University of Massachusetts Dartmouth
The School for Marine Science and Technology

COASTAL SYSTEMS PROGRAM

Technical Memorandum

Lake Wequaquet Dissolved Oxygen Monitoring Program and Bearses Pond Sediment Core Sampling

Summer 2015

To: Darcy Karle, Conservation Administrator, Town of Barnstable
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Re: Continuous Monitoring at Main Basin and Bearses Pond (Station #5), Bearses Pond sediment cores, and Bearses Pond Management Options

Date: March 22, 2016

I. Overview

Lake Wequaquet is the largest pond in the Town of Barnstable and the third largest on Cape Cod with a surface area of nearly 600 acres. The Lake has a number of connected basins, including Bearses Pond, Gooseberry Pond and the large Main Basin (Figure 1). The Town has pursued a number of active management initiatives for the lake, including a regular water quality monitoring program and aquatic plant control. Although water quality conditions in Bearses Pond have been a concern for a number of years, there has been growing concern over expansion of poor water quality into the main basin of the lake. These concerns were heightened during the summers of 2012 and 2013 by observations that suggested that the frequency of short-term algal blooms had increased.

During 2014, the Town asked scientists from the Coastal Systems Program at the School for Marine Science and Technology, University of Massachusetts Dartmouth (CSP-SMAST) to install continuous monitoring devices in the Main Basin and Bearses Pond. These devices were installed because past water quality data showed occasional low dissolved oxygen conditions deep in the main basin[1] and an increase in the frequency or duration of these conditions could be a cause of the increased frequency of algal blooms. Trend analysis of water clarity had showed significantly diminishing conditions over the last 10 years, which would also be consistent with more "particles" in the water from an increased frequency of noticeable algal blooms.[2] The 2014 monitoring showed regularly impaired and fluctuating conditions in Bearses Pond, but dissolved oxygen conditions in the Main Basin did not drop low enough to support substantial sediment phosphorus release and algal blooms.[3] Fluctuations in Bearses Pond conditions seemed to be related to weather conditions (*e.g.*, windy conditions keep the water column mixed and aerated and sediment demand in check). Review of historic weather conditions also suggested that warmer weather in 2012 may have played a significant role in the enhancement of algal blooms in the Main Basin.

Given the clear role of the sediments in creating the impaired conditions in Bearses Pond, both for oxygen uptake and phosphorus release, CSP-SMAST scientists were asked by the Town to collect sediment cores from the pond in the summer of 2015 to help evaluate management options. This effort was paired with another late summer installation of continuous monitoring devices to help evaluate whether year-to-year changes in weather conditions were a key factor in determining algal bloom frequency in the Main Basin. This technical memorandum summarizes the results these activities.

II. Water Quality Monitoring: Continuous and Snapshot Sampling

In order to monitor 2015 water quality conditions in Lake Wequaquet and Bearses Pond, CSP-SMAST staff installed four continuous monitoring devices (sondes) at shallow and deep locations in each basin similar to the same monitoring completed in 2014. The oxygen monitoring sites were located near historic water quality sites to allow direct comparison of the historical and recent oxygen data. The Lake Wequaquet sampling site was near the historical sampling station W2 and the Bearses Pond sampling site was near historical sampling station W5 (see Figure 1). Devices were installed on August 6, 2015 and removed on October 27, 2015; the 2014 installation was August 15 to October 7. Devices were programmed to record dissolved oxygen concentrations, temperature, and water depth every 15 minutes and chlorophyll every hour. The devices were set in pairs with the a shallow sensor set in the upper mixed layer deep enough to avoid impacts from boat wakes and a deep sensor set 1 m off the bottom. CSP-SMAST staff also collected temperature and dissolved oxygen profiles, a clarity reading, and water quality samples four times (5/28, 8/6, 10/6, and 10/27) during the monitoring period. Water quality samples were collected using the standard Cape Cod PALS sampling protocol. Samples were analyzed at the Coastal Systems Analytical Facility (SMAST) under QA/QC procedures approved by MassDEP and USEPA for PALS parameters plus ortho-phosphate.

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[1] Eichner, E. 2009. Lake Wequaquet Water Quality Assessment. Completed for the Town of Barnstable and the Cape Cod Commission. Coastal Systems Program, School of Marine Science and Technology, University of Massachusetts Dartmouth. 81 pp.

[2] Eichner, E. May, 2013. Technical Memorandum: Lake Wequaquet Water Quality Trend Analysis. To: Gail Maguire, Lake Wequaquet Protective Association. 9 pp.

[3] Eichner, E., B. Howes, and D. Schlezinger. February, 2015. Technical Memorandum: Lake Wequaquet Dissolved Oxygen Monitoring Program, August – October 2014. To: Rob Gatewood, Conservation Administrator, Town of Barnstable. Coastal Systems Program, School of Marine Science and Technology, University of Massachusetts Dartmouth. 24 p.

The shallow and deep sondes at the Bearses Pond station (W5) were set at average depths of 2.5 m and 4.6 m (2.5 m and 5 m in 2014). Both sondes recorded all four parameters throughout their deployment. During the recording period, each sonde recorded 7,873 readings of depth, temperature, and dissolved oxygen and 1,919 readings of chlorophyll-a concentration were recorded at the shallow station.

The shallow and deep sondes at the Main Basin station (W2) were set at average depths of 2.25 m and 7.9 m, which are roughly the same depths as in 2014 (2.7 m and 8 m in 2014). Both sondes recorded depth, temperature, and dissolved oxygen throughout their deployment, but only the shallow sonde reliably recorded chlorophyll-a concentrations. During the recording period, the shallow sonde recorded 7,873 readings of depth and temperature, 7,801 readings of dissolved oxygen, and 1,960 readings of chlorophyll-a concentration. The deep sonde recorded 7,081 readings of temperature and depth and 7,087 readings of dissolved oxygen.

II.A Monitoring Results (Temperature)

Temperature data collected during 2015 shows higher temperatures and greater differences between shallow and deep readings than during the summer than in 2014[4] (Figure 2). Maximum 2015 shallow temperature in Bearses Pond was 28.3°C, while the maximum shallow temperature in the Main Basin was 27.2°C. Corresponding temperatures in 2014 were 26.0°C and 24.8°C, respectively. Similar differences, although at slightly lower temperatures are seen in the deep readings. Comparison of the snapshot data shows that the 8/6 surface temperatures in both basins had the highest recorded August readings on record (back to 1986).

Shallow and deep temperatures in Bearses Pond were again higher than in the Main Basin, but the differences between the shallow and deep readings are greater in 2015 than in 2014. Bearses shallow August 2015 average temperature was 26.6°C, while the Main Basin averaged 25.8°C. Bearses deep August 2015 average temperature was 25.8°C, while the Main Basin averaged 23.7°C. Corresponding 2014 average surface temperatures and Bearses Pond deep were ~2°C cooler, but the Main Basin average was only 0.6°C cooler.

The resulting differences in shallow and deep temperatures result in much higher resistance to thermal mixing in the Main Basin than was measured in 2014 (Figure 3). During August 2015, the Main Basin had 2-3X higher resistance to thermal mixing than during the corresponding 2014 period. Readings show that the Main Basin was generally thermally stratified from early August (the installation of the devices) until early September. Bearses Pond experienced one significant period of strong resistance (~8 days in 2015) during both the 2014 and 2015 recordings, but generally had low resistance to thermal mixing. However, the duration of this stratification event is sufficient to cause concern for potential phosphorus release (see below).

II.B Monitoring Results (Dissolved Oxygen)

Review of dissolved oxygen (DO) data also shows significant changes from 2014[5] to 2015. Deep 2015 recordings in both basins are generally below the MassDEP minimum concentration

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[4] Eichner, E., B. Howes, and D. Schlezinger. February, 2015. Technical Memorandum: Lake Wequaquet Dissolved Oxygen Monitoring Program, August – October 2014.

[5] *Ibid*.

of 5 mg/L[6] throughout August (Figure 4). Average September readings increased, but the Main Basin average remained below the 5 mg/L regulatory minimum. The average August deep DO concentration in Bearses Pond was 3.96 mg/L, while the Main Basin average was 0.33 mg/L (*e.g.*, anoxic and sufficient to cause sediment phosphorus regeneration). The corresponding 2014 average concentrations were 6.44 mg/L and 7.73 mg/L, respectively. In September 2015, the Bearses Pond average increased to 5.74 mg/L with 20% of the readings below the MassDEP minimum, while in the Main Basin, the average was 4.44 mg/L with 49% of the readings below the MassDEP minimum. Deep readings in Bearses Pond also did not experience significant fluctuations that were recorded in 2014. Deep readings from both basins converged toward similar concentrations in mid-September; this did not happen in 2014, where Bearses Pond concentrations remained higher than Main Basin concentrations until the devices were removed in early October.

