Bank Street Bogs at Cold Brook Evaluation of Natural Nitrogen Attenuation/Baseline Assessment

FINAL REPORT

September 2016

for the

Town of Harwich

Prepared by:

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Bank Street Bogs at Cold Brook: Evaluation of Natural Nitrogen Attenuation/Baseline Assessment

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September 2016

Prepared for

Town of Harwich
Wastewater Implementation Committee

and

CDM Smith
Boston, MA

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Cover photo: mid-bog culvert (11/25/14)

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Executive Summary

Bank Street Bogs at Cold Brook
Evaluation of Natural Nitrogen Attenuation/Baseline Assessment
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The Bank Street Bogs are located along Cold Brook in southern Harwich. The Brook begins at Grass Pond, which is located between Forest Street and Bank Street and flows south and then east, passing through a former cranberry bog. The Brook then flows under Bank Street and into the Bank Street Bog system before passing under Hoyt Road and then under Route 28 before flowing into Saquatucket Harbor (Figure EX-1). Saquatucket Harbor is an estuary exchanging tidal waters with Nantucket Sound.

How the Bank Street Bogs ecosystem is managed is of interest to both the Town Harwich and the Harwich Conservation Trust (HCT), which owns the former cranberry bog system. The now fallow bog system is directly upstream of Saquatucket Harbor and captures significant groundwater, discharging it to the stream entering the estuary. As such, the bogs are well positioned to capture watershed nitrogen during transport. Returning the bogs to a more natural freshwater aquatic system that supports natural processes, including attenuation of nitrogen, is an interest of both the Town and the HCT, as it would address the water quality impairments in the Harbor and provide a restored bog ecosystem. The impairments of Saquatucket Harbor were identified through the Massachusetts Estuaries Project (MEP). The MEP assessment of concluded that this estuary is moderately to significantly impaired with regular hypoxia, high chlorophyll concentrations, and impaired benthic animal habitat.[1] No eelgrass was noted during a review of historic information, so eelgrass restoration was not set as a goal for restoration. The MEP team recommended that an initial target for restoration of the system would be reduction of the average total nitrogen concentration at a “sentinel station” within Saquatucket Harbor from 0.65 mg/L to 0.5 mg/L. MassDEP has recommended 0.5 mg/L TN as regulatory limit for Saquatucket Harbor in its draft TMDL.[2] The MEP report included a scenario indicating that one option to attain the Saquatucket Harbor nitrogen goal was septic system nitrogen load reductions of 80% and 55% in the Saquatucket Harbor and Cold Brook subwatersheds, respectively.[3] The MEP team also noted that there appear to be a number of ways to achieve the TN reductions without wastewater infrastructure changes.

The MEP assessment included measurements of streamflow and nitrogen loads leaving the Bank Street Bogs system. Based on these measurements, the MEP team concluded that the Bank Street Bogs system was removing approximately 35% of the nitrogen load discharged to it from its watershed. In other wetland systems and ponds in the region, the MEP team has measured nitrogen attenuation rates of 50% or higher. Based on these results, it was thought that attaining

[1] Howes B., H.E. Ruthven, J.S. Ramsey, R. Samimy, D. Schlezinger, and E. Eichner. 2010.
[2] Massachusetts Department of Environmental Protection. April, 2015. DRAFT Allen, Wychmere and Saquatucket Harbor Embayment Systems Total Maximum Daily Loads For Total Nitrogen (Report # 96 TMDL-15 Control #312.0). 39 pp.
[3] Table VIII-2, 2010 Allen, Wychmere and Saquatucket Harbor MEP report.

Figure EX-1. Bank Street Bogs/Cold Brook Locus Map. Red outlined area is the Bank Street Bog System, while the blue line indicates the current primary flow path of flow in Cold Brook from Grass Pond to Saquatucket Harbor. Based on March 2012 aerial from Google Earth.

the MEP target of 55% nitrogen reduction in the Cold Brook subwatershed by effective management in the Bank Street Bogs was a reasonable goal. Past monitoring also suggested that even higher natural nitrogen attenuation was possible and would allow the Town to avoid some portion of watershed wastewater sewering that would otherwise be necessary to meet the Saquatucket Harbor nitrogen TMDL. CSP/SMAST staff discussed the potential role of aquatic restoration of the Bank Street Bogs within the context of town-wide nitrogen management with Town staff and their wastewater consultant, CDM Smith. Based on these discussions, it was decided to further evaluate the Bank Street Bogs/Cold Brook system for potential opportunities to restore some aquatic habitats and enhance the natural nitrogen removal. Initially, CSP/SMAST and CDM Smith staff reviewed available MEP and post-MEP data. This review noted a need to synthesize all the available data, as well as a number of data gaps, including: 1) stream flow, water levels, and nutrient transformations within the different portions of the bog system, 2) characterization of the former irrigation pond, and 3) a complete elevation survey of the bogs. CSP/SMAST and CDM Smith worked together with the Town of Harwich to design a two-year project to address these needs.

In order to assess water flows and nutrient loads, CSP/SMAST staff developed and implemented a refined monitoring program integrated with data collection to fill noted data gaps. Water flows and water quality samples were measured/collected at eight stations with flows supplemented with stream gauges at four stations (Figure EX-2). Instantaneous flow measurements and water quality samples were collected at all stations for at least one year between July 8, 2014 and July 7, 2015 with extended monitoring at CB-1, CB-6, and CB-8 to complete an assessment of the irrigation pond. The monitoring program had: a) weekly measurements during warmer months (four events per month, May thru September), b) biweekly measurements during temperature transition months (two events per month for October, and April), and c) monthly during colder temperature months (November thru March). A minimum of 30 instantaneous flow measurements were collected at each station and 35 were collected at the "extended" stations. Stream gauges programmed for continuous measurements were located at the inflow of Cold Brook to the Bank Street Bog system (CB-1), at the inlet/outlet of the connected, active cranberry bog (CB-2), as flow exited Cell 3 (CB-5), and as Cold Brook flowed out of the Bank Street Bog system (CB-8). Stream gauges recorded water level readings every 10 minutes.

The results of the stream monitoring revealed some important considerations for management discussions. The stations at the head of the bog system and from the adjacent cranberry bog (stations CB-1 and CB-2) had comparable flows for limited periods, but were generally highly inconsistent likely due to the regular manipulation of boards at Bank Street dam and at the cranberry bog. Mean flow at the next downstream station (CB-3) was not statistically different from CB-1, suggesting no additional watershed inflow occurs between these stations. In contrast, flows from CB-3 to the most downgradient station at the outlet of the system (CB-8) showed a marked flow pickup especially between the upper system (CB-5) and the lower system (CB-7). Tidal influences were seen in the gauge records up to the middle of the system (CB-5), but there was no salinity measured until station CB-6, which is near the irrigation pond. Stream measurements were strongly influenced by season with summer reductions in flow of 78% at CB-3 with diminishing seasonal effect moving downstream. Flow at the system outlet (CB-8), which is near the former MEP stream gauge site, had higher flow than 2004/2005 MEP mean, which was consistent with measurements of higher than average precipitation and groundwater levels during the 2014/2015 monitoring period. Comparisons of flow between stations showed that nearly 60% of the flow leaving the system was collected at the lower stations (CB-7 and CB-8).

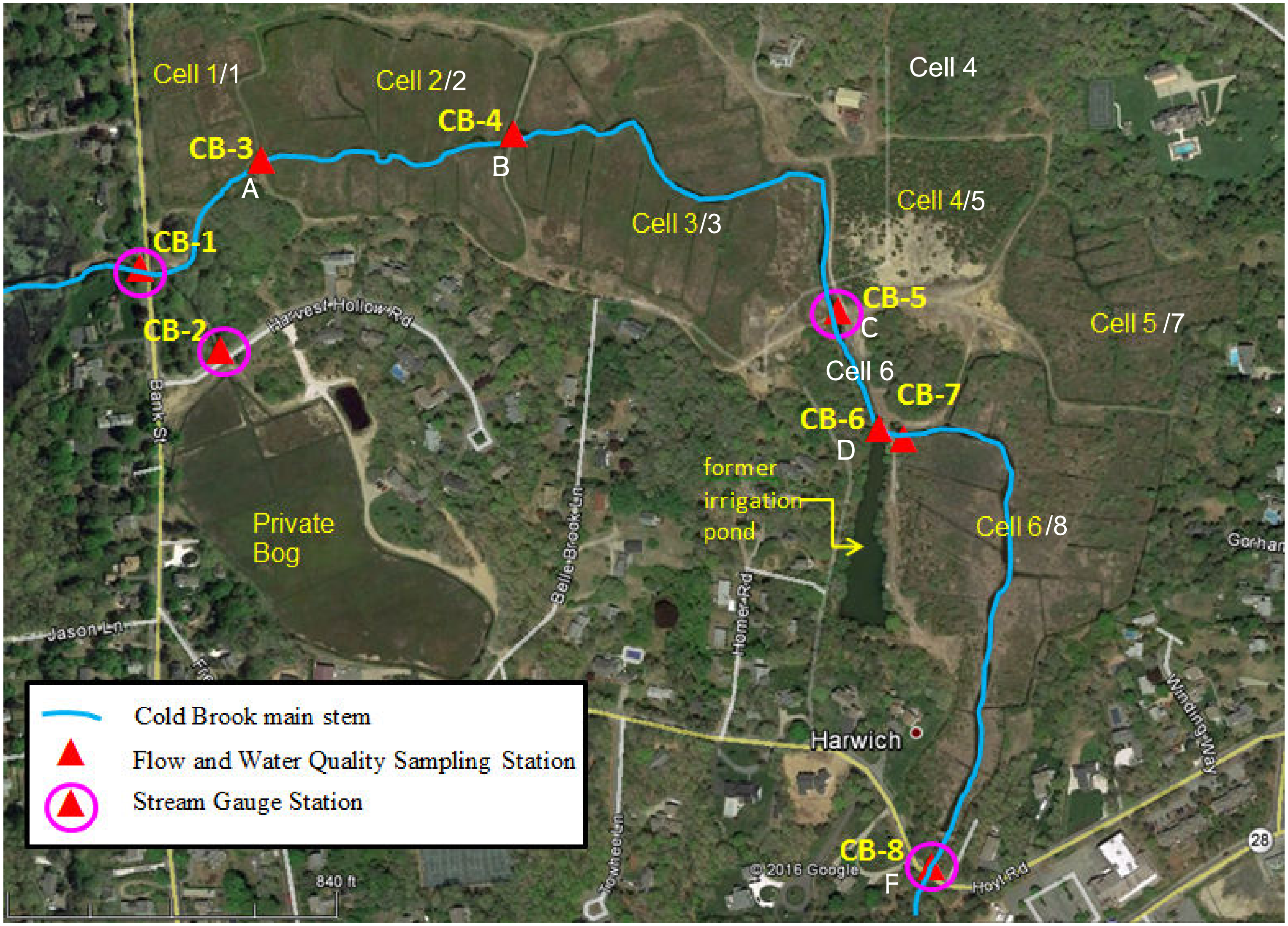

Figure EX-2. CSP/SMAST Bank Street Bogs/Cold Brook Flow, Water Quality and Stream Gauge Stations. Stream gauges recorded stage every 10 minutes for 14 months, between July 2014 and September 2015, while other sampling stations had instantaneous flow readings and water quality samples collected at least monthly with weekly sampling during summer and biweekly during spring and fall. MassDER cell numbers and monitoring station designations are indicated with white labels; yellow labels are generally used throughout this report.

