avoiding double counting
Effective Ext. Load			78	kg/yr	Product of external load and portion that is available
Int. Reserves			210	kg	Calc from measured avail sed P, 10 cm active depth, 7 ha contributory area
Pre-trtmnt Fraction of ASP:			0.22		Plausible fraction that becomes effective internal load, yields match for model value derived as maximum expected internal load
Int. Load			46.2	kg/yr	Increased ASP availability based on post-TMDL load reaction of internal load
Fraction Load Sedimented:			0.37		Average from LLRM model calculations
Int. Load Inactivated			0.90		90% reduction of internal load
Post-trtmnt Fraction of ASP			0.05		Decreased int load availability as a function of changed reserves quality, lesser concentration gradient, possibly more oxygen
Non-refractory Portion of Sed Load			0.65		Assumes no change in non-refractory portion from before TMDL loading was achieved (might increase slightly based on BMPs)

		In-Lake Pre-trtmt	All reduct. Achieved	Year 1	2	3	4	5	6	7	8	9	10	11	12
Ext. Load	118	118	104	104	104	104	104	104	104	104	104	104	104	104	104
Effective Ext. Load	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00
Int. Reserves	210.00	210.00	20.33	44.57	67.89	90.32	111.90	132.67	152.64	171.86	190.34	208.13	225.23	241.69	257.53
Int. Load	46.20	46.20	1.02	2.23	3.39	4.52	5.60	6.63	7.63	8.59	9.52	10.41	11.26	12.08	12.88
Total Load	164.20	164.20	105.02	106.23	107.39	108.52	109.60	110.63	111.63	112.59	113.52	114.41	115.26	116.08	116.88
Total Effective Load	124.20	124.20	79.02	80.23	81.39	82.52	83.60	84.63	85.63	86.59	87.52	88.41	89.26	90.08	90.88
Sedimented Load		60.75	38.86	39.30	39.74	40.15	40.55	40.93	41.30	41.66	42.00	42.33	42.65	42.95	43.24

	13	14	15	16	17	18	19	20	21	22	23	24	25
Ext. Load	104	104	104	104	104	104	104	104	104	104	104	104	104
Effective Ext. Load	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00
Int. Reserves	272.76	287.41	301.51	315.07	328.12	340.67	352.75	364.36	375.54	386.29	396.63	406.58	416.15
Int. Load	13.64	14.37	15.08	15.75	16.41	17.03	17.64	18.22	18.78	19.31	19.83	20.33	20.81
Total Load	117.64	118.37	119.08	119.75	120.41	121.03	121.64	122.22	122.78	123.31	123.83	124.33	124.81
Total Effective Load	91.64	92.37	93.08	93.75	94.41	95.03	95.64	96.22	96.78	97.31	97.83	98.33	98.81
Sedimented Load	43.53	43.80	44.06	44.31	44.55	44.78	45.01	45.22	45.43	45.63	45.82	46.00	46.18

Figure 4: Response of Ticklenaked Pond to Achievement of TMDL with Concurrent Reduction of Internal Loading