Shallow readings were also different from year to year. Bearses Pond shallow August 2015 DO readings were generally ~2 mg/L less than corresponding 2014 readings, some of which is due to lower oxygen solubility and some due to likely increased oxygen uptake associated with the blooms. The number of shallow readings in the Main Basin was only substantial in 2015; the DO probe stopped recording after 128 readings in the 2014 deployment. All shallow concentrations were greater than the MassDEP minimum throughout the 2015 sonde deployment period. It should be noted that the August 6 snapshot surface dissolved oxygen was the lowest recorded among all the August available readings back to 1986; likely due to the exceptionally high temperature readings.

Review of DO saturation levels generally mirrored the dissolved oxygen concentrations, but Main Basin 2015 levels were substantially greater than atmospheric saturation (>100%) from mid-August through mid-September (Figure 5). From August 27 to September 10, DO saturation levels in the Main Basin average greater than 120% of atmospheric saturation. Readings this high can only be sustained by a substantial phytoplankton community. Surface saturation levels in Bearses Pond were consistently in the 90-92% range.

II.C Monitoring Results (Chlorophyll-*a*)

Review of chlorophyll-*a* data generally showed similar readings in both 2014[7] and 2015 in Bearses Pond, but the longer 2015 deployment had some notable results. Readings in the Main Basin were notably lower in August 2015, but generally matched 2014 September readings before increasing in October (Figure 6). In Bearses Pond, shallow readings in 2014 generally fluctuated around 2 μg/L throughout the recording period. Similar readings occurred in 2015, but then began to rise in late August, increased significantly in early October to readings in an 8 to 12 μg/L range, and then rose again in late October; the devices were removed in early October 2014. Deep readings in Bearses Pond in 2015 followed a similar pattern to 2014 with regular periods of 5 to 7 days where concentrations were 8-10 μg/L followed by a drop to ~2 μg/L for a similar period. These readings also increased significantly in early October and generally matched the shallow readings until late October when shallow readings increased substantially and deep readings decreased substantially.

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[6] 314 CMR 4.05(3)(b); CMR = Code of Massachusetts Regulations

[7] Eichner, E., B. Howes, and D. Schlezinger. February, 2015. Technical Memorandum: Lake Wequaquet Dissolved Oxygen Monitoring Program, August – October 2014.

In the Main Basin, chlorophyll-a concentrations also showed significant changes from 2014 to 2015. In 2014, shallow chlorophyll-a concentrations had an average deployment concentration of 5.7 µg/L with August, September, and October averages of 5.9, 5.4, and 6.3 µg/L, respectively. In 2015, the respective monthly averages were 1.5, 4.3, and 5.4 µg/L with a deployment average of 3.8 µg/L. Given that the shallow DO concentrations in August 2015 were elevated, averaging 112% of air equilibration, it suggests that excessive rooted plants may play a more important role in the Main Basin than previously thought. The increase of chlorophyll-a concentrations in September and October suggest that phytoplankton were more dominant during these periods, perhaps due to shading and/or senescence of the rooted plants. The failure of the deep chlorophyll-a sensor in 2015 does not allow comparison with the shallow readings; during 2014, deep readings began to increase in mid-September, though not as rapidly as the shallow readings. The August 6 snapshot shallow sample had the lowest summer chlorophyll-a recorded at the Main Basin sampling site.

III. Bearses Pond Sediment Core Sampling Results

In the 2014 Technical Memorandum, CSP-SMAST staff reviewed the collected data, including a comparison to past historic data, including PALS Snapshot data, the 2009 Water Quality Assessment,[8] the 2011 Technical Memorandum,[9] and the 1989 Diagnostic/Feasibility Study.[10] This review noted that water quality conditions in Bearses Pond are consistently impaired and that sediment regeneration of phosphorus plays an important role in creating the impaired conditions. CSP-SMAST recommended that the town consider collecting and incubating sediment cores in Bearses Pond as the next step in an adaptive management strategy to further refine the understanding of the pond ecosystem and potential strategies to restore its water quality.

Working with the town, CSP-SMAST collected 8 cores from the pond on May 28, 2015 along with accompanying water quality samples from the pond water column. Core locations were selected based on the bottom topography, spatial coverage, sediment thickness information,[11] and extent of past hypoxic water column conditions (Figure 7). These undisturbed sediment cores were collected by SCUBA diver and were incubated at *in situ* temperatures to evaluate nutrient regeneration from the sediments under oxic and anoxic conditions. Sampling was targeted for early in the summer with the hope of avoiding significant anoxia and accompanying phosphorus release to the water column prior to core collection. Dissolved oxygen concentrations were all high enough at the time core collection to avoid significant chemical release (*i.e.,* deepest DO at 5 m was 7.1 mg/L).

Observations during the collection of the sediment cores noted that most of the collection locations had sediments of fluid, soft mud, although in two locations this layer was relatively

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[8] Eichner, E. 2009. Lake Wequaquet Water Quality Assessment.

[9] Eichner, E. and B. Howes. March 2011. Technical Memorandum: Lake Wequaquet 2010 water quality monitoring. To: Rob Gatewood, Conservation Administrator, Town of Barnstable. Coastal Systems Program, School of Marine Science and Technology, University of Massachusetts Dartmouth. 11 p.

[10] IEP, Inc. and K-V Associates. 1989. Diagnostic/Feasibility Study of Wequaquet Lake, Bearses, and Long Pond. Prepared for Town of Barnstable, Conservation Commission. Sandwich and Falmouth, MA.

[11] Woods Hole Group. 2013. Wequaquet Lake Profiling and Phosphorus Management Planning. East Falmouth, MA.

thin (Table 1). Observation of submerged aquatic vegetation was noted at four of the locations with the most extensive coverage (90%) at BP5. Samples were collected at depths ranging from 2.7 to 6 m. The predominance of floccy, fluid mud at all sediment locations is consistent with previous fine grained sediment mapping in Bearses Pond.[12] This type of material in Cape Cod kettle ponds is predominantly due to deposition and breakdown of phytoplankton.

During the collection of sediment cores, standard handling, incubation, and sampling procedures were followed based on the methods of Jorgensen (1977), Klump and Martens (1983), and Howes (1998). During the core incubations, water samples were withdrawn periodically (n=6 to 15) and chemical constituents were assayed. Rates of sediment nutrient release/uptake were determined from linear regression of analyte concentrations through time. Cores are incubated to first sustain aerobic conditions, matching conditions when oxygen conditions are near atmospheric equilibrium throughout the water column (*i.e.,* when the cores were collected). Dissolved oxygen is then removed and sediment conditions move through a redox sequence that begins with chemical release (severing of weak chemical bonds, usually iron-phosphorus bonds) and ends with anoxia, similar to water column conditions where dissolved oxygen concentrations are less than 1 mg/L. In this way, the core incubation follows the dissolved oxygen conditions that occur in Bearses Pond and these measurements can be directly compared to conditions observed in the pond.

Determination of sediment flux needs to consider both a)_the nutrients released from the sediments and b) the nutrients returned to the sediments as particulates (mostly phytoplankton) settle out of the water column and back to the sediments. The balance between these two processes determines the net sediment flux. Under aerobic conditions, the negative rates for phosphorus in all cores in Table 2 indicate that when the water overlying the sediments has sufficient dissolved oxygen, the sediments collect phosphorus. This results in part from a chemical sorption of ortho-phosphate onto oxidized iron minerals. Since the sediment oxygen demand measurements were relatively consistent among the cores, this suggests that the rates of aerobic phosphorus flux could reasonably be averaged (mean = -12 µMoles/m2/d). If this rate is applied to the estimated 80% of the pond bottom covered by the fine grained sediments,[13] the rate of phosphorus addition to the sediments was a bit less than as the rate of phosphorus addition to the pond from its watershed[14] (0.08 kg/d into the sediments and 0.1 kg/d from the watershed). When estimated deposition of phosphorus from the water column was considered, the net phosphorus flux into the sediments under aerobic conditions was comparatively large (1.0 kg/d). These measurements help to explain the large amount of soft mud that covers the bottom of Bearses Pond.

When hypoxic conditions initially occur and transition to anaerobic conditions, weakly-bound phosphorus is released from the sediments and back into the overlying water. In Bearses Pond this chemical release flux out of the sediments was substantially greater than aerobic flux (mean = +37 µMoles/m2/d or 0.24 kg/d; 3X the aerobic flux into the sediments). This regeneration has been regularly confirmed in summer water quality sample results showing much higher TP concentrations deep in the pond compared to shallow concentrations (*e.g*., 8/6 TP

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[12] *Ibid*.

[13] *Ibid*.