Water quality samples focused on nitrogen and phosphorus, with analysis performed at the Coastal Systems Analytical Facility (SMAST) under QA/QC procedures approved by MassDEP and USEPA for a variety of nutrient components (nitrogen and phosphorus, both inorganic and organic and dissolved and particulate), particulate organic carbon, salinity and phytoplankton pigments (only assayed for irrigation pond samples). These were the same procedures used in the previous MEP Cold Brook study. Review of N to P ratios throughout the Bank Street Bogs generally showed that phosphorus is the limiting nutrient, which means phosphorus availability will determine phytoplankton and algal growth within the freshwaters of the system. Seasonal readings show that these ratios decrease in the summer, but phosphorus continues to be the nutrient limiting plant growth. Seasonal decreases in N/P ratios are likely due the addition of phosphorus through internal summer TP releases from the bog sediments.

Mean total nitrogen (TN) concentrations were generally comparable at all stream stations, ranging between 77 and 101 µM, but nitrogen fractions comprising the TN did vary depending on the station setting. Mean organic nitrogen, both dissolved (DON) and particulate (PON), concentrations were generally highest in the lowest flow settings (*i.e.*, CB-1, CB-2, and CB-6), while dissolved inorganic nitrogen (DIN) were significantly highest in the regions of highest groundwater inflow (*i.e.*, CB-4, CB-5, CB-7, and CB-8). DIN concentrations were generally composed of mostly of nitrate-N at all stations except CB-1 where ammonium dominated. Seasonal concentration comparisons generally showed higher organic concentrations during the summer and higher DIN concentrations during the winter, paralleling the uptake and release associated with plant growth. DIN as nitrate is the predominant form of nitrogen in groundwater inputs, while organic forms tend to be associated with biological activity in surface waters systems, such as bogs or streams.

Total phosphorus (TP) mean concentrations generally showed no statistically significant differences between stations except for near the active cranberry bog (CB-2) and in the middle of the upper bog (CB-4). Most of the TP was as organic forms with inorganic P comprising between 10 and 43% of the total phosphorus pool. Summer mean TP concentrations were significantly higher than winter concentration at all of the upper stations (CB-1 through CB-4) and summer inorganic P means were significantly higher at stations slightly lower in the system (CB-3, CB-4, and CB-5). TP and inorganic P would be mobilized in summer conditions as temperatures rise and bacterial populations in the organic rich bogs create lower oxygen conditions and free phosphorus from iron:phosphorus solids. Inorganic phosphorus is very immobile in aquifer soils; phosphorus within Cold Brook is generally related to decay processes and sediment release within its surface water systems.

Mean alkalinity and pH readings increased (*i.e.*, became less acidic) in stream waters moving downstream through the bog system. For example, mean pH at CB-1 was 5.9, while it was 6.6 at CB-8. Mean seasonal pH readings generally did not have significant differences, but four stations had higher summer readings. Higher summer pH is generally associated with greater photosynthesis during the summer and higher microbial activity within aquatic sediments. Higher photosynthesis would be consistent with the greater availability/higher concentrations of TP. When aquatic plants photosynthesize they take hydrogen ions and carbon dioxide out of the water causing pH to increase. Higher summer alkalinities are likely related to the summer mobilization of carbon in the bogs; particulate organic carbon concentrations have significant summer increases at all of the stations with higher alkalinities.

Comparison of this project's mean total nitrogen concentrations to those collected during 2004/2005 MEP monitoring indicate that the 2014/2015 levels are higher. Mean TN concentration in 2014/2015 at CB-8 was 86.8 µM (1.22 mg/L) with 60% being DIN. During 2004/2005, the mean TN concentration was 0.961 mg/L (68.6 µM) with 70% DIN.[4] Comparison of the DIN concentrations shows only a slight increase from the MEP monitoring (48 µM in 2004/2005 to 52 µM in 2014/2015). Based on the TN and DIN data it appears that the bog system is receiving more watershed DIN than it was in the past, but continues to transform it to organic forms at a high rate. The high DIN levels in streamwater exiting the bogs suggest that enhanced attenuation within this system is possible.

Combining the concentration data with the flow data also shows an increase in TN loads leaving the Bank Street Bog system. Since nitrogen is not the limiting nutrient with the Bank Street Bog system, it is expected that changes in nitrogen loads would largely follow changes in water flows. Mean daily TN loads generally follow changes in water flow; relationships between loads at stations are not significantly different from the relationships between water flows at stations. This extends to seasonal loads where winter TN loads were significantly higher at all stations except CB-1 and CB-6. Summer reductions from winter loads were highest at CB-3 (73%) and gradually decreased at each subsequent downstream station with a minimum reduction of 39% at CB-8; these reductions generally paralleled the seasonal flow reductions.

Based on the collected 2014/2015 data, the amount of TN loads leaving the Bank Street Bog system has increased since the 2004/2005 MEP measurements. MEP measurements showed an average TN loading rate of 9.9 kg N/d[5] leaving the Bank Street Bog system at CB-8, while the 2014/2015 water year had an average TN load of 15.8 kg N/d (a 59% increase). Using the previously discussed corrections in 2014/2015 flow for higher precipitation and groundwater levels, the higher TN concentration in 2014/2015 still results in an estimated 26% increase in N load to Saquatucket Harbor. If the MEP watershed N loads are held constant, this load would represent a 13% decrease in attenuation (from 35% to 22%) within the Cold Brook watershed. Whether this is a "true" drop in the attenuation rate due to changes within the Cold Brook system or whether there are other factors, such as increased watershed loads that are altering the incoming N loads would require an expanded project. Some of this change may be due to a revised watershed configuration suggested by the internal flow measurements completed during this project; the internal Cold Brook subwatershed boundaries/groundwater flows are likely different than what is in the MEP/USGS modeled characterization. Since the MEP stream monitoring was designed to measure stream flows and loads just upstream of the estuaries, the load comparison between the 2004/2005 and 2014/2015 is only available at CB-8 (the outlet of the Banks Street Bogs system) and it is unclear what other changes within the Cold Brook watershed may have led to the increased N load in discharging waters.

[4] Table IV-5 in Allen, Wychmere, and Saquatucket Harbors MEP Report (2010).
[5] Table IV-5 in Allen, Wychmere, and Saquatucket Harbors MEP Report (2010).

Mean TP loads have many of the same relationships as TN, but seasonal variations are not as closely tied to flow; this should not be surprising given the more limited availability of phosphorus. In much the same way as TN loads, mean TP loads based on a whole year were not significantly different ($\rho<0.05$) at CB-1 and CB-3, but each subsequent downstream station, save CB-6, had a significantly higher mean load than the adjacent upstream station. This indicates that each bog cell was contributing phosphorus to Cold Brook waters. Seasonal reductions during the summer in mean TP loads generally showed a 50 to 60% drop and most of the seasonal load reductions are less than the seasonal mean flow reductions.

The near constancy of the seasonal TP reduction along most of Cold Brook combined with phosphorus limitation suggests that water has a similar residence times within each of the bog cells; if the residence times were significantly different between cells it would be reasonable to expect significant differences between TP reductions in each of the cells. Given the differences in the sizes of cells and the area of the channels within each cell, these differences should alter residence time and seasonal TP reductions in each of the cells. The nearly constant seasonal TP reductions suggest that TP reductions are largely occurring within the main stem of Cold Brook.

The assessment of the former irrigation pond showed that it is impaired by excess nutrients, it serves as a near constant source of water and nutrients, and has a local influence on downstream conditions (CB-7). The assessment included many of the standard pond assessment techniques including development of a bathymetric map, measurement of sediment depth, assessment of a potential contributing area and collection of dissolved oxygen (DO) and temperature profiles, clarity/Secchi readings, water quality samples, and sediment cores. DO/temperature profile readings on six dates between July and October 2014 showed resistance to thermal mixing early in the sampling. The pond's deep DO concentrations were below the MassDEP minimum late in the sampling, and a phytoplankton bloom in August raised DO saturation levels as high as 172%. Average chlorophyll-a concentration on the three sampling dates during the bloom are ~5X those earlier in the summer. Clarity in the pond averaged 31% of the water column with a range of 24% to 40%; a pond this shallow should have light penetration to the bottom. TP and TN concentrations at CB-6 generally matched surface pond concentrations, but deep samples showed TP concentrations nearly 3X surface concentrations, which indicated sediment regeneration. This regeneration would be a consistent source that even out the TP levels at CB-6 over the year. These stable readings also impacted readings at the closest downstream brook station (CB-7). Salinity readings in the pond also show some salinity stratification with indications that tidal water periodically enters the pond and generally sinks to the bottom and is only slowly mixed upwards into the full water column.

Pond sediment cores showed that the pond sediments generally take up nitrogen and phosphorus when bottom waters are aerobic, with the greatest rate of uptake in the deepest, southern portion. Sediment testing for metals, PCBs, VOCs, and other hydrocarbon was undertaken for evaluation of potential reuse options if sediments were removed. Sample results showed some concerns about arsenic and total petroleum hydrocarbons near the inlet, but not in the main/deepest portion of the pond. If the soft sediment deposits are removed from the pond, the volume of the pond would increase by 35%.

Review of the pond hydrology showed that CB-6 flow is likely composed of a large portion of tidal water. Review of the tidal prism at nearby CB-5 shows that average CB-6 flow approximates the likely tidal prism flow. Water quality data shows that this flow likely interacts mostly with the upper portion of the water column in the irrigation pond.