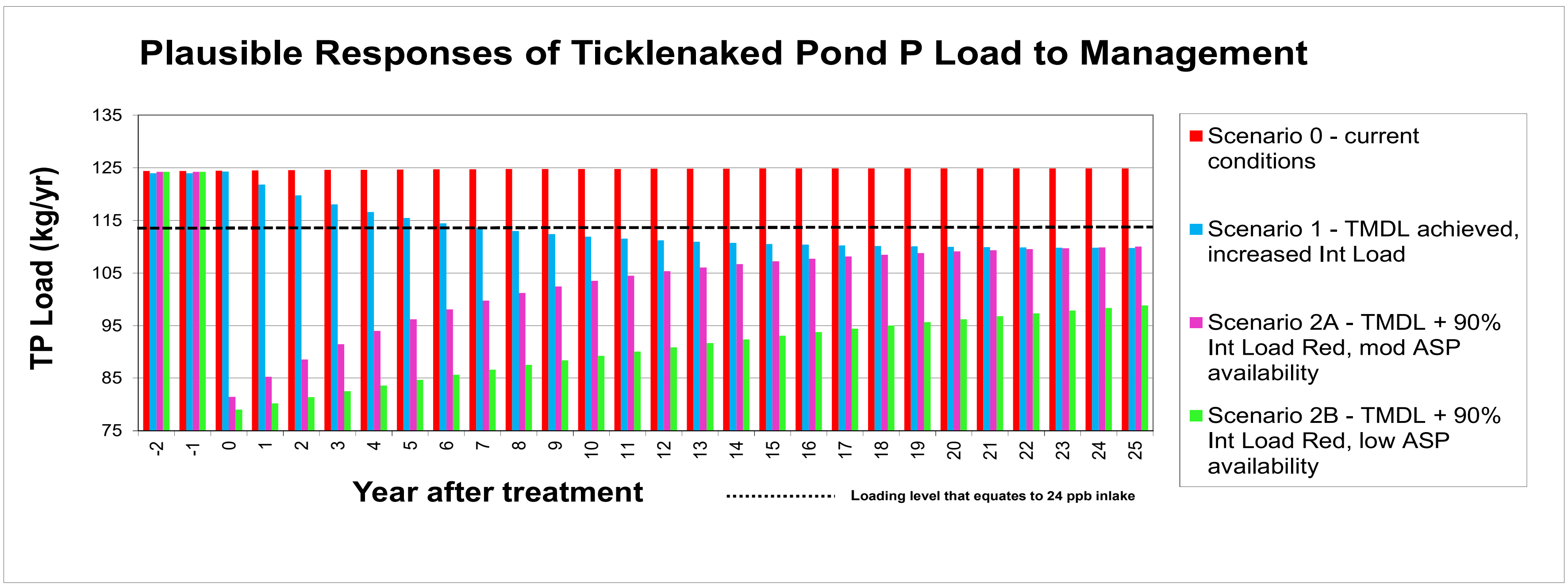


Table 17: Initial Expected Conditions Under Various Possible Management Scenarios

	Management Option						
		90% Internal Load Reduction		25% External Load Reduction + 90% Internal Load Reduction		33% External Load Reduction + 90% Internal Load Reduction	
Variable	Current Conditions	Initial Value After Management	Long-term Value after Management	Initial Value After Management	Long-term Value after Management	Initial Value After Management	Long-term Value after Management
Average in-lake TP concentration (ug/L)	32	25	32	20	25	18	22
Average in-lake CHL concentration (ug/L)	13.6	10.1	13.5	7.3	9.7	6.4	8.4
Average in-lake SDT (m)	1.6	1.9	1.6	2.4	2.0	2.5	2.2
Bloom Probability							
Probability of Chl >10 ug/L **(% of time)**	64.4%	41.2%	63.9%	18.8%	37.8%	12.7%	27.9%
Probability of Chl >15 ug/L **(% of time)**	33.0%	15.1%	32.4%	4.5%	13.1%	2.5%	8.1%
Probability of Chl >20 ug/L **(% of time)**	15.5%	5.4%	15.1%	1.2%	4.5%	0.6%	2.4%
Probability of Chl >30 ug/L **(% of time)**	3.4%	0.8%	3.3%	0.1%	0.6%	0.0%	0.3%
Probability of Chl >40 ug/L **(% of time)**	0.8%	0.1%	0.8%	0.0%	0.1%	0.0%	0.0%

5.0 Aluminum Dose

At such time as it is deemed appropriate to inactivate the internal load to Ticklenaked Pond, aluminum compounds can be used to bind P on what is generally believed to be a permanent basis. Once fully reacted, the compounds that are formed are insoluble and release of P is not subject to fluctuations in oxygen, or to pH within a normally observed range (>5 and <10 SU). One can bind P with iron if oxygen is provided at all times; the iron releases the P under anoxic conditions. P can also be bound by calcium, but the pH must be high (>9 SU) to get the compounds to settle out, and must generally be higher than 8 SU to remain out of solution. Because the dissolved oxygen near the pond bottom is very low at times, and the pH is not consistently high in Ticklenaked Pond, the use of aluminum compounds is recommended. This is the way virtually all internal load reduction treatments have been accomplished in New England over the last 25 years.