[14] Eichner, E. 2009. Lake Wequaquet Water Quality Assessment.

concentrations). When this flux rate was balanced with the estimated deposition of phosphorus from the water column, the net release from the sediments under chemical release conditions was 0.3 kg/d added to the water column. Estimates of total phosphorus mass in the pond based on snapshot water quality measurements generally showed that this flux rate was a reasonable functional measurement.

As all the weakly-bound phosphorus is released, decomposition of organic materials (*e.g.*, remainders of phytoplankton) becomes the predominant source of energy and chemical components for growth for sediment bacteria. This flux in Bearses Pond was roughly equivalent to the aerobic flux but out of the sediments rather than adding to them (mean = +14 µMoles/m2/d or 0.09 kg/d). For most of the cores, phosphorus release during this phase was exhausted following a month of incubation (*e.g.*, 30 days), but the core from BP7 (in the northeast section of the pond at a depth of 4 m) was still releasing phosphorus after 74 days of incubation. Since most of the anoxic events in Bearses Pond tend to be transitory (1-2 days), it is likely that the majority of the phosphorus that could be released during this phase remains within the sediments and is not extensively cycled into the water column. When this flux rate was balanced with the estimated deposition of phosphorus from the water column, the net flux rate phosphorus under anaerobic conditions was into the sediments (-0.3 kg/d).

Collectively, the sediment core collection and incubation data indicated that the initial onset of anoxia releases a large mass of phosphorus from the sediments, while aerobic and anaerobic conditions favor phosphorus deposition to the sediments. Since the continuous monitoring shows that large scale anoxic conditions within a meter of the sediments tend to be relatively infrequent, but hypoxic conditions are pervasive, it suggests that anoxia in the Bearses Pond sediments likely occurs frequently enough to have significant releases over the course of a summer. However, the large net aerobic flux (>3X the chemical release) means that once sufficient oxygen is added, the sediments will relatively quickly remove any phosphorus added during the anoxic/hypoxic periods. These relationships also help to explain the extensive fine grained sediment in the pond, which is likely due to frequent reworking of the sediments as they transition between the different oxic states.

IV. Discussion of Monitoring

The continuous readings and the snapshot sample results show that the Main Basin in Lake Wequaquet and, to a lesser extent, Bearses Pond have varying water quality results from year to year and these varying conditions will determine the extent of water quality impairment. In 2014, continuous readings in the Main Basin did not show low/anoxic dissolved oxygen concentrations that would allow sediment regeneration of phosphorus and provide a likely explanation for the algal blooms that occurred so frequently in 2012 and 2013. However, during the 2015 continuous DO reading deployment, the Main Basin showed persistent deep anoxia (<1 mg/L DO) throughout August and ~50% of the readings below the MassDEP regulatory minimum of 5 mg/L during September (see Figure 4). Snapshot results from August 6 confirmed high total phosphorus concentrations indicative of sediment phosphorus regeneration and surface concentrations exceeding regional TP standards: shallow >3X and deep >13X the Cape Cod ecoregion standard (Appendix A).

These water quality changes suggest that there factors outside of the pond that can play a significant role in determining the water quality conditions in the Main Basin from year-to-year, month-to-month, and day-to-day. Project staff has reviewed a number of annual/seasonal factors including groundwater levels and precipitation, but the factor most closely associated with the worst water quality conditions is pond water column temperatures. Review of previous weather conditions in the 2014 monitoring technical memo showed that 2014 summer water column temperatures were colder than any other snapshot readings during 2001 to 2012.[15] On the other hand, 2015 water column temperatures were the highest recorded August readings available for the Main Basin. Higher temperature water has a lower capacity for holding dissolved oxygen, supports higher rates of biological oxygen uptake, and these high temperatures also likely played a significant role in the rise in resistance to thermal mixing in the Main Basin. The relative isolation of bottom waters and the lack of atmospheric replenishment of the sediment oxygen demand would create the anoxia that was measured in 2015. This finding suggests that water temperature is an important factor to consider when trying to anticipate what water quality conditions are likely to be in the Main Basin during summer seasons.

Readings in 2015 also noted that characteristics of the pond ecosystem, specifically the balance between phytoplankton and rooted plants are important to consider too. During August 2015, dissolved oxygen levels in the Main Basin exceeded atmospheric balance (>100%), but surface chlorophyll-a concentrations were less than ecoregion levels. By September, chlorophyll-a concentrations had risen to levels 3-4X the Cape Cod ecoregion standard and was generally consistent with those measured in 2014. The August 2015 readings suggest rooted plants may have been the more dominant plant community in the Main Basin ecosystem, but that this balance shifted to favor phytoplankton in September and October. It is unclear what is driving this transition between these responses, but comparison of 2014 and 2015 readings suggest that it is not a water clarity issue, but the change between August and September 2015 suggests that it may also be a temperature-related issue.

Bearses Pond 2015 readings also indicate increased impairment, likely due to the rise in water column temperature, but its shallower depth creates less resistance to thermal mixing and allows some of the oxygen demand to be attenuated by atmospheric replenishment. Deep dissolved oxygen readings were consistently below MassDEP regulatory minimum: 96% of August readings were below the 5 mg/L standard in 2015, while 29% were less than the standard in 2014. However, concentrations at the deep sonde device did not become anoxic in either year and shallow dissolved oxygen saturation levels were generally near 100% in both years (105% average in 2014, 92% average in 2015). Resistance to the thermal mixing between the two sonde depths generally was not sufficient to resist water column mixing except for an ~8 day period in late August 2015; a similar stratification occurred in early September in 2014. Just like the Main Basin, Bearses Pond had relatively low surface chlorophyll-a concentrations during August with a subsequent rise in September and an even larger rise in October. Snapshot total phosphorus results from August 6 were generally consistent with past snapshot data indicating contributions from sediment phosphorus regeneration: shallow >2X and deep >4X the Cape Cod ecoregion TP standard (Appendix A).

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[15] Eichner, E., B. Howes, and D. Schlezinger. February, 2015. Technical Memorandum: Lake Wequaquet Dissolved Oxygen Monitoring Program, August – October 2014.

V. Discussion of Bearses Pond Management Options

CSP-SMAST staff noted in the 2014 Technical Memorandum that Bearses Pond was impaired based on the comparison to MassDEP regulatory standards and Cape Cod ecoregion standards. Staff also noted that conditions in the Main Basin were not as impaired and recommended that the Town approach restoration in the overall Lake Wequaquet system within an adaptive management framework with stepwise restoration activities, accompanying monitoring, and subsequent review and adjustment of future restoration/management activities based on monitoring results. Staff further recommended that the Town pursue collection and incubation of sediment cores in Bearses Pond as a first step toward reviewing water quality management options for Bearses Pond and its relationship to the rest of the Lake Wequaquet system.

The 2015 data collection revealed that Bearses Pond summer conditions are relatively consistent with regular bottom hypoxia, high chlorophyll concentrations, and release of phosphorus from the sediments. The 2015 data also showed that the Main Basin can experience the same anoxic and high chlorophyll conditions, but they do not occur every summer, but likely occurred in 2012-2013. Sediment cores have not yet been collected from the Main Basin.

Review of available water quality results show that both Bearses Pond and the Main Basin are phosphorus-limited, such that additions of phosphorus stimulate plant growth. Therefore, reduction of phosphorus within the system will improve water quality. Comparison of relative phosphorus contributions to Bearses Pond show that during the summer the sediments are the predominant source of phosphorus within the pond and the core incubation information showed that the sediment release is predominantly related to the rapid chemical release phase (*i.e.*, breaking of Fe-P bonds).

Since the ultimate source of the sediment phosphorus are watershed sources, management of watershed loads needs to be considered in the long run, but reducing the sediment source will provide immediate improvement while watershed options are considered. Typical watershed phosphorus reductions include: sewering, moving septic system leachfields further from the pond, restricting lawn areas, restricting lawn fertilizers, and removing direct stormwater discharges. Evaluating each of these options and their potential costs would need to be addressed in detailed land use assessment that included location and distance to the pond of existing septic system leachfields, location and measurement of stormwater loads from direct stormwater discharge around the pond, and an evaluation and assessment of lawn sizes and fertilizer practices for pond-adjacent properties. This effort could build on the previous work that addressed some of these components (*e.g.*, Tighe and Bond, 2003).

Addressing the internal phosphorus loads is a common issue in lake water quality management. There is a large potential phosphorus pool in the sediments of most ponds, but much of it is only mobilized if low oxygen conditions occur. Typical management options to limit the phosphorus regeneration from the sediments generally fall into two categories: a) adding more oxygen near the sediments or b) adding chemicals to prevent release from the sediments. Dredging to remove the sediments is another option, but is usually ruled out as being too expensive.