The elevation survey of the Bank Street Bogs system was completed using a Leica Viva GNSS/GPS with RTK enabled, which provides elevation accuracies on the order of +/-10 mm. Approximately 1,355 point elevations were collected and contoured (Figure EX-3). Staff determined the cell volumes using the cell banks and average, maximum, and minimum elevations of the bog surface and Brook channel within each bog cell. Staff also completed a bathymetric survey and sediment depth assessment of the system's former irrigation pond. Comparison of the bog surface elevations to past determination of the peat depths shows that selected areas within Cells 2, 3, and 5 have a peat thickness of more than 2.5 m and peat filled depressions with bottom elevations of -1 to -1.5 m NAVD88. This finding means that prior to the peat deposition (likely beginning 5,000 to 10,000 years ago), these depressions likely functioned like small ponds within flow path of Cold Brook.

Management within and around the Bank Street Bogs system involves a number of parties including the Town, the Harwich Conservation Trust, the Massachusetts Division of Marine Fisheries, Massachusetts Division of Environmental Restoration and a number of consultants throughout the years. The purchase of the Bogs by the Harwich Conservation Trust in 2001 and the gradual natural reclamation by the surrounding plant communities has brought up a number of management issues, including: a) decades-long discussions of adequate flows for both migratory passage of eels to Grass Pond and use by the adjacent cranberry bog, b) how the landscape and ecosystems of the bog property will be managed, and c) discussions about potential opportunities to enhance natural removal of watershed nitrogen as part of a plan to restore the Bog system and the Saquatucket Harbor Estuary.

MassDER has proposed an extensive reworking of the Bogs including excavation of large portions of Cells 2 and 3 (removing most of the surface area of the bog to intersect groundwater), alteration of the Cold Brook channel, filling of bog ditches, and removal of many of the Brook control flumes (Princeton Hydro, 2015). Based on data collected during this project including the bog surface elevations and water level readings, staff review of the proposed excavations suggest that there will be standing water in the deepened areas for much of the year. If these areas were deepened more to function more like ponds, they would have a better opportunity to remove nitrogen. The greater the volume created, the longer the residence time of water and the greater the nitrogen attenuation potential. As currently proposed, these depressions would have maximum residence times of 5 to 7 days each, but may provide slightly more since they are linked in series. These are relatively short residences times, so how much enhancement of nitrogen attenuation they provide is likely to be low. CSP/SMAST staff has recommended evaluation of deeper pond depressions in Cells 2 and 3. Depending on the configuration of the ponds (area, depth) and whether Cold Brook goes through or around these ponds, residence times could be extended to a month or more.

The N removal benefits of increasing the residence times are well established. Natural nitrogen attenuation in water systems has been evaluated for many decades. Factors impacting nitrogen

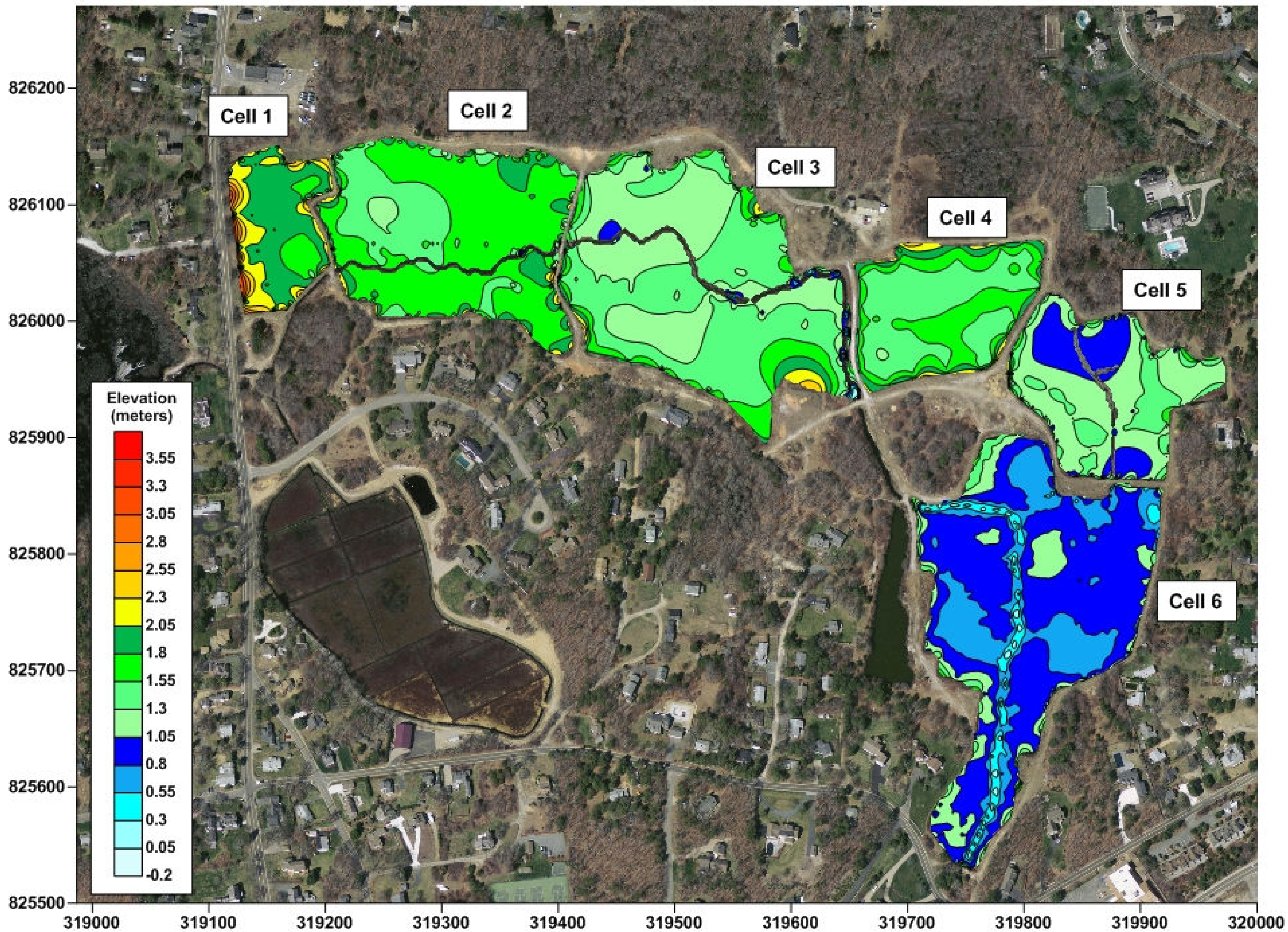

Figure EX-3. Bank Street Bogs/Cold Brook Elevations. All elevations are in NAVD88 and should have accuracies on the order of +/-10 mm. Mean bog surface elevations begin at 2.01 m in Cell 1 and gradually decrease to 0.93 m in Cell 6.

retention in aquatic systems include denitrification (*i.e.*, releasing N to the atmosphere), macrophyte storage (*i.e.*, uptake and storage of N in plant tissues), and retention of particulate matter (*i.e.*, settling of particulates to sediments within the system). Studies have found that natural wetland systems receiving only non-anthropogenic N inputs are very retentive, removing 50%-100% of total N inputs.[6] However, studies have also shown that systems receiving additional anthropogenic nitrogen can remove substantially less[7] and may attain a nitrogen saturation, becoming transformers of N (changing nitrate+nitrite to organic forms), but not attenuators of nitrogen.[8] Reviews looking at a variety of systems have found that the percentage of N retention/attenuation is strongly predicted by residence time; the longer the residence time the greater the N retention.[9]

During the course of the review of the draft version of this Management Plan, some have expressed concern that the addition of these proposed ponds would create poor water quality conditions within the ponds. Freshwater ponds are phosphorus sensitive; phosphorus amounts will determine the water quality and whether the ecosystem is impaired. Since phosphorus movement in groundwater is very slow (*e.g.*, 20-50 years to move 100 m) and there is little additional future development potential on any of the parcels upgradient of the Bank Street Bogs, the only additional phosphorus that could reasonably be added to these ponds would be internal additions from the reworked bog system. So the water conditions within these ponds will be a product of their depth and volume, the plant community that is allowed to develop in and around time, and how they are managed with the rest of the system. The depth and volume of these ponds is yet to be significantly reviewed, but data from most Cape Cod ponds have shown that ponds less than 9 m deep have well mixed water columns; these ponds are currently proposed as shallower than 9 m. Well-mixed ponds generally have sufficient dissolved oxygen to ensure that phosphorus retained in the pond sediments is not regenerated, so this potential route of additional phosphorus to impair water quality conditions is unlikely and the ponds would generally work as phosphorus sinks, attenuating some portion of the phosphorus load moving downstream. Further evaluation is warranted as additional design details are discussed, but the addition of these ponds would provide both nitrogen and phosphorus attenuation and add to the habitat diversity discussed in the MassDER proposal.

Addition of these proposed ponds would also have the added potential benefit of providing some permanent spawning habitat for eels. Eels currently travel up Cold Brook to try to spawn in Grass Pond, which is upstream of Bank Street, but are often impeded by low flow conditions. MassDMF has developed a number of management strategies to get eels past the Bank Street dam including hand transport and installation of a pump. Grass Pond is approximately 20 acres

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[6] *e.g.*, Johnston, C. 1991. Sediment and nutrient retention by freshwater wetlands: effects on surface water quality. *Critical Reviews in Environmental Control.* 21:491-565.

[7] *e.g.*, Novitzki, R.P. 1978. Hydrology of the Nevin Wetland near Madison, WI, U.S. Geological Survey, Water Resources Investigation 78-49: temperate cattail marsh receiving wastewater removed only 21% N

[8] *e.g.*, US Department of Agriculture. 2011. Assessment of Nitrogen Deposition Effects and Empirical Critical Loads of Nitrogen for Ecoregions of the United States. L.H. Pardo, M.J. Robin-Abbott, and C.T. Driscoll, editors. Available at: http://www.nrs.fs.fed.us/pubs/gtr/gtr_nrs80.pdf

[9] *e.g.*, Saunders, D.L. and J. Kalff. 2001. Nitrogen retention in wetlands, lakes and rivers. *Hydrobiologica*. 443:205-212.; Toet, S., Van Logtestijn, R.S.P., Kampf, R., Schreijer, M., and J.T.A. Verhoeven. 2005. The effect of hydraulic retention time on the removal of pollutants from sewage treatment plan effluent in a surface-flow wetland system. *Wetlands*. 25(2): 375–391.

with a measured maximum depth of 3 ft.[10] If the proposed ponds are included in the restoration of the Bank Street Bogs, the combined area within Cell 2 and 3 would be slightly greater than 10 acres or a bit more than half of the area of Grass Pond. If these areas could be utilized as a backup for Grass Pond, it could ensure that eel spawning grounds are always available, subject to natural groundwater fluctuations, and create some additional time for resolving all of the management issues associated with maintaining timely flow for the cranberry grower and passage to Grass Pond.