Dose determination is a function of the concentration of P that must be inactivated, the depth of sediment that is to be treated, and the area that has been targeted for treatment. VT ANR staff collected surficial sediment samples representing the upper 10 cm of sediment at 8 locations within the pond (Figure 4), and tested the samples at Spectrum Labs in Agawam, MA for available sediment phosphorus by sequential extraction. The resulting values (Table 18) range from 147 to 529 mg P per dry weight gram of sediment (mg/kg DW). For scale, values <50 mg/kg DW are considered low, while values >200 mg/kg DW are considered high, based on sampling of a wide range of lakes in New England and the potential internal load represented. For Ticklenaked Pond, only one sample had a value lower than 200 mg/kg DW, and the average for 9 samples (8 stations with one duplicate) was 306 mg/kg DW. Total P was tested as well, and averaged 2133 mg/kg DW; available sediment P was therefore about 14% of the total. However, some of the total that did not extract as available P can become available over time, mainly through decomposition, and that rate becomes an assumption in the analysis of the longevity of treatment results.

It is generally believed that only the P in the upper 4 to 10 cm of sediment interacts with the water column (Cooke et al. 2005). There can be some upward mobilization of P, but studies and field work have indicated that inactivating a mass of P equal to that calculated for the upper 10 cm of sediment is adequate to get maximum reduction in internal loading (Cooke et al 1993, Rydin and Welch 1998, Welch and Cooke 1999). For the sediment samples tested from Ticklenaked Pond, the average quantity of P in the upper 10 cm in a square meter of sediment is 2.91 g. In pure lab work, the actual ratio necessary to bind aqueous P to Al is nearly 1:1 by weight, but this does not hold up in lake sediment applications. Many other elements in the sediment compete for binding sites in forming the Al complexes, and P bound to iron must be transferred to Al, requiring enough Al to shift the chemical equilibrium (James 2011). The minimum effective dose is typically estimated at a ratio of 10:1. At P concentrations that are relatively low (<100 mg/kg), the necessary ratio can be as high as 100:1. In the absence of lab assays demonstrating the relationship of P inactivation to aluminum dose, we generally assume a target ratio of 20:1, although recent work by James (2011) suggests that this ratio could be higher.

Figure 5: Potential Treatment Zones in Ticklenaked Pond. Stations Listed as White Numbers, Available Sediment P as Red nUmbers, Red Lines Delineate Possible Treatment Zones, Denoted by Red Letters