Techniques for adding oxygen typically involve either adding air directly or moving water within the pond to address the sediment oxygen demand. These types of approaches require a commitment to operate forever to ensure phosphorus remains in the sediments. Adding air is called aeration and generally includes a diffuser of some sort installed on or near the pond bottom that adds air or oxygen from shoreline-based pumps. Other artificial circulation techniques include downdraft or updraft pumping, which use pumps to exchange surface or bottom waters, respectively, in order to bring higher oxygen waters down to the sediments. Details to consider in the review of these approaches include whether pumps need to be operated all year, electricity costs, depth and type of aeration. Past issues in design of these approaches have included ensuring that phosphorus-rich bottom waters are not transferred to the phytoplankton populations near the surface, noise issues associated with siting of pumps, land costs for compressor siting, functional efficiency, and whether seasonal stratification patterns will be adversely impacted. Median cost values for aeration systems in the MassDEP Pond Management FGEIR are: $1,800/acre for capital costs and $135 /acre for annual operational costs.[16] Based on these estimates, preliminary planning costs for a traditional aeration system in Bearses Pond would be $118,800 for capital costs and nearly $9,000 per year for operational costs. Updraft circulators (*e.g.*, Solar Bees) bring deep water to the surface and typically cost $50,000 per unit with $5,000 per year maintenance. Recent concerns have been raised about the efficiency/area of influence of these units, which could impact the number of units required.[17] Original costing estimates assumed 35 acre coverage, while more recent evaluations suggest effective mixing zones of 1 to 5 acres. At 35 acre coverage, two units at a capital cost of $100,000 would be necessary in Bearses Pond, while 5 acre coverage would require 14 units at a capital cost of $700,000. Additional costs for either approach would also be incurred for permitting and annual monitoring/reporting. Review of detailed comparison is beyond the scope for this project, but these details should include: review of various aeration/circulation approaches, how various approaches fit within the Bearses Pond system and neighborhood goals, approach-specific costing, and determination of 10 year cost of operation.

Sediment phosphorus inactivation through chemical addition is typically attained by adding salts of aluminum, iron, or calcium that chemically bind with the phosphorus, form solid precipitates that sink to the bottom of the pond and form a barrier to phosphorus release at the sediment surface. Alum is usually the optimal choice in anoxic/low pH settings because its phosphorus precipitates/solids are not sensitive to solubilizing in low oxygen or the low pH conditions typically found in Cape Cod ponds. Three Barnstable ponds have had alum treatments: Hamblin Pond, Mystic Lake, and Lovell's Pond. Alum applications generally work for 10 or more years with length of time dependent on the features of the pond, the application process and dose, and the control of external watershed loads. Aluminum sulfate and sodium aluminate are generally used in a 2:1 mix to buffer pH reductions that would occur if only aluminum sulfate was used. Cape Cod ponds are particularly susceptible to pH reductions because of low initial pH and minimal alkalinity available for buffering. Based on the data from the sediment cores, the approximate cost for an alum treatment for Bearses Pond would be $20,000. Review of detailed

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[16] Massachusetts Department of Environmental Protection and Department of Conservation and Recreation. 2004. Eutrophication and Aquatic Plant Management in Massachusetts, Final Generic Environmental Impact Report. Executive Office of Environmental Affairs, Commonwealth of Massachusetts. 514 pp.

[17] Schafran, G., Engebrigtsen, P., Yoon, J., Sherman, B. and J.C. Brown. 2007. Influence of surface circulators on reservoirs/lake water composition: observations and theoretical considerations. Presentation at National NALMS Conference. Orlando, FL.

assessment is beyond the scope for this project, but these details should include: refined review of the treatment area, calculation of permitting and monitoring costs, and assessment of potential Natural Heritage issues (*e.g.*, endangered mussel species), and determination of 10 year cost of operation.

VI. Conclusions and Recommendations

The collected data from past years and the 2015 monitoring show that Bearses Pond is consistently impaired by low oxygen, high chlorophyll-a and high total phosphorus conditions, while the Main Basin generally also has high chlorophyll-a and total phosphorus levels, but only occasional summers of significantly impaired low oxygen conditions. Monitoring indicates that the Main Basin conditions will be the worst when water column temperatures are higher than average. Results from this summer show that both basins will require some management activities to ensure acceptable water quality.

Past assessments show that water quality in the Main Basin is likely influenced by conditions in Bearses Pond.[18] In the 2014 Technical Memorandum, CSP-SMAST staff suggested that the Town consider water quality management in Bearses Pond accompanied by monitoring in the Main Basin to better understand Bearses Pond influences and begin to restore the clearly impaired Bearses Pond. The 2015 sediment core collection and incubation in Bearses Pond completed in this project clearly indicates that the sediments are a significant phosphorus source and that the magnitude of their influence is based largely on dissolved oxygen conditions. A preliminary review of potential options to either improve oxygen conditions (*e.g.*, aeration) or suppress phosphorus regeneration (*e.g.*, alum treatment) indicated that an alum treatment is the likely lowest cost option. Further review of options, their associated costs, and community acceptance is recommended as a next step. Whatever option is selected for Bearses Pond should be accompanied by continuing monitoring in both basins so that management strategies for the Main Basin can then be developed. CSP-SMAST is available to assist the town in these efforts.

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[18] *e.g.*, Eichner, E. 2009. Lake Wequaquet Water Quality Assessment.

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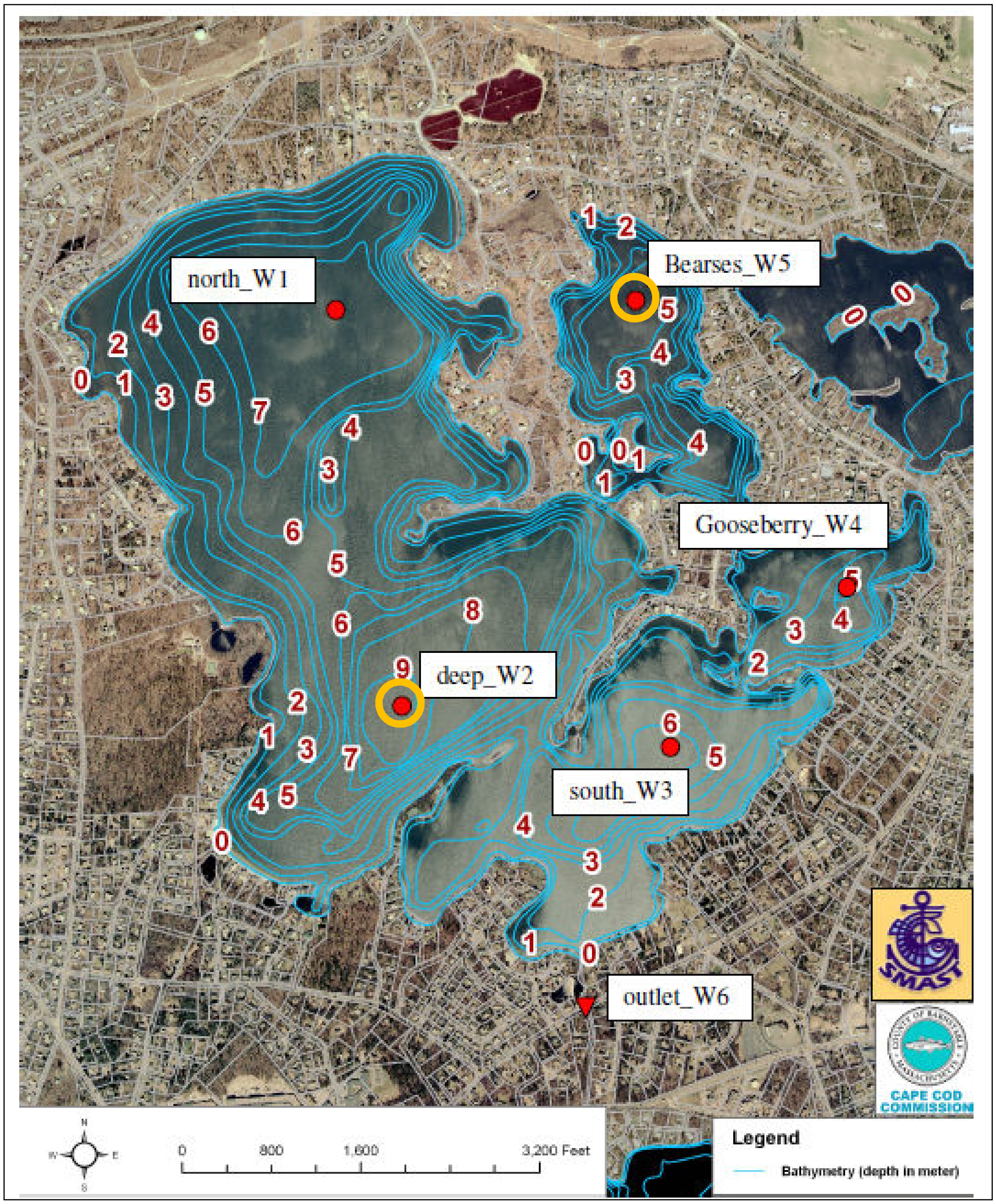

Figure 1. Time-Series Oxygen & Chlorophyll Monitoring Stations in Lake Wequaquet. Continuous sampling devices were installed near W2 and W5 (orange circles). During 2015, these devices recorded dissolved oxygen concentrations, temperature, and water depth every 15 minutes and chlorophyll every hour between August 6 and October 27. A similar installation in 2014 occurred between August 15 to October 7.Modified from Figure II-1 from Lake Wequaquet Water Quality Assessment (Eichner, 2008).