In addition to the modifications in the proposed bog excavation areas, CSP/SMAST staff also proposes that HCT and the Town consider creation of another pond in Cell 4 (cell 5 in MassDER numbering). Cell 4 is a mostly sandy cell with large portions that do not have residual wetland plants and ground-penetrating radar has indicated it historically contained a portion of the Cold Brook channel along its northern edge. It is located directly upgradient of the portion of the Bogs that measurements show had 60% of the Brook flow and nitrogen load. Restoring this area by creating an isolated pond, fed by groundwater, would have the opportunity to intercept and focus a significant portion of the Cold Brook upgradient watershed flow and N load. Given the area of Cell 4, a simple conical pond of 5.1 acres could be installed and with a 10% slope could attain a maximum depth of 6 m. If this cell intercepted a third of the flow headed to CB-8, its residence time would be approximately 5 days. If the pond was flat-bottomed, its volume and residence time would nearly triple (15 days). If the whole cell was used, the residence time would nearly double again (27 days). Longer residence times are associated with greater N removals.

In addition to the modifications within the existing cells, CSP/SMAST staff also proposes that HCT and the Town consider modification of the former irrigation pond to create more nitrogen attenuation opportunities. Staff proposes a) removal of the sediments in the southernmost portion of the pond and b) installation of a flapper valve or similar structure to allow Cold Brook flow into the pond but prevent brackish tidal waters from entering. Reducing the salinity stratification in the pond would reduce the sediment nitrogen and phosphorus release in summer and its transport downstream. In addition, reduction of the phosphorus would drive the system toward more consistent nitrogen:phosphorus ratios, reduce the algal blooms and low oxygen events, and improve the pond habitat. This modification would also increase nitrogen removals by enhancing coupled nitrification-denitrification in the pond sediments with the result being another portion of the system lowering watershed nitrogen reaching nitrogen-impaired Saquatucket Harbor.

Figure EX-4 summarizes the potential integration of key portions of CSP/SMAST and MassDER restoration proposals. As mentioned, MassDER recommends removal of peat and sand layers of the cranberry bog to allow the water table to interact with the bog surface and be exposed to the atmosphere. CSP/SMAST has recommended deepening of the planned excavations to create ponds within the bog cells, as well as creation of a pond within the mostly upland area of Cell 4 and limits on tidal water entering the irrigation pond. Figure EX-4 also includes the proposed MassDER changes in the Cold Brook channel through the Bank Street Bogs.

[10] CDM Smith. 2016. Final Comprehensive Wastewater Management Plan/ Single Environmental Impact Report, Town of Harwich, Massachusetts. Boston, MA.

Finally, it is clear from the comparison of data collected during this project and past projects that the Bank Street Bog system is complex with varying conditions both on a seasonal and year-to-year basis. Implementation of whatever management strategies are finally selected in both the Bank Street Bog system and the overall Saquatucket Harbor watershed could be done in a step-wise fashion with regular assessment of ecological changes and reductions in N loads. This type of adaptive management approach may offer the opportunity to alter and adapt strategies as the system comes into a new ecological balance. It is recommended that monitoring, synthesis of data, and regular feedback be part of any planned alteration of the Bank Street Bog system.

Moving these proposals forward will require more extensive discussions and certainly will require addressing regulatory issues, which may be facilitated by Agency discussions around planned modifications. CSP/SMAST staff is available to assist the Town, HCT, and any of the management partners with those discussions and/or to refine any evaluations and conclusions in this report.

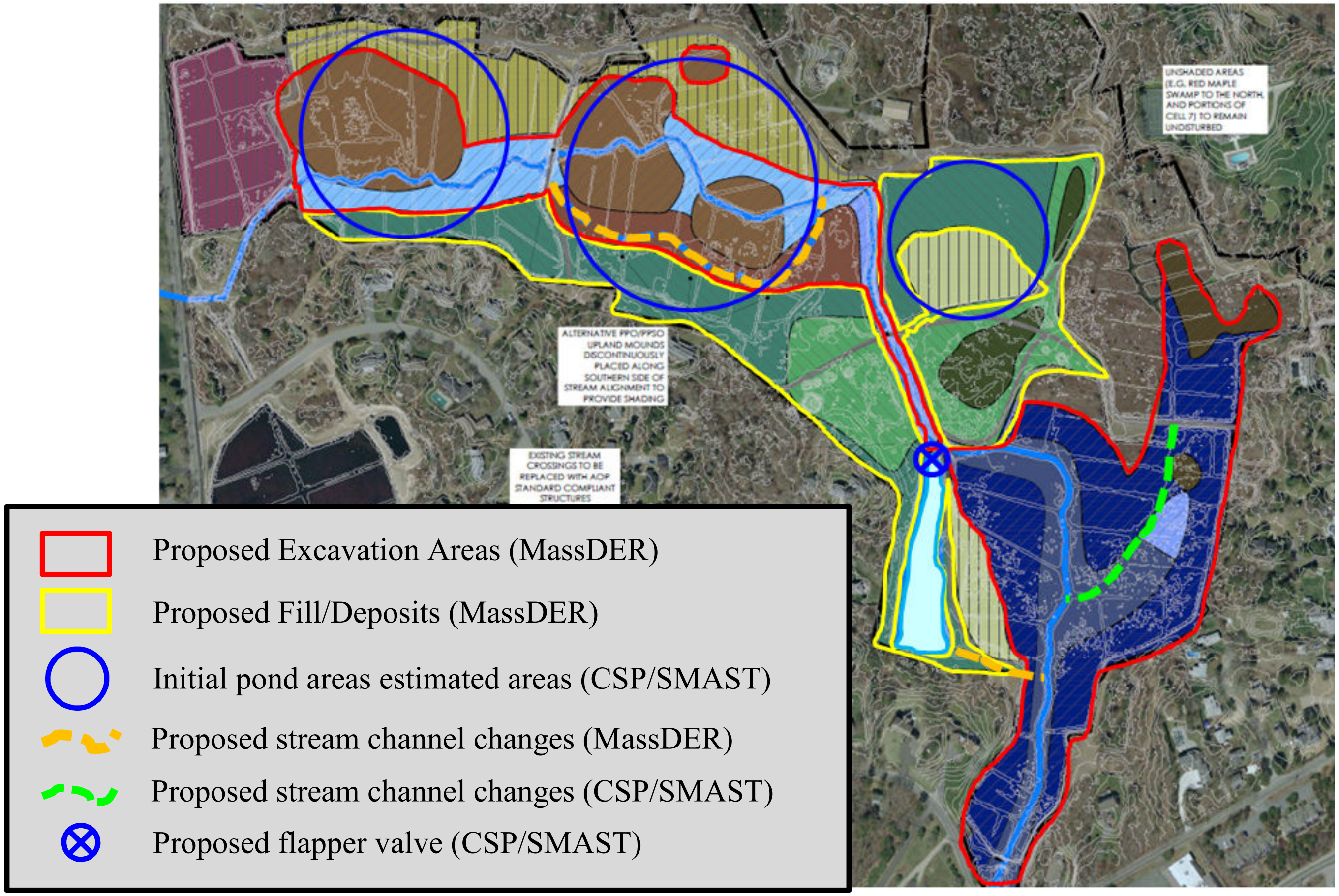

Figure EX-4. Summary of current proposed changes within the Bank Street Bog system. Details of proposed changes are still being discussed and will still require regulatory and funding review, but this figure generally summarizes the current status. MassDER has proposed a number of habitat types (details in Princeton Hydro, 2015; colored areas above). Attaining habitat types will include excavation of some areas (outlined in red) and fill of others (outlined in yellow). Excavated areas will have bog peat and sand removed, the remaining surface "roughened", and the underlying water table exposed. Areas not outlined will be altered but no net change in elevation. In this report, CSP/SMAST has proposed inclusion of deeper ponds (dark blue circles) mostly in the proposed excavation areas and addition of a pond in the portion of the system receiving the greatest groundwater inputs (Cell 4) to enhance nitrogen attenuation by increasing residence time in the system. Actual pond areas will depend on a number of factors. CSP/SMAST has also proposed additional N attenuation through making the irrigation pond a completely fresh water pond by installing a flapper valve to allow Brook water to flow in, but keep tidal water out; MassDER has proposed connecting the pond to the Brook at the southern end to allow it to become more brackish. MassDER has also proposed "plugging" of bog ditches throughout the system and replacing Brook culverts between the cells.

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I. Introduction

The Bank Street Bogs are located along Cold Brook in southern Harwich adjacent to Nantucket Sound. The Brook begins at Grass Pond, which is located between Forest Street and Bank Street and flows south and then east, passing through a former cranberry bog. The Brook then flows under Bank Street and into the Bank Street Bog system before passing under Hoyt Road and then under Route 28 before flowing into the Saquatucket Harbor Estuary (Figure I-1). Saquatucket Harbor is an artificially created marine basin currently functioning as a tidal estuary, which exchanges tidal waters with Nantucket Sound.

Management options for the Bank Street Bogs ecosystem are of interest to both the Town Harwich and the Harwich Conservation Trust (HCT), which owns the former cranberry bog system. The Bank Street Bogs were purchased by the HCT in 2001. Since the bogs are directly upstream of Saquatucket Harbor, there is the potential to enhance natural processes within the bogs to remove transiting nitrogen to address the water quality and habitat impairments in the Harbor that were identified through the Massachusetts Estuaries Project (MEP).[1]

The MEP was implemented through a team of experts led by the Coastal Systems Program, School of Marine Science and Technology at the University of Massachusetts Dartmouth (CSP/SMAST) to determine water quality and ecosystem status of estuaries throughout southeastern Massachusetts. The MEP involved extensive characterization of each estuary including watershed delineations, monitoring of inputs from streams, measurement of water quality and tidal constituents, and development of individualized linked watershed/estuary models that can be used during Comprehensive Wastewater Management Planning (CWMP) by watershed towns to evaluate water quality management options. The Massachusetts Department of Environmental Protection (MassDEP) uses the MEP findings for each estuary to develop regulatory water quality targets or TMDLs[2] for impaired waters. More recently the Cape Cod Commission has used simplified versions of the MEP analysis as the basis for its 208 planning.