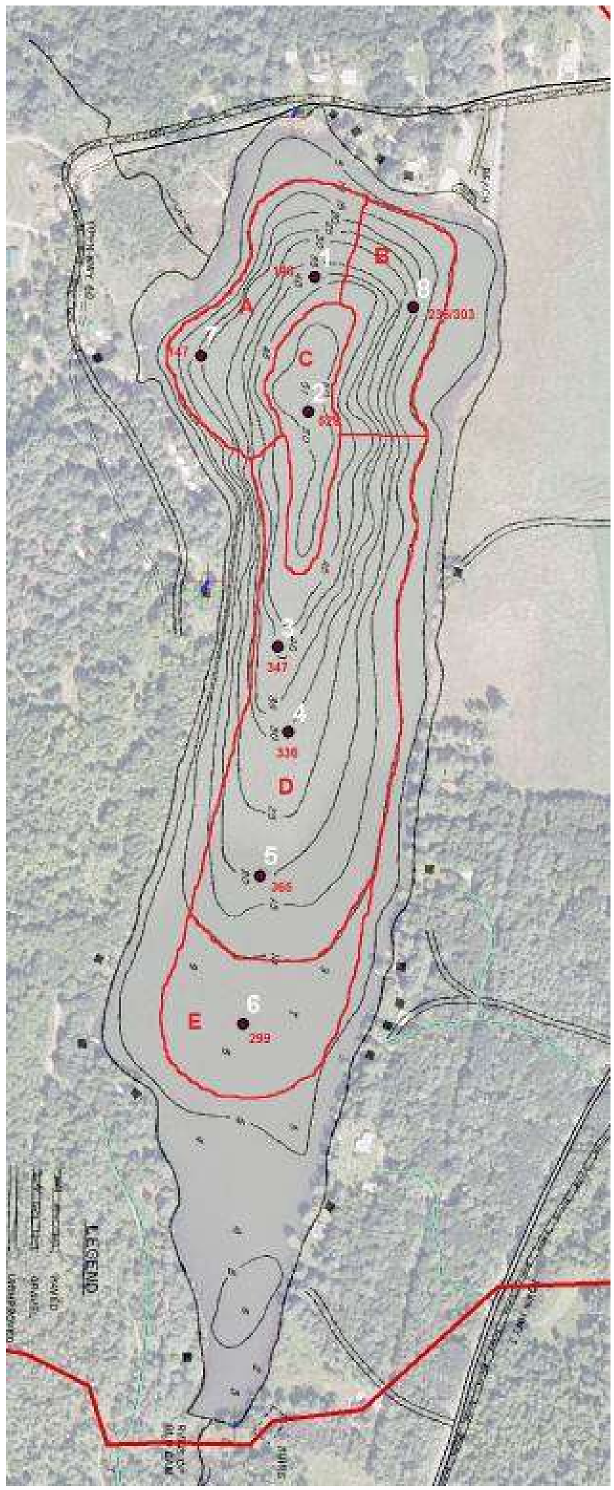


Table 18: Aluminum Dosing Calculations for the Treatment of 12.3 Hectares of Ticklenaked Pond

Alum Dosing Calculations										
Defined Lake Area	A		B		C	D			E	All Areas
Sampling Station	1	7	8a	8b	2	3	4	5	6	Total
Total Sediment P (mg/kg DW)	2010	1820	1700	1840	2810	2280	2310	2440	1990	
Mean Available Sediment P (mg/kg DW)	196	147	236	303	529	347	336	365	299	
Target Depth of Sediment to be Treated (cm)	10	10	10	10	10	10	10	10	10	
Volume of Sediment to be Treated per m2 (m3)	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	
Specific Gravity of Sediment	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	
Percent Solids (as a fraction)	0.09	0.15	0.06	0.05	0.07	0.07	0.06	0.05	0.04	
Mass of Sediment to be Treated (kg/m2)	13.5	22.1	8.6	7.1	9.9	10.2	8.6	7.2	6.3	
Mass of P to be Treated (g/m2)	2.65	3.24	2.02	2.14	5.24	3.54	2.87	2.63	1.88	
Target Area (m2)	20000		15000		10000	58600			19300	122900
Aluminum sulfate (alum) @ 11.1 lb/gal and 4.4% aluminum (lb/gal)	0.4884		0.4884		0.4884	0.4884			0.4884	
Sodium aluminate (aluminate) @ 12.1 lb/gal and 10.38% aluminum (lb/gal)	1.256		1.256		1.256	1.256			1.256	
Stoich. Ratio (ratio of Al to P in treatment)	20		20		20	20			20	
Resulting areal dose (g Al/m2)	59		42		105	60			38	
Ratio of alum to aluminate for combined treatment (volumetric)	2.00		2.00		2.00	2.00			2.00	
Aluminum Load										
Dose (kg/area)	1058		605		1047	4148			727	7586
Dose (lb/area)	2328		1332		2304	9126			1600	16690
Dose (gal alum) for Alum treatment alone	4768		2727		4718	18685			3275	34173
Application (gal/ac) for Alum alone	961		733		1902	1286			684	
Dose (gal alum) @ specified ratio of Alum to Aluminate	2086		1193		2064	8174			1433	14950
Dose (gal aluminate) @ specified ratio of Alum to Aluminate	1043		596		1032	4087			716	7475
Application (gal/ac) for Alum in Alum+Aluminate Trtmt	421		321		832	562			299	
Application (gal/ac) for Aluminate in Alum+Aluminate Trtmt	210		160		416	281			150	
Anticipated days of treatment in area (assumes 4000 gal alum/day)	1		1		1	3			1	6
Unit Cost										
Alum	$1.00		$1.00		$1.00	$1.00			$1.00	
Aluminate	$3.00		$3.00		$3.00	$3.00			$3.00	
Chemical Cost										
Alum alone	$4,768		$2,727		$4,718	$18,685			$3,275	$34,173
Alum + Aluminate combination	$5,214		$2,982		$5,160	$20,436			$3,582	$37,375