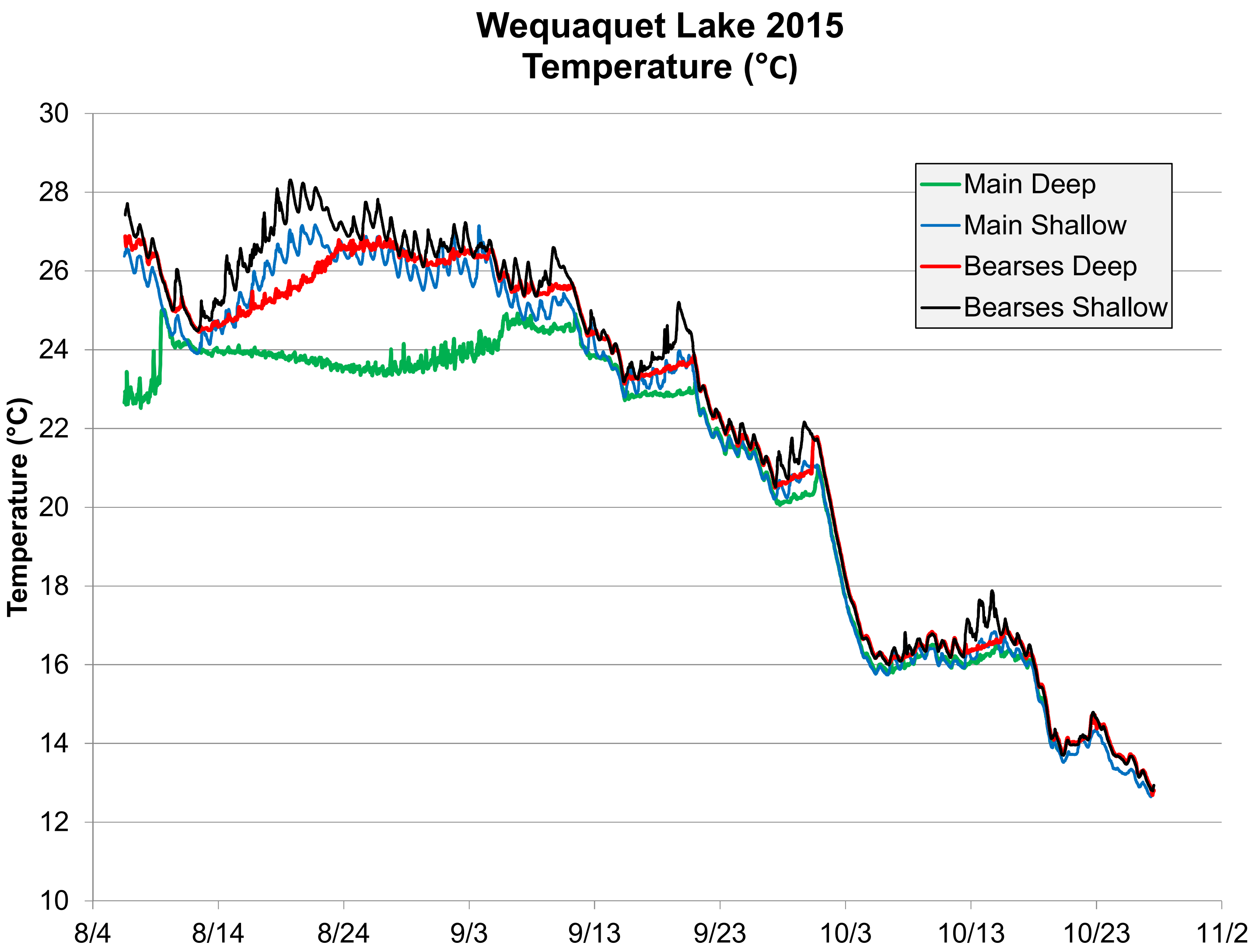

Figure 2. Lake Wequaquet 2015 Temperature Readings: Continuous Records in Main Basin and Bearses Pond. Recordings were collected between August 6 and October 27. The shallow and deep sondes at the Bearses Pond station (W5) were set at average depths of 2.5 m and 4.6 m, while the corresponding sondes at the Main Basin station (W2) were set at average depths of 2.25 m and 7.9 m. Readings show some shallow and deep temperature separation until early September; separation is greatest in the Main Basin.

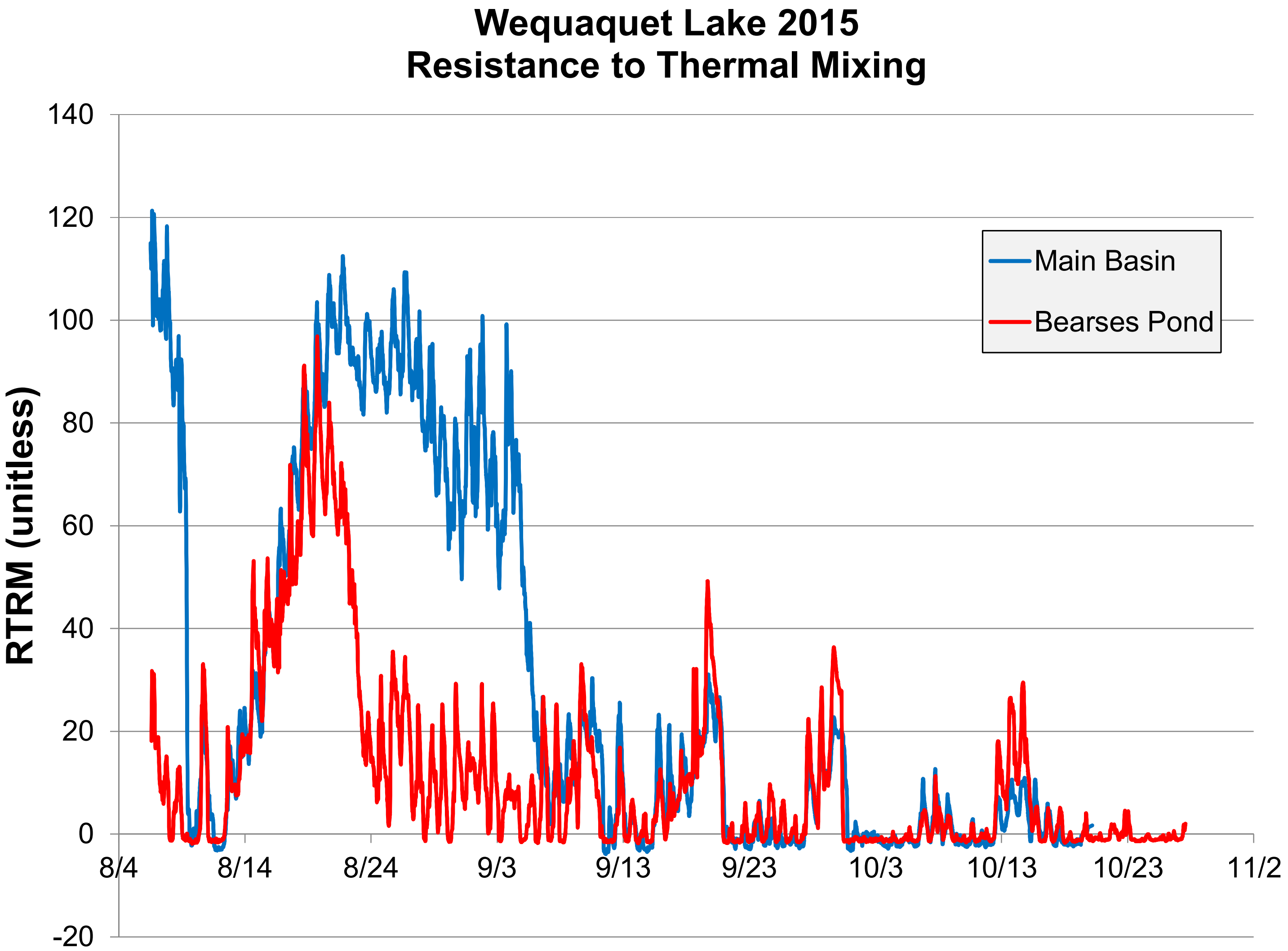

Figure 3. 2015 Relative Resistance to Thermal Mixing in Lake Wequaquet: Main Basin and Bearses Pond. Main Basin generally had high RRTM until early September, while Bearses Pond generally had low RRTM with brief periods (1-2 days) exceeding the RRTM threshold of 30 generally associated with temperature stratification and a more significant ~8 day period in mid-August.