The MEP assessment of Saquatucket Harbor concluded that the Saquatucket Harbor ecosystem was moderately to significantly impaired with regular hypoxia, high chlorophyll concentrations, and impaired benthic habitat.[3] No eelgrass was noted during a review of historic information, so eelgrass restoration was not a goal of restoration. The MEP team recommended that an initial target for restoration of the system would be reduction of the average total nitrogen concentration at a "sentinel station" within Saquatucket Harbor from 0.65 mg/L to 0.5 mg/L. MassDEP has recommended 0.5 mg/L TN as regulatory limit for Saquatucket Harbor in its draft TMDL.[4]

The MEP assessment included an example watershed nitrogen reduction scenario to meet the TN target in Saquatucket. This scenario included septic system nitrogen load reductions of 80% in

[1] Howes B., H.E. Ruthven, J.S. Ramsey, R. Samimy, D. Schlezinger, and E. Eichner. 2010. Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Allen, Wychmere and Saquatucket Harbor Embayment Systems, Harwich, Massachusetts. Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection, Boston, MA. 191 pp.

[2] Total Maximum Daily Loads

[3] Howes B., H.E. Ruthven, J.S. Ramsey, R. Samimy, D. Schlezinger, and E. Eichner. 2010.

[4] Massachusetts Department of Environmental Protection. April, 2015. DRAFT Allen, Wychmere and Saquatucket Harbor Embayment Systems Total Maximum Daily Loads For Total Nitrogen (Report # 96 TMDL-15 Control #312.0). 39 pp.

the Saquatucket Harbor subwatershed and 55% in the Cold Brook subwatersheds.[5] The MEP team also noted that there are a number of ways to achieve the TN reductions without wastewater collection and treatment and included a preliminary evaluation of one potential option in the MEP report: enhancing natural nitrogen attenuation within the Bank Street Bogs/Cold Brook prior to discharge into the Saquatucket Harbor Estuary.

Stream measurements collected at the outlet of the Bank Street Bogs during the MEP assessment showed that the overall system was removing 35% of the watershed nitrogen flowing into it. In other wetland systems and ponds in the region, the MEP team has measured nitrogen attenuation rates of 50% to 80%. Based on these results, it was thought that attaining the 55% nitrogen reduction in the Cold Brook subwatershed in the MEP example scenario by enhancing natural attenuation was reasonable possibility and would allow the Town to avoid some portion of watershed wastewater sewering that would otherwise be necessary to meet the Saquatucket Harbor nitrogen TMDL. CSP/SMAST staff discussed this finding with Town staff and their wastewater consultants, CDM Smith, and it was decided to further evaluate the Bank Street Bogs/Cold Brook system for potential opportunities to enhance the nitrogen removal. A phased approach was determined to be the most cost effective strategy.

Initially, CSP/SMAST staff worked with CDM Smith to complete a combined survey of the MEP data and post-MEP characterizations of portions of the Cold Brook system. This survey suggested a number of data gaps that needed to be addressed in order to develop management options for the Bank Street Bogs. These data gaps included: 1) stream flow, water levels, and nutrient transformations within the different portions of the bog system, 2) characterization of the former irrigation pond, and 3) a complete elevation survey of the bogs, including the bog channels and the surrounding banks. It was also clear that there was a need for synthesis and organization of all the available information as a prelude to development of a management plan.

CSP/SMAST and CDM Smith worked together with the Town of Harwich to prepare a two-year project to address these needs and develop a system management plan. The first year of this effort was focused on gathering and reviewing the post-MEP Bank Street Bogs/Cold Brook assessments (Task 1) and collecting streamflow, water levels and nutrient transformation within the different portions of the Cold Brook bog throughout a whole year (Task 2A). First year activities were summarized in a 2015 CSP/SMAST Technical Memorandum.[6] The second year involved completion of a second summer of water quality data collection to have some sense of inter-annual variation (Task 2B), a characterization and monitoring of the irrigation pond (Task 3), a complete elevation survey of the bog and its channels, volume estimates of each bog cell, a habitat assessment (Task 4), and development of a summary report, including a review of potential management options, nutrient reductions, and accompanying public discussions (Task 5). This current Bank Street Bogs/Cold Brook Assessment summarizes each of these tasks, reviews potential management strategies, and proposes a recommended series of the strategies for action.

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[5] Table VIII-2, 2010 Allen, Wychmere and Saquatucket Harbor MEP report.

[6] CSP/SMAST Technical Memorandum.. January 29, 2015. Interim Report on Cold Brook Natural Nitrogen Attenuation Project, Harwich, MA. From: E. Eichner, B. Howes, D. Schlezinger, R. Samimy, and M. Bartlett, Coastal Systems Program. To: David Young, Vice President, CDM Smith. 23 pp.

Figure I-1. Bank Street Bogs/Cold Brook Locus Map. Red outlined area is the Bank Street Bogs, while the blue line indicates the current primary path of Cold Brook from Grass Pond to Saquatucket Harbor. Based on March 2012 aerial from Google Earth.

II. History of Management, Regulation and Assessment of Cold Brook/Bank Street Bogs

In order to provide context for future management of Cold Brook System, it is important to consider past assessments and management actions in the area and how historic uses have changed the ecology of the aquatic system. Cold Brook is part of the Saquatucket Harbor watershed (Figure II-1). Saquatucket Harbor was created in 1968-1969 by dredging a large pocket salt marsh surrounding what was then known as the Andrews River (Figure II-2). This tidal marsh river system appeared to be similar to other nearby wetland-dominated tidal river systems along Vineyard Sound, including Herring River, Swan Pond River, and Red River. Historic maps and photographs show the salt marsh surrounding the Andrews River extending up to Route 28 with Cold Brook entering from the west and Carding Brook flowing in from the east. Historic reports named the easternmost brook Cold Brook, but later references have switched these names and this convention will be used in this report. Remnants of the primary stream channel of the Andrews River can be seen in the remaining wetlands surrounding Saquatucket Harbor.

Cold Brook begins at Grass Pond, exiting through an earthen berm (known as Wheeler Dike[17]). The brook flows through a former cranberry bog that was abandoned during the 1950's, through another earthen berm/dam, and under Bank Street. Between Bank Street and Hoyt Road, there are two cranberry bogs that are connected to the brook: an active 7 acre bog south of Harvest Hollow Road and a 35 acre bog system that ceased cranberry production in the 1990s and is now owned and managed by the Harwich Conservation Trust (HCT). The larger bog system includes a number of flow control structures that could be used to isolate water flows in various cells of the bog and an irrigation pond (Figure II-3). Cold Brook flows through the larger Bank Street bog system, passes under Hoyt Road and then Route 28/Main Street, finally discharging into the northwestern corner of Saquatucket Harbor.

Cold Brook is a water of the Commonwealth of Massachusetts. As such, there are regulatory issues associated with any management activities associated with the Brook and its surrounding wetlands, including exemptions and historic accommodations for cranberry bog agricultural activities. In 1927, a Massachusetts Division of Waterways license (No. 769) was issued to construct and maintain dams and spillways at the Grass Pond berm and at the pond outlet upstream of Bank Street for the purpose of cranberry cultivation.[18] The Wheeler Dike berm near Grass Pond has deteriorated and the elevation of boards in the Bank Street dam outlet has been subject of a number of regulatory discussions among the town, land owners, and MassDEP and its preceding organization, MassDEQE.[19] The Waterways license is still valid and held jointly by the owner of the active bog and HCT. Both parties also hold MassDEP Water Management Act Registrations that allow specified annual total and daily average volumes of water for cranberry production. State laws also require that property owners allow passage for sea-run fish.[20] Any activities within the bogs and along the brook will also be subject to the Massachusetts Wetlands Protection Act (WPA), which is locally administered by the Harwich

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[17] MassDMF memo from Bradford Chase to HCT and John Sennott. March 15, 2011. Subject: Recommended Water Flow Management Plan for Grass Pond and Cold Brook.

[18] Massachusetts Division of Waterways (No. 769) license was issued to George Weekes in March, 1927

[19] *e.g.*, July 23, 1981 MassDEQE letter to Carver Crowell regarding the outlet board elevation being too high; April 20, 2011 Harwich Conservation Commission letter to MassDEP asking for help with board height compliance.

[20] MGL c. 130, Section 19 administered by MassDMF.

Conservation Commission, which reviews activities near wetlands and also exempts many cranberry growing activities.

In 2011, Brad Chase, MassDMF submitted a memo to HCT and the owner of the active bog with a Recommended Water Flow Management Plan for Grass Pond and Cold Brook.[21] The primary purpose of the plan was to "allow compatible water flow use for existing agricultural practices and the annual eel migration." No formal agreement was reached regarding the plan, although it was extensively discussed among all parties. The plan recommendations included the following:

1) no changes in water flow or volume between March 1 and July 31 on either side of Bank Street with exceptions allowed for flooding for common bog practices (*e.g.*, late frost protection, fertilizer and herbicide application, etc.),
2) installation of an eel ramp with a 360 gallon per hour pump upstream of Bank Street at the existing dam between March 1 and July 31 to maintain adequate flow
3) sufficient October releases at the Bank Street dam to allow silver eels to exit Grass Pond and reach Saquatucket Harbor
4) regular communication among HCT, MassDMF and the bog owner about uses of water that will impact flows or eel migration.

The MEP assessment of the Saquatucket Harbor system, including Bank Street Bogs/Cold Brook was finalized in 2010, but most data collection occurred during 2004 to 2005 with estuarine water quality collected between 2001 and 2008.[22] The monitoring of Cold Brook included flow and water quality measurements over one hydrologic year (2004-2005) at a location upstream of Route 28. The assessment also included delineation of the overall Harbor watershed with subwatersheds for each of the streams and ponds, and collection of parcel-specific information to develop whole watershed and subwatershed nitrogen loads. The combined information was used to evaluate the site-specific attenuation of the Cold Brook subwatershed, as well as combined watershed/estuary water quality model. This MEP model has been validated against multiple datasets so that it can be reliably used to test nitrogen management strategies and their ability to attain the nitrogen TMDL.