For general consideration, the necessary dose of aluminum necessary to inactivate the average 2.91 g/m^2 of available sediment P in Ticklenaked Pond is estimated at 58 g/m^2. This is based simply on a stoichiometric ratio of 20:1 for Al:P. Final dose determination is best achieved by performing lab assays with the target sediment and the Al chemicals that are to be used in the actual treatment. However, typical doses in New England have ranged from 10 to 100 g/m^2, and a dose of 58 g/m^2 is not unusual. If the target area is 7 ha, then the total dose of Al needed from average available sediment P and a ratio of 20:1 will be about 4,060 kg Al. However, the area represented by the sampling pattern for Ticklenaked Pond suggests a possible treatment area of 12.3 ha. With the range of available sediment P values obtained, it would be best to estimate the dose separately for each possible target area.

Figure 4 indicates the location of sediment sampling sites and the available sediment P concentrations for those sites. Figure 1 also shows the logical subdivision of the pond into treatment zones based on those data. Table 3 contains the results of the lab tests, while Table 19 presents combined results corresponding to treatment zones. The total dose based on this approach is 7,586 kg, suggesting an average areal dose of 62 g/m^2, slightly higher than the 58 g/m^2 estimated from just the average available sediment P values; the difference is a function of weighting concentration by area to be treated, but is not a large difference. Areal doses for the five possible target areas range from 38 to 105 g/m^2.

Shallow lakes or shallow portions of lakes have been treated, but it is not typical to treat areas <15 ft deep, and even less typical to treat areas <10 ft deep. Although available sediment P could be released under localized anoxic conditions, the portion mixing into the oxygenated waters above in an available state is expected to be low. However, it is very common for filamentous mat forming algae, including mainly chlorophyta (green algae) and cyanophyta (cyanobacteria) to utilize available sediment P in these shallower areas, so treatment may be justified.

Further discussion may be warranted in the planning stages for a treatment of Ticklenaked Pond, but the delineation in Figure 4 is based on the following:

- All areas >10 ft will be treated, except along the west shore where steep slopes tend to cause soft sediment to slough into deeper water. Treating in deeper water with lesser slope will still result in some drift of aluminum floc into the shallower areas, so this slope will not be ignored, but it does not need to be specifically included in the treatment zone.
- One area <10 ft deep, corresponding to station 6 at the southern end of the lake, was included since it contained an elevated available sediment P concentration and could potentially contribute to internal load, or at least foster substantial algal mat development.
- The dividing line for the deepest and most P-rich zone was arbitrarily set between the 25 and 30 ft contours.
- Dividing lines between zones A, B and D were arbitrarily set to be roughly equidistant from specific sampling points representing those zones. The estimated necessary dose is almost the same for zones A and D, and the difference between doses for A or D and B is minor, so this is not a critical assumption in treatment planning.