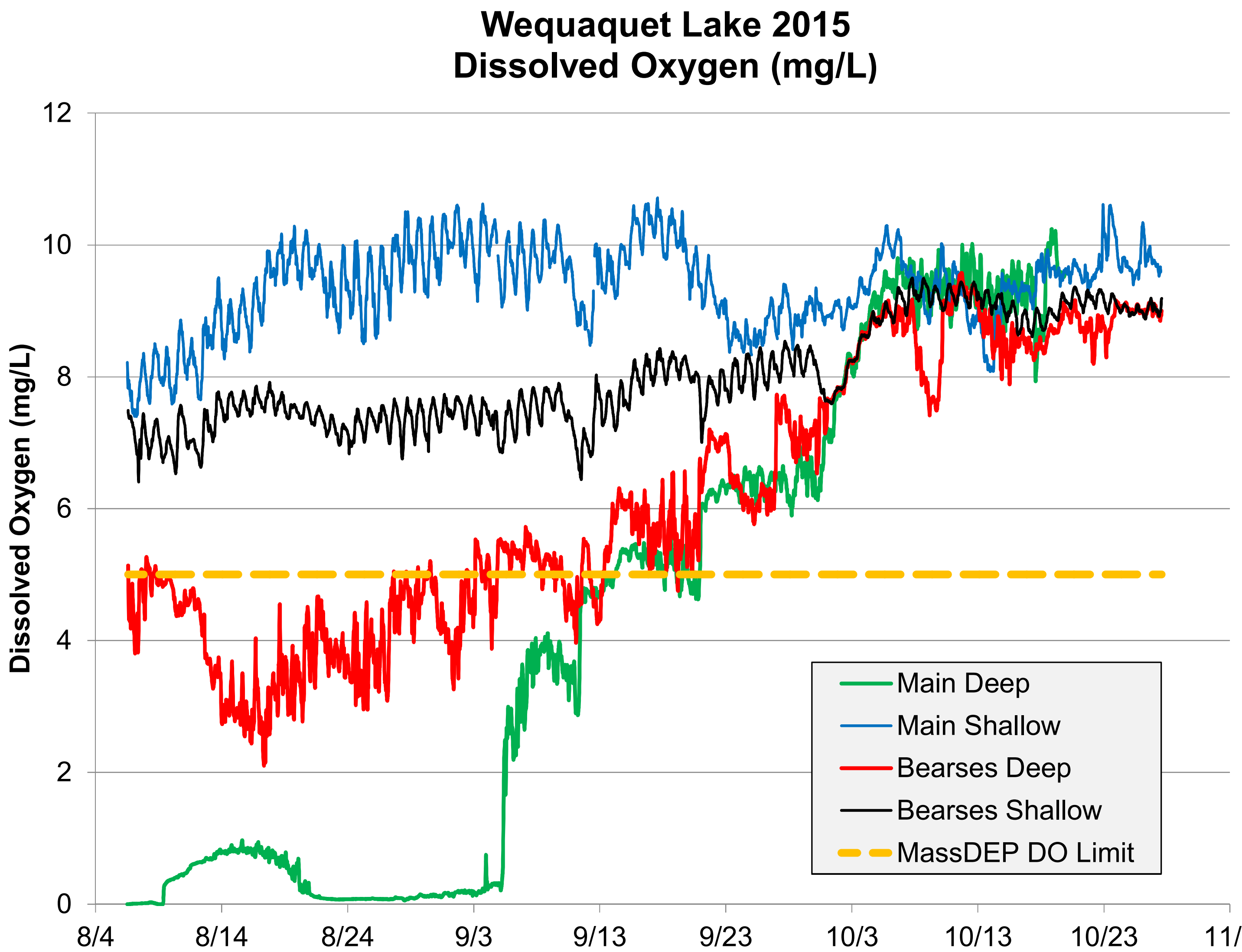

Figure 4. Lake Wequaquet 2015 Dissolved Oxygen Readings: Continuous Records in Main Basin and Bearses Pond. Recordings were collected between August 6 and October 27. Deep recordings in both basins (Bearses 4.6 m; Main 7.9 m) were generally below the MassDEP regulatory minimum of 5 mg/L until early September. Readings in the Main Basin were also generally anoxic and sufficiently prolonged to produce chemical phosphorus release from associated bottom sediments.

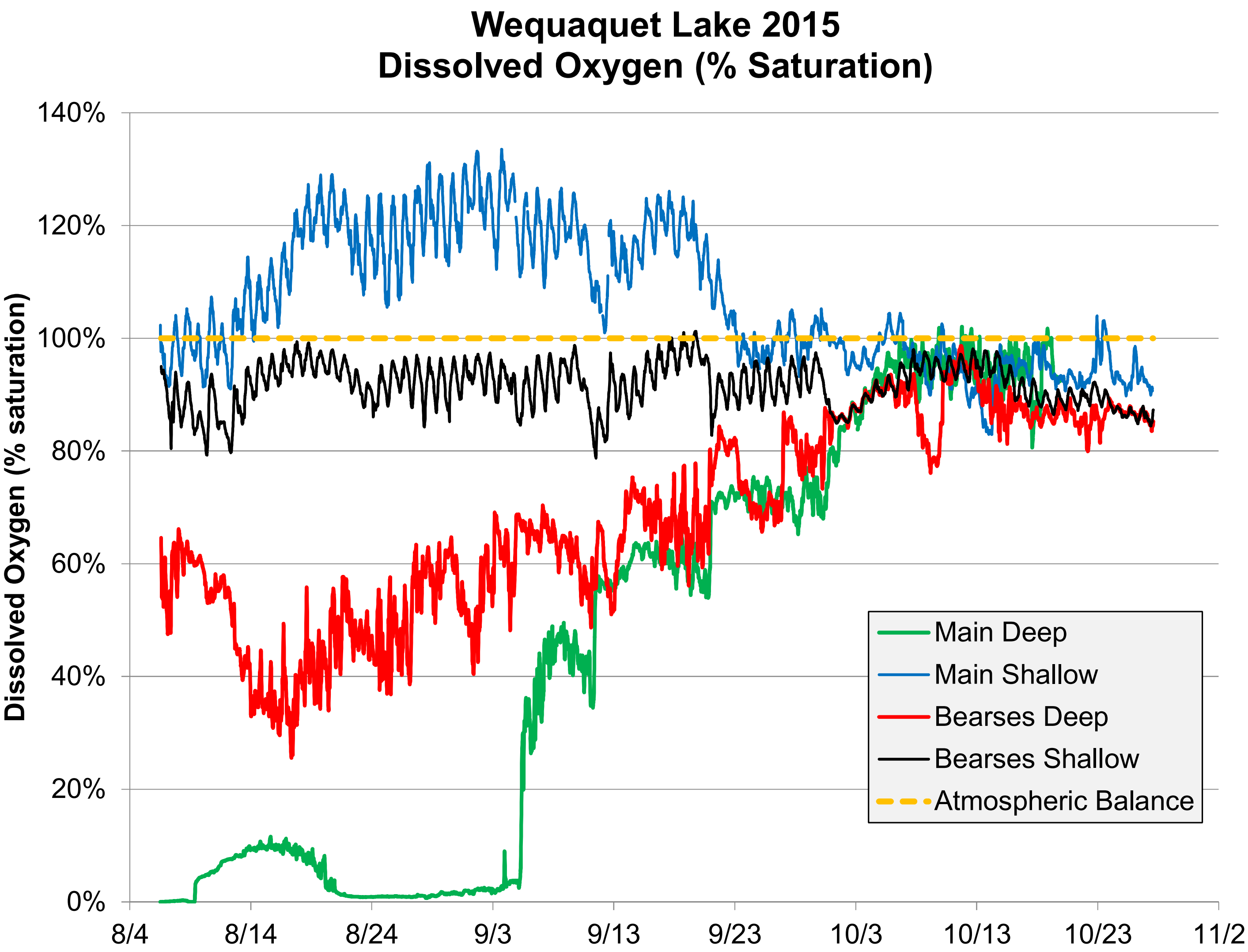

Figure 5. Lake Wequaquet 2015 DO Saturation Readings: Continuous Records in Main Basin and Bearses Pond. Recordings were collected between August 6 and October 27, 2015. Shallow readings in the Main Basin were notably above atmospheric balance from mid-August to late September. These types of conditions are generally indicative of a significant phytoplankton population. Shallow readings in Bearses Pond were generally consistent, but slightly depressed throughout the continuous recording period.