There have been a number of projects in the Cold Brook area that have been conducted mostly following the MEP assessment. The town, CDM Smith, and CSP/SMAST contacted the various land owners and consultants who had conducted studies in the area and also discussed the various management objectives for the Cold Brook system. These studies and planning activities have included the following reports:

2007: Zaremba Environmental Consulting. Ecological Evaluation of the Bank Street Bog Complex. Completed for the Harwich Conservation Trust. 20 pp.

- Primarily characterized plant species found within HCT bog property, but also discussed potential management approaches (relatively passive vs. relatively active)
- Identified two rare plant species (thread-leaf sundew and freshwater cordgrass) as well as a significant number of invasive species

[21] MassDMF memo from Bradford Chase to HCT and John Sennott. March 15, 2011.
[22] Howes B., H.E. Ruthven, J.S. Ramsey, R. Samimy, D. Schlezinger, and E. Eichner. 2010.

- For the purposes of the survey, the site was divided into 8 areas. 274 plant species were listed within the overall bog system and within each area are noted in a table. Density/frequency is sometimes described in the area narratives, but not quantified for each area or for the overall system.

2010: Haley and Ward, Inc. Cold Brook Fishway Restoration Report. Completed for the Harwich Conservation Trust. 22 pp.

- Completed elevation surveys of selected connections ("flumes") between bog cells using "NAD83 datum."[23] Selected spot elevations throughout the system, but not a comprehensive survey of the channels and banks that could be used to determine potential volumes within each bog cell or the streams.
- Collected a single round of streamflow measurements to determine existing flows within the system (information not presented in report). Used these measurements to model stormflows (25 and 100 year storms) and propose designs for replacement and/or removal of existing culverts and water control structures within the bog
- Noted tidal influence within the bog system up to the irrigation pond outlet (site D in Figure 4), but unclear if this is salt water or retained freshwater
- Evaluated costs for removing selected flumes at four locations, installing pedestrian walkways and footbridges at four locations, and maintaining road access at one location

2011: Geosyntec Consultants. Cold Brook Tidal Assessment. Completed for Mass Department of Fish and Game, Division of Ecological Restoration. 10 pp.

- Installed 5 water level recorders with 6 minute recording intervals for 29 days between May 12 and June 10, 2011. Recorders were installed in an area generally between the bog and Saquatucket Harbor with a primary focus on the impact on tidal elevations of the dam between Route 28 and Hoyt Road (Figure II-4).
- Generally found that tidal movement was relatively unobstructed between gauge locations with truncation of the lower portion of the tidal range caused by higher channel elevations closer to and within the bog (Figure II-5). These readings were collected prior to the removal of the dam.
- Tidal recordings in Saquatucket Harbor show a much lower minimum tide (-3.21 ft) than the MEP readings for Saquatucket Harbor (-2.18 ft) (Table 1). The tidal range is similar between the two datasets but the mean elevations are generally between 1.04 and 1.19 ft lower in the Geosyntec readings than the MEP readings. This difference suggests a difference in the benchmark elevation datum.

[23] NAD83 is a horizontal datum, such as latitude and longitude. NAVD29 or NAVD88 would provide a standard vertical (elevation) datum.

2012: Horsley Witten Group. Sediment characterization including core samples and chemical analysis, well installation, and a ground penetrating radar (GPR) assessment of sand and peat horizons. Completed for Massachusetts Department of Fish and Game, Division of Ecological Restoration.

- GPR assessment completed by Hager GeoScience, Inc. (HGI) 13 pp. + 4 plates. The four plates show: 1) the GPR tracklines within the HCT bog system, 2) the bottom of the sand layer beneath the bog cranberry plants, 3) the bottom of the peat layer beneath the sand, and 4) the thickness of the peat. Depths of the sand ranged from 1 to 3 ft, while peat thicknesses ranged from 1.5 to >10 ft. The >10 ft thickness is in Cell 2 (Figure II-6) and had a depth greater than the radar signal. The series of peat filled basins appears to show that the original stream channel prior to the deposition of the peat was along a path different than the primary channel today.
- Beginning and end points for GPR tracklines had elevation data collected with Sokkia 2700 ISX RTK GPS, which has relative accuracy of less than 5 cm horizontally and 10 cm vertically. All elevations were reported relative to land surface rather than a common elevation datum. Depths of sand and peat were calculated by average electromagnetic wave velocities at various radar frequencies and, as such "should be used to provide trends only and not absolute depths." HGI predicted a ±10% depth error with potentially greater error where data separation is greatest.
- GPR signal quality can be confounded by brackish waters and HGI noted that readings in the southernmost portion of the bogs (Cells 7 and 8) had diminished signal quality and were likely more interpretative.
- The soil analysis results (primarily completed by ESS Laboratory, Cranston, RI) focus on lead, pesticides, semi-volatile hydrocarbons, metals, herbicides, nitrogen, and carbon. Notably, no phosphorus analysis was completed. Samples were collected from both sand and peat layers at 4 sites that matched well installations completed by HW, but details of sampling procedures are not provided. Sieve analysis was also completed on sand samples. No summary interpretation memo is provided.
- Laboratory results detected very low concentrations or trace detections of various pesticides or breakdown products, as well as arsenic, chromium, beryllium, zinc, and lead in both sand and peat, but all concentrations are below the most stringent of MassDEP standards (*i.e.*, soils in drinking water supply areas (S1/GW1)).
- Well logs show that well holes were hand augered and wells were generally 4 to 7 feet deep with continuously slotted or perforated PVC throughout their depth. Most well holes encountered medium to coarse sand after passing through 1 to 3 feet of peat.

2013: Massachusetts Department of Fish and Game, Division of Ecological Restoration. Planning process summary. 6 pp.

- Proposed plan for changes to HCT bog system with management goals in each bog cells, including:
    a) reorientation of existing berms and construction of walking trails and four footbridges,
    b) reorientation of stream channel and digging of new portions,

c) filling and grading of irrigation pond and parts of existing stream channel,
d) excavation of sand from large areas of southern bogs,
e) removal of large areas of underlying peat in northern bogs,
f) modification of the Bank Street culvert,
g) removal of dam at south of Hoyt Road.

Alternatives are also presented for more extensive system changes. No management proposals are offered for Grass Pond or assessment of potential impacts on Saquatucket Harbor or meeting its nitrogen TMDL.

2014: Stantec Consulting Services, Inc. Letter summarizing site visit at Carding Mill Dam on Cold Brook between Hoyt Road and Route 28. Completed for Massachusetts Department of Fish and Game, Division of Ecological Restoration. 5 pp.

- Site visit completed to "observe the dam and adjacent structures to prepare a scope of work for preparation of a reconnaissance level report describing a potential approach for removal of the dam."
- Concluded that "the severely deteriorated condition of the dam necessitates that immediate measures be taken to substantially remove or repair it." Primary concern is that "stone masonry wall along the right side of the outlet conduit is in a state of incipient failure, that this failure will result in a collapse of the overlying cut stone blocks, and that this collapse will likely result in occlusion of the outlet conduit."
- Dam was removed in March 2014.[28]

2014: Horsley Witten Group. Memorandum to Franz Ingelfinger, Massachusetts Department of Fish and Game, Division of Ecological Restoration, RE: 2014 Hydrologic Data Update Report. 22 pp.

- Measurement of instantaneous streamflow at four locations within Bank Street Bogs on eight visits between May and August 2014. Developed rating curves at three locations (SG1, SG2, and SG3) with relatively poor correlations (R^2 between 0.45 and 0.76). Noted increased flow from upstream to downstream and suggested that the weir upstream of Bank Street is likely "artificially" holding back upstream water from entering the Bank Street bogs.

2015: Princeton Hydro, LLC. Charrette Summary Memorandum, HCT's Bank Street Bogs Nature Preserve to Franz Ingelfinger, Massachusetts Department of Fish and Game, Division of Ecological Restoration. 12 pp.

- Design charrette was held June 17, 2015 with interested parties to discuss site details and a design concept. PH prepared a design concept that is largely similar to the 2013 MassDER proposal while acknowledging that "there are still issues that bear further consideration and are continuing subjects of discussion."

[28] Before and after pictures are available at: http://harwichconservationtrust.org/cold-brook-dam-removal-project/

Table II-1. Comparison of MEP and Geosyntec Tidal Elevations in Saquatucket Harbor. All elevations in feet NAVD88. The tidal range is similar between the two datasets but the mean Geosyntec elevations are generally ~ 1.1 ft lower than the MEP elevations, which suggest that the benchmark elevation datum are different in the two datasets.

measure	Geosyntec	MEP	Difference
	H5 station	Harbor station	
	feet NAVD88	feet NAVD88	feet
Mean Higher High Water	2.18	3.34	1.16
Mean High Water	1.83	2.87	1.04
Mean Tide Level	-0.14	0.98	1.12
Mean Low Water	-2.11	-0.92	1.19
Mean Lower-Low Water	-2.39	-1.23	1.16
Tidal Maximum	3.18	4.17	0.99
Tidal Minimum	-3.21	-2.18	1.03
Mean Tide Range	3.93	3.79	-0.14