Use of aluminum sulfate (alum) alone or a combination of alum and sodium aluminate (aluminate) is normally based on the potential for deleterious pH shifts during treatment. With alum treatment at the suggested doses of 38 to 105 g/m^2, the fully mixed concentration of aluminum will be on the order of 10 to 20 mg/L if added all at once. Treatment with alum tends to use up about 1 mg/L of alkalinity for each 1 mg/L of aluminum; with alkalinity averaging close to 60 mg/L in Ticklenaked Pond, it would not be necessary to buffer the alum to avoid pH depression. Further, to minimize potential toxicity, it is recommended that in lake aluminum concentrations be maintained at <5 mg/L during treatment, so doses on any given day of a multi-day treatment would result in lower concentrations and pH tracking would allow adjustment of application rates if any shifts were observed, prior to additional treatment. However, better pH control is obtained when the alum is buffered, aluminate is an effective buffer for this use, balancing pH while contributing aluminum for inactivation. The chemical cost differential is not large, but use of alum and aluminate instead of alum alone does tend to raise labor costs and lengthen the time of treatment, potentially affecting overall project cost.

If the potential treatment zones are adjusted to eliminate any area with water <15 ft deep, zone A is reduced by 12.5%, zone B by almost 20%, and zone D by just over 22%. This reduced the overall treatment area to 8.5 hectares, still more than the 7 hectares assumed to be contributing in modeling, but appropriate to the observed conditions. Re-calculation by the approach illustrated in Table 18 yields the dose and chemical cost estimates in Table 19. Treated area is reduced by 30% and cost is reduced by 25%, the lack of proportion relates to the lack of change in zone C, where the highest dose would be applied.

Labor costs vary with the applicator and distance from the sources of both chemicals and equipment. Labor costs also increase somewhat with the addition of sodium aluminate, as two chemicals must be handled and the targeted balance of alum and aluminate requires more effort and can slow treatment. Additional costs for permitting and monitoring can also vary among states, experience in Vermont is limited, so estimation is difficult. As a rough rule of thumb, the cost for treatment elements beyond the chemical cost is expected to be one to two times the chemical cost. The distance of the site from the few application companies will tend to raise costs, while the potential to perform this treatment with alum only will reduce cost. For estimation purposes, a cost of 1.5 times the chemical cost is suggested. This translates to a total project cost of $85,400 for the 12.3 ha area and $64,100 for the 8.5 ha area, each with alum alone.

Refinement of exact doses with lab assays is recommended. This would involve treating aliquots of sediment (for which the available sediment P is known) with aluminum at levels that correspond to a range of possible doses (40, 60, 80 and 100 g/m^2 are suggested), then retesting for available sediment P. The resultant graph of available sediment P vs. dose is expected to follow a curvilinear decline, and a treatment dose can be selected based on P inactivation, diminishing returns for additional aluminum, and cost. Such assays cost about $1,500 per site, and tests for any zone being considered for treatment should be conducted. This will refine the final dose selection and cost beyond what has been provided in Tables 18 and 19.

Table 19: Aluminum Dosing Calculations for the Treatment of 8.5 Hectares of Ticklenaked Pond