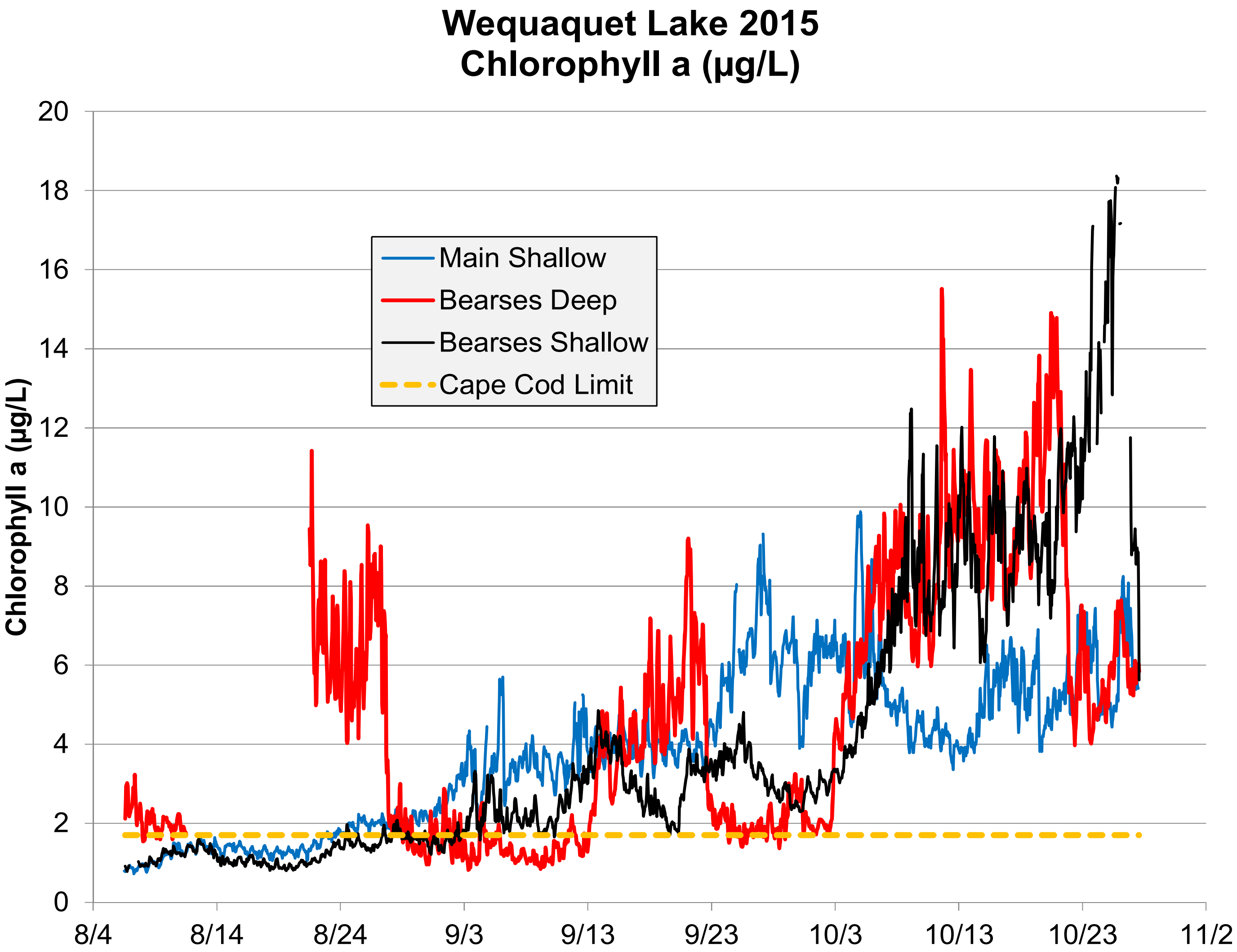

Figure 6. Lake Wequaquet 2015 Water-column Chlorophyll Readings: Continuous Records in Main Basin and Bearses Pond. Recordings were collected between August 6 and October 27, 2015. Shallow readings in both basins were notably low in August before rising above the Cape Cod ecoregion standard in September and nearly doubling again in October. Readings suggest that rooted plants were outcompeting phytoplankton in August and then reversed in September. Water-column was vertically well mixed in both basins from the last week in September to November.

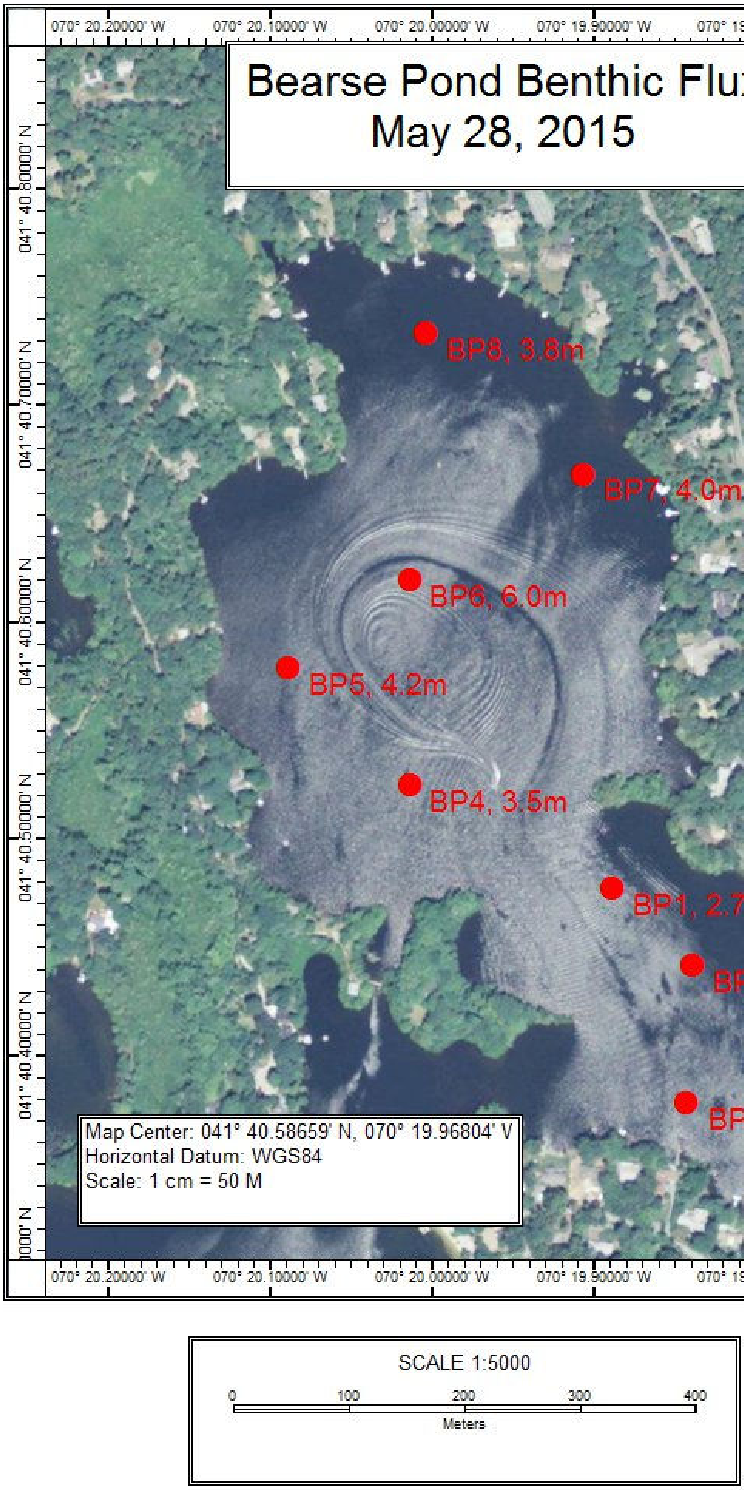

Figure 7. Sediment Core Collection Sites in Bearses Pond. CSP-SMAST staff collected intact undisturbed cores from 8 locations on May 28, 2015. Cores were collected by SCUBA diver and were incubated at *in situ* temperatures to evaluate nutrient regeneration from the sediments under oxic and anoxic conditions using standard CSP-SMAST procedures.

Table 1. Bearses Pond Sediment Core Site Observations (May 28, 2015).
Cores were collected by SCUBA diver. Observations noted during the collection of cores.