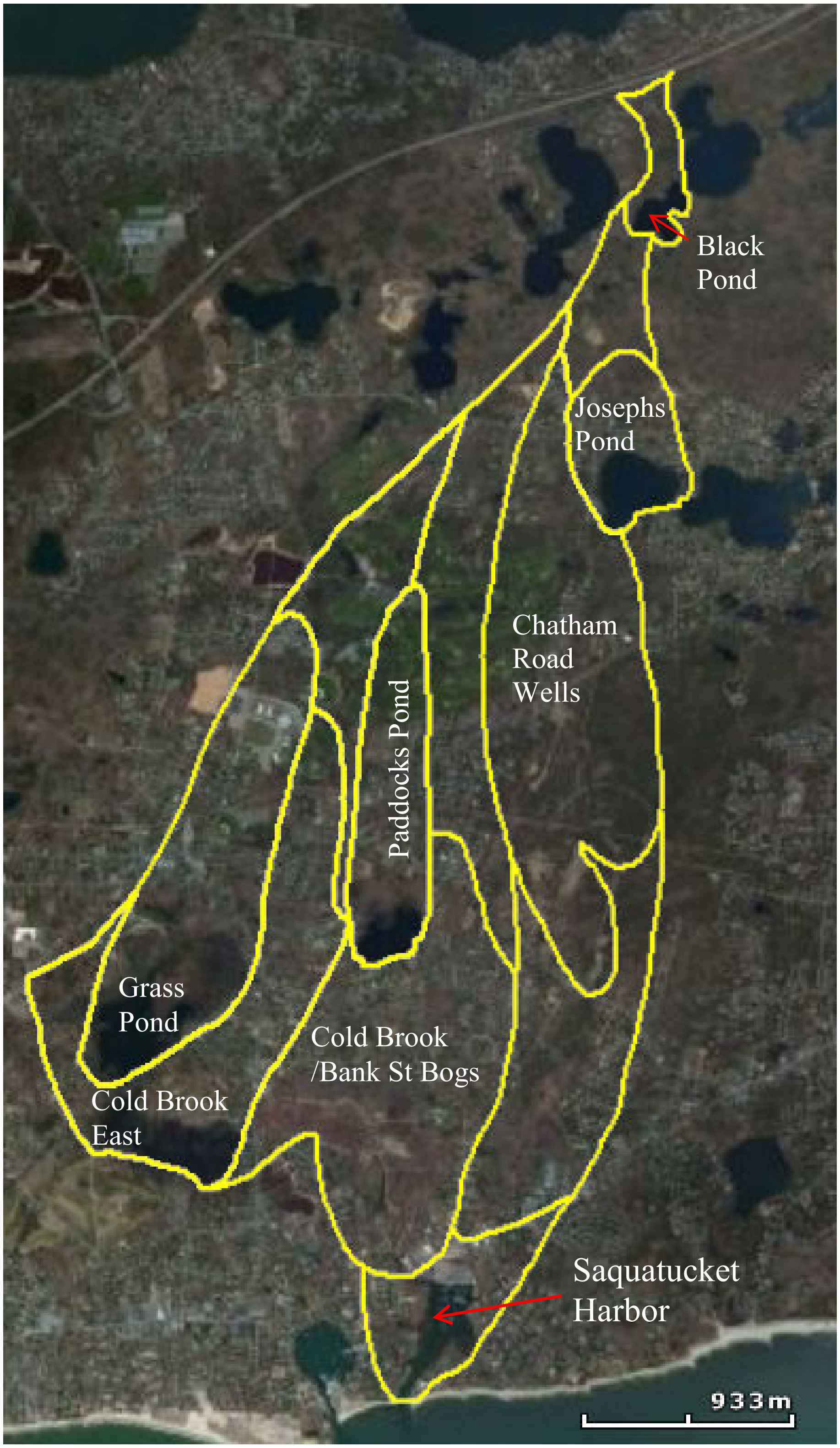

Figure II-1. Saquatucket Harbor Watershed. Watershed from 2010 MEP report showing subwatersheds to ponds, public water supply wells, and streams within the overall Harbor contributing area. Streamflow measurements at Hoyt Road confirm the estimated watershed flow based on watershed as shown.

Figure II-2. 1964 Aerial Photograph of Andrews River Estuary, Harwich. Andrews River was dredged in 1968-1969 to create Saquatucket Harbor. The southern portion of the Cold Brook/Bank Street cranberry bog system is shown in the upper portion of the photo.

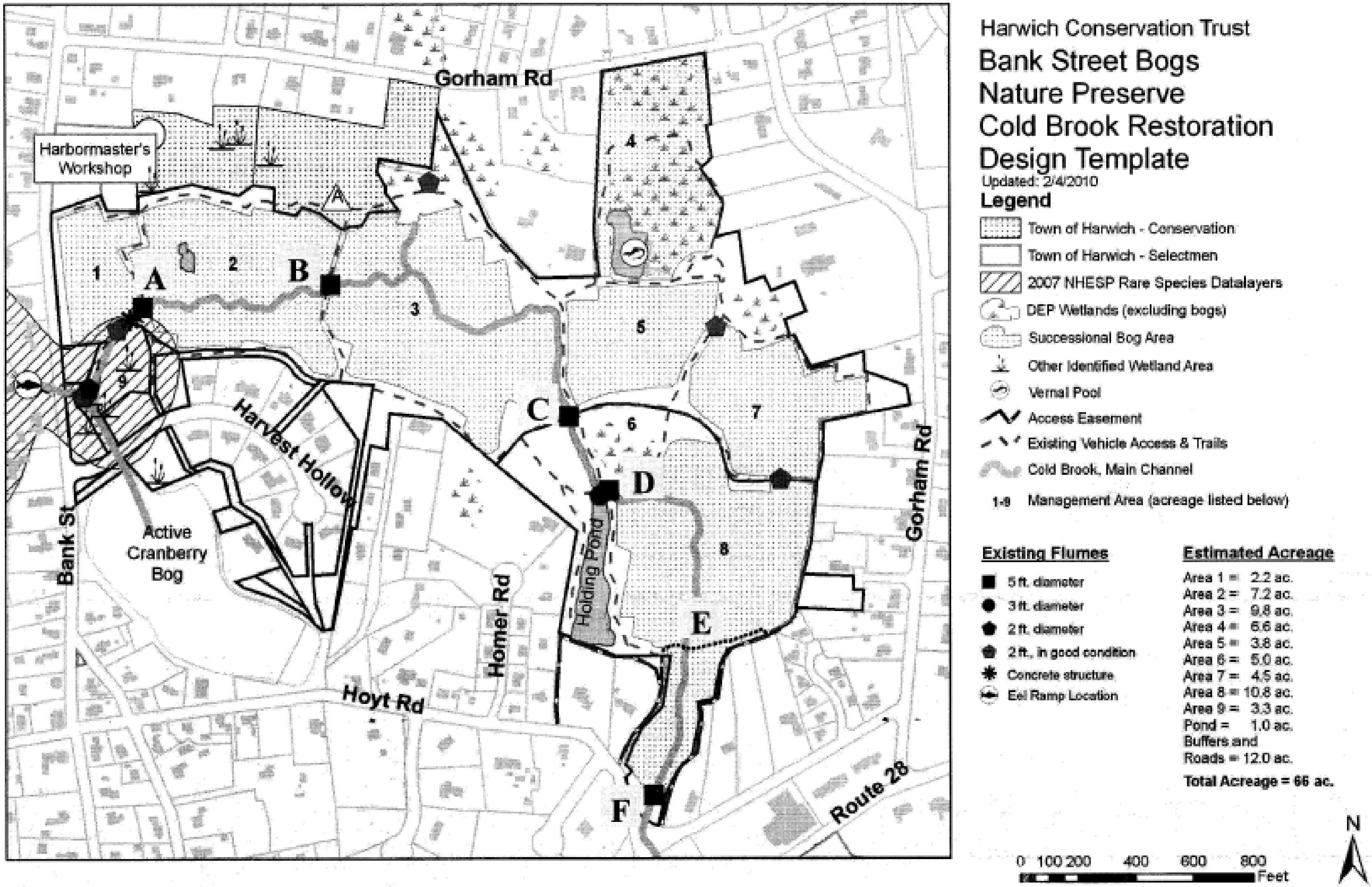

Figure II-3. Location of flume control structures with the Bank Street Bogs/Cold Brook study area. Flume structures can be opened or closed to allow water to move between bog cells. Modified from Attachment A in Haley and Ward, Inc. (2010).

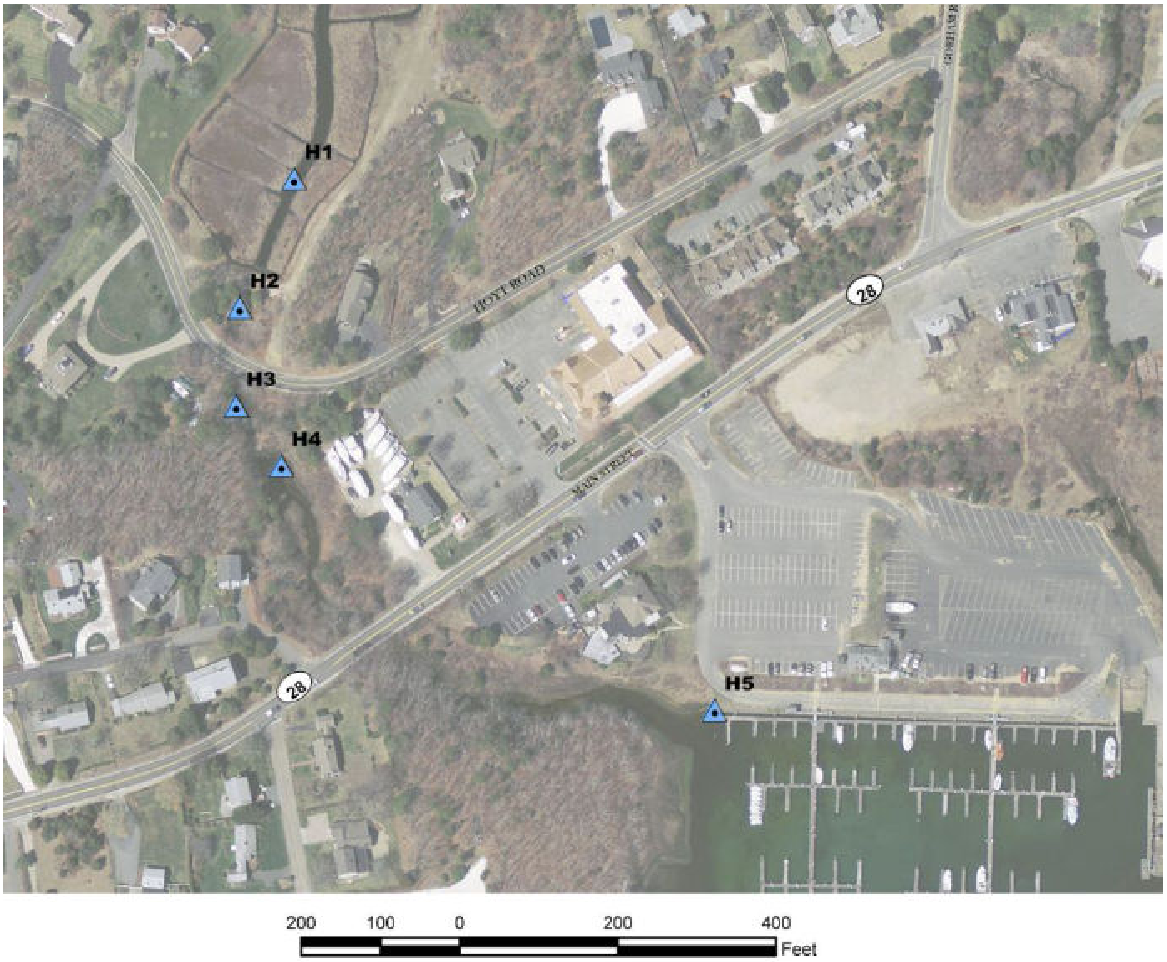

Figure II-4. Cold Brook tide gauges locations for Geosyntec Consultants. Gauges (5) were installed and recorded between May 12 and June 10, 2011 (29 days) using 6 minute recording intervals. Modified from Figure 4 in Geosyntec Consultants (2011).