Alum Dosing Calculations										
Defined Lake Area	A		B		C	D			E	All Areas
Sampling Station	1	7	8a	8b	2	3	4	5	6	Total
Total Sediment P (mg/kg DW)	2010	1820	1700	1840	2810	2280	2310	2440	1990	
Mean Available Sediment P (mg/kg DW)	196	147	236	303	529	347	336	365	299	
Target Depth of Sediment to be Treated (cm)	10	10	10	10	10	10	10	10	10	
Volume of Sediment to be Treated per m2 (m3)	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	
Specific Gravity of Sediment	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	
Percent Solids (as a fraction)	0.09	0.15	0.06	0.05	0.07	0.07	0.06	0.05	0.04	
Mass of Sediment to be Treated (kg/m2)	13.5	22.1	8.6	7.1	9.9	10.2	8.6	7.2	6.3	
Mass of P to be Treated (g/m2)	2.65	3.24	2.02	2.14	5.24	3.54	2.87	2.63	1.88	
Target Area (m2)	17500		12100		10000	45600			0	85200
Aluminum sulfate (alum) @ 11.1 lb/gal and 4.4% aluminum (lb/gal)	0.4884		0.4884		0.4884	0.4884			0.4884	
Sodium aluminate (aluminate) @ 12.1 lb/gal and 10.38% aluminum (lb/gal)	1.256		1.256		1.256	1.256			1.256	
Stoich. Ratio (ratio of Al to P in treatment)	20		20		20	20			20	
Resulting areal dose (g Al/m2)	59		42		105	60			38	
Ratio of alum to aluminate for combined treatment (volumetric)	2.00		2.00		2.00	2.00			2.00	
Aluminum Load										
Dose (kg/area)	926		488		1047	3228			0	5690
Dose (lb/area)	2037		1074		2304	7101			0	12517
Dose (gal alum) for Alum treatment alone	4172		2200		4718	14540			0	25630
Application (gal/ac) for Alum alone	961		733		1902	1286			0	
Dose (gal alum) @ specified ratio of Alum to Aluminate	1825		962		2064	6361			0	11212
Dose (gal aluminate) @ specified ratio of Alum to Aluminate	912		481		1032	3181			0	5606
Application (gal/ac) for Alum in Alum+Aluminate Trtmt	421		321		832	562			0	
Application (gal/ac) for Aluminate in Alum+Aluminate Trtmt	210		160		416	281			0	
Anticipated days of treatment in area (assumes 4000 gal alum/day)	1		1		1	2			0	5
Unit Cost										
Alum	$1.00		$1.00		$1.00	$1.00			$1.00	
Aluminate	$3.00		$3.00		$3.00	$3.00			$3.00	
Chemical Cost										
Alum alone	$4,172		$2,200		$4,718	$14,540			$0	$25,630
Alum + Aluminate combination	$4,562		$2,406		$5,160	$15,903			$0	$28,031

6.0 References

AECOM. 2009. Treatment summary for Phosphorus Inactivation in Long Pond, Brewster and Harwich, Massachusetts. AECOM, Westford, MA.

BEC. 1993. Diagnostic/Feasibility Study of Hamblin Pond, Barnstable, Massachusetts. Baystate Environmental Consultants, Inc. East Longmeadow, MA.

Cooke, G.D., E.B. Welch, S.A. Peterson, and S.A Nichols. 2005. Restoration and Management of Lakes and Reservoirs, Third Edition. Taylor and Francis, Boca Raton, Fl.

Cooke, G.D., E.B. Welch, A.B. Martin, D.G. Fulmer, J.B. Hyde, and G.D. Schrieve. 1993. Effectiveness of Al, Ca, and Fe salts for control of internal phosphorus loading in shallow and deep lakes. Hydrobiologia 253:323-335.

ENSR. 2001. Analysis of Phosphorus Inactivation Issues at Lake Pocotopaug, East Hampton, CT. ENSR, Willington, CT.

ENSR. 2008. Alum treatment analysis for Cedar Lake Aquatic Ecosystem Feasibility Study, Cedar Lake, Indiana. ENSR, Willington, CT.

James, W.F. 2011.Variations in the aluminum:phosphorus binding ratio and alum dosage considerations for Half Moon Lake, Wisconsin. Lake and Reservoir Management. 27:128-137.

Mattson, M., Godfrey, P.J., Barletta, R.A. and A. Aiello. (edited by K. Wagner). 2004. Generic Environmental Impact Report for Eutrophication and Aquatic Plant Management in Massachusetts. MADCR/MADEP, Boston, MA

Rydin, E. and E.B. Welch. 1998. Aluminum dose required to inactivate phosphate in lake sediments. Wat. Res. 32:2969-2976.

Vermont Agency of Natural Resources. 2009. Phosphorus Total Maximum Daily Load (TMDL) for Ticklenaked Pond.
http://www.anr.state.vt.us/dec/waterq/mapp/docs/mp_TMDL.Ticklenaked_Pond_Final_Approved.pdf

Welch, E.B. and G.D. Cooke. 1999. Effectiveness and longevity of phosphorus inactivation with alum. Lake Reserv. Manage. 15:5-27.