Core site	Latitude	Longitude	Collection Depth (m)	Sediment Description (field observation)	Aquatic Vegetation (field observation)	Fauna (field observation)
BP1	41 40.364	70 19.785	2.7	Fluid mud with floc layer over medium coarse sand		Rocks, mussel shell hash
BP2	41 40.378	70 19.842	4.8	Fluid mud with floc		
BP3	41 40.477	70 19.888	3.6	Fluid mud with floc with rocks surrounding	40% coverage	Burrows, rocks surrounding
BP4	41 40.525	70 20.014	3.5	Fluid mud with floc	20% coverage	
BP5	41 40.599	70 20.089	4.2	Fluid mud	90% coverage	
BP6	41 40.62	70 20.014	6	Fluid mud with floc		
BP7	41 40.669	70 19.906	4	Fluid mud layer over medium coarse sand	Small 2-3 inch branched	Catfish, burrows
BP8	41 40.734	70 20.004	3.8	Very soft fluid mud, mottled surface		

Table 2. Bearses Pond Nutrient Release from Undisturbed Sediments.

Undisturbed intact sediment cores were collected at eight sites in Bearses Pond on May 28, 2015. Cores were incubated at water temperatures at the time of core collection. Cores were incubated to measure nutrient release under both aerobic and anaerobic conditions with particular focus on the anaerobic, chemical release phase. Sediment release rates presented below represent averages of multiple (6-15) samples during each incubation phases. Note that cores were collected at different depths and sites to allow determination of spatially distributed rates (*i.e.,* are not replicates), which is reflected in the observed rates. Cores took approximately 3 days to reach anoxic conditions following aerobic incubation and were incubated anaerobically for a total of 74 days. Cores had significant reserves of iron (400 to 750 µMoles/m2), which may explain why deep phosphorus concentrations drop so significantly in the October 2015 samples. Core BP6 developed a leak during the anaerobic phase of incubation allowing air to enter and creating erratic results. Phosphorus release from core from BP7 did not decrease before the end of the 74th day suggesting that chemical release was still occurring. Due to these events, chemical release and anaerobic release in BP6 and BP7 should be carefully considered.

Sediment Sample Site	Water Depth	Bulk Density	Sediment Oxygen Demand	Aerobic Flux Rate		Chemical Release	Anaerobic Flux Rate
				Ammonium	Phosphorus	Total P	Phosphorus
	M	g/cm^3	mM/m^2/d	all rates in µMoles/m^2/d		µMoles/m^2/d	µMoles/m^2/d
BP1	2.7	1.13	23.5	914	-23	34	4
BP2	4.8	0.06	27.4	1,318	-17	25	15
BP3	3.6	0.06	37.1	1,625	-14	47	14
BP4	3.5	0.05	20.8	1,160	-4	44	20
BP5	4.2	0.06	33.0	1,205	-15	33	16
BP6	6	0.02	17.2	894	-8	ND	-38 [19]
BP7	4	0.07	24.4	1,259	-10	ND	29
BP8	3.8	0.09	35.7	985	-3	37	13

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[19] Phosphorus uptake by surficial sediments is common under aerobic conditions, such as in the headspace water over a core that was anaerobic and then aerobic.

Appendix A. 2015 Lake Wequaquet Water Quality Sample Results. All analysis completed at the Coastal Systems Analytical Facility Laboratory (SMAST). NS = No Sample; ND = No Data

POND	SAMPLE ID	Depth (M)	Date	Number of Samples	Total Depth (M)	Secchi Depth (M)	% Secchi	Weather	Wind	DO (mg/L)	Temp C	pH	Alk (mg CaCO3/L)	Chla (ug/L)	Phaeo (ug/L)	TP (uM)	TN (uM)
Lake Weqauquet	W2	0.15	8/6/2015	3	9.5	2.55		ND	ND	4.56	26.5	6.93	17.4	0.18	0.88	1.12	28.83
Lake Weqauquet	W2	1	8/6/2015							7.48	26.6	NS	NS	NS	NS	NS	NS
Lake Weqauquet	W2	2	8/6/2015							7.44	26.5	NS	NS	NS	NS	NS	NS
Lake Weqauquet	W2	3	8/6/2015							7.45	26.4	9.97	17.1	0.27	1.18	1.19	35.14
Lake Weqauquet	W2	B	8/6/2015							ND	ND	6.48	30.7	0.48	4.12	4.41	59.05
Lake Weqauquet	W5	0.15	8/6/2015	3	5.92	2.75		ND	ND	7.49	27.8	6.97	16.4	0.23	0.98	0.72	40.29
Lake Weqauquet	W5	1	8/6/2015							7.46	27.8	NS	NS	NS	NS	NS	NS
Lake Weqauquet	W5	2	8/6/2015							7.44	27.4	NS	NS	NS	NS	NS	NS
Lake Weqauquet	W5	3	8/6/2015							7.47	27.4	6.99	16.5	0.40	1.26	0.86	29.98
Lake Weqauquet	W5	B	8/6/2015							ND	ND	6.67	18.2	0.60	2.16	1.36	34.56
Lake Weqauquet	W2	0.5	10/6/2015	2	9.8	2.85		CLOUDLESS	STEADY WIND	10.03	16.2	6.95	12.8	5.80	0.75	0.53	28.78
Lake Weqauquet	W2	1	10/6/2015							10.03	16.2	NS	NS	NS	NS	NS	NS
Lake Weqauquet	W2	2	10/6/2015							9.94	16.2	NS	NS	NS	NS	NS	NS
Lake Weqauquet	W2	3	10/6/2015							9.96	16	NS	NS	NS	NS	NS	NS
Lake Weqauquet	W2	4	10/6/2015							9.9	16	NS	NS	NS	NS	NS	NS
Lake Weqauquet	W2	5	10/6/2015							9.89	15.9	NS	NS	NS	NS	NS	NS
Lake Weqauquet	W2	6	10/6/2015							9.95	15.9	NS	NS	NS	NS	NS	NS
Lake Weqauquet	W2	7	10/6/2015							9.85	15.9	NS	NS	NS	NS	NS	NS
Lake Weqauquet	W2	8	10/6/2015							9.87	15.8	NS	NS	NS	NS	NS	NS
Lake Weqauquet	W2	9	10/6/2015							8.5	15.8	6.93	13.0	5.23	1.26	0.56	28.19
Lake Weqauquet	W5	0.5	10/6/2015	2	6	2.7		CLOUDLESS	STEADY WIND	9.48	16.5	6.78	11.9	5.05	0.75	0.53	28.78
Lake Weqauquet	W5	1	10/6/2015							9.54	16.6	NS	NS	NS	NS	NS	NS
Lake Weqauquet	W5	2	10/6/2015							9.52	16.4	NS	NS	NS	NS	NS	NS
Lake Weqauquet	W5	3	10/6/2015							9.5	16.1	NS	NS	NS	NS	NS	NS
Lake Weqauquet	W5	4	10/6/2015							9.21	16	NS	NS	NS	NS	NS	NS
Lake Weqauquet	W5	5	10/6/2015							9.25	16	6.94	12.0	5.32	0.62	0.45	28.19
Lake Weqauquet	W2	0.15	10/27/2015	2	9.4	2.8		ND	ND	10.02	13.2	6.80	13.1	1.79	0.52	0.53	28.83
Lake Weqauquet	W2	1	10/27/2015							10.2	12.9	NS	NS	NS	NS	NS	NS
Lake Weqauquet	W2	2	10/27/2015							10.1	12.9	NS	NS	NS	NS	NS	NS
Lake Weqauquet	W2	3	10/27/2015							9.68	12.8	NS	NS	NS	NS	NS	NS
Lake Weqauquet	W2	4	10/27/2015							9.72	12.8	NS	NS	NS	NS	NS	NS
Lake Weqauquet	W2	5	10/27/2015							9.4	12.8	NS	NS	NS	NS	NS	NS
Lake Weqauquet	W2	6	10/27/2015							9.3	12.7	NS	NS	NS	NS	NS	NS
Lake Weqauquet	W2	7	10/27/2015							9.3	12.7	NS	NS	NS	NS	NS	NS
Lake Weqauquet	W2	8	10/27/2015							9.27	12.7	6.92	12.6	2.27	0.63	0.75	30.27
Lake Weqauquet	W5	0.15	10/27/2015	2	5.9	2.55		ND	ND	9.35	13.6	6.70	11.8	5.14	0.69	0.68	36.00
Lake Weqauquet	W5	1	10/27/2015							9.3	13.4	NS	NS	NS	NS	NS	NS
Lake Weqauquet	W5	2	10/27/2015							9.22	13.2	NS	NS	NS	NS	NS	NS
Lake Weqauquet	W5	3	10/27/2015							9.15	12.9	NS	NS	NS	NS	NS	NS
Lake Weqauquet	W5	4	10/27/2015							9.15	12.8	6.75	12.2	4.71	1.27	0.68	32.56