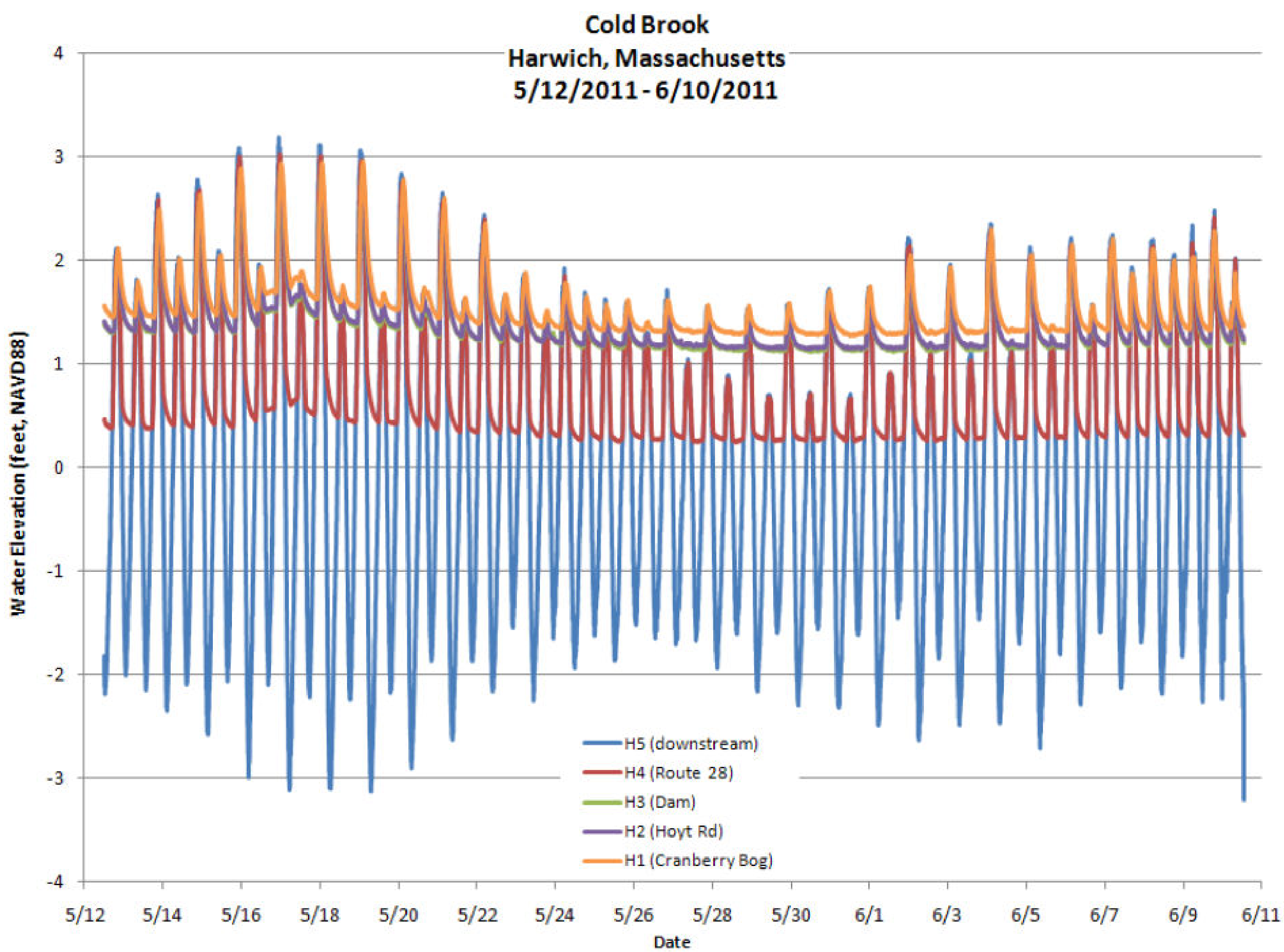

Figure II-5. Cold Brook tidal elevation record for Geosyntec Consultants. Generally tidal flow generated roughly equivalent high tide heights throughout the system. Significant truncation of the lower portion of the tidal range is caused by higher channel bottom elevations found closer to and within the bog. This is typical of salt marsh systems where the low tides are higher than adjacent coastal waters. Modified from Figure 1 in Geosyntec Consultants (2011).

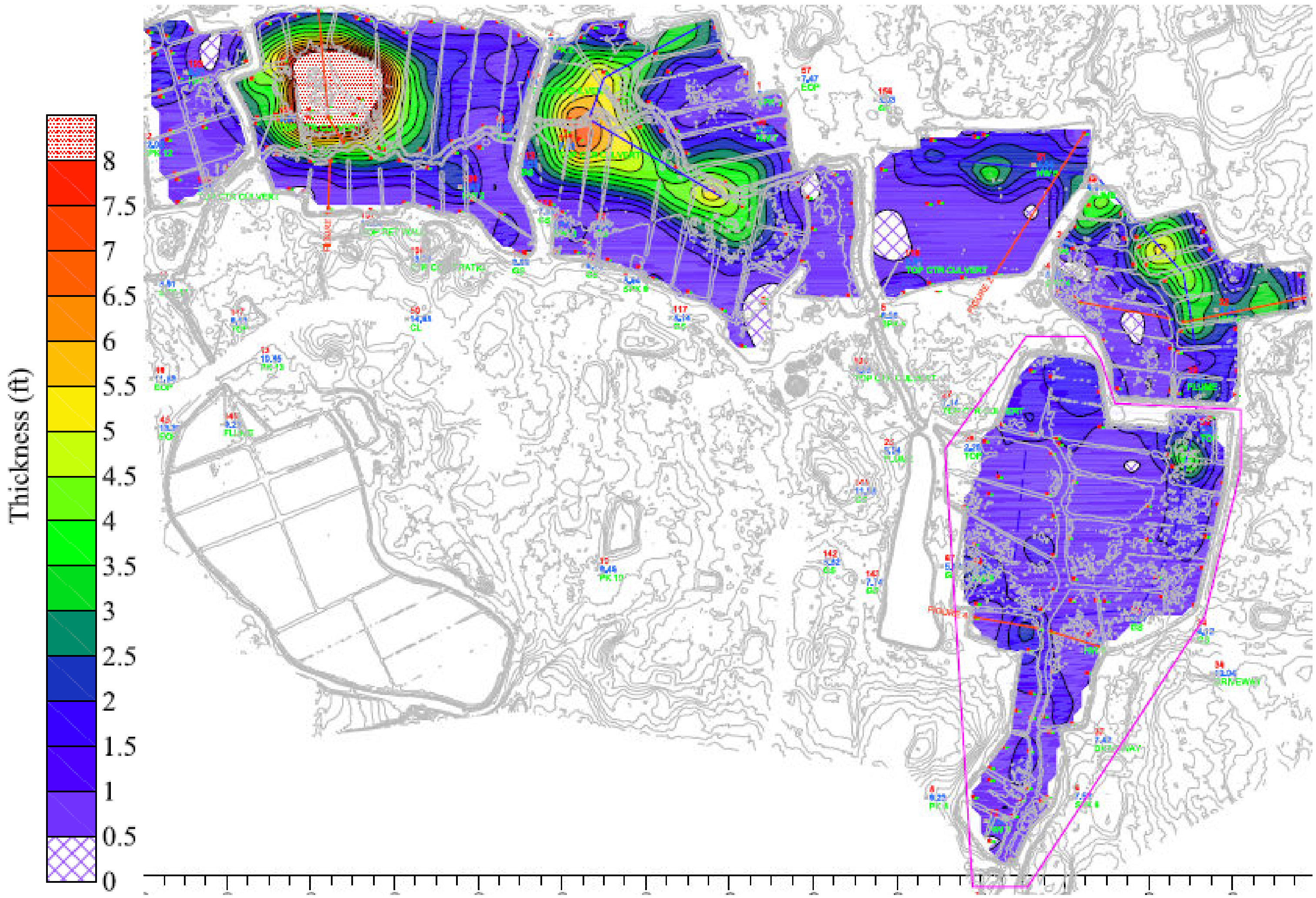

Figure II-6. Peat Depth estimated from Ground Penetrating Radar Assessment of Cold Brook Bog. GPR assessment was completed by Hager GeoScience, Inc. (HGI); modification of Plate 4. Peat thicknesses ranged from 1.5 to >10 ft (±10% depth error). The >10 ft thickness exceeded the radar signal and is located in Cell 2 in the northwest portion of the bog system. The series of peat filled basins appear to be residuals of the original stream channel prior to the deposition of peat. HGI also encountered diminished signal quality in the southernmost cells outlined in pink, potentially due to presence of residual salinity from tidal waters.

III. Physical Features: Elevations, Volumes

Following the review of the projects completed in and around the Bank Street Bog/Cold Brook system, it was clear that there were a number of data gaps, as well as pieces of information/data that had not been reviewed together to ensure that all of them were congruent. In preparation of development management options, CSP/SMAST reviewed the available data and supplemented it to fill in identified key data gaps. This section discusses the elevation survey and determination of bog cell volumes of the Bank Street Bogs.

The Cold Brook Bog system includes six bog cells, surrounding upland, and a former irrigation pond. The bog cells are generally separated by access roads with flume structures or culverts that allow water to pass to the next downgradient cell. CSP/SMAST staff collected elevation data in transects across the bog surfaces, in the channels, and along the margins rising to the surrounding upland. Elevations were determined using a Leica Viva GNSS/GPS with RTK enabled. Approximately 1,355 point elevation readings were collected (Figure III-1). A single nearby reference point, <15km away, gave elevation accuracies on the order of +/-10 mm. All elevations are in NAVD88.

Based on the CSP/SMAST elevation data, project staff determined the average, maximum, and minimum elevations within each of the bog cells (Table III-1). The bog cells generally have a gentle gradient along Cold Brook; mean elevation of the bog surface in Cell 1 was 2.0 m NAVD88 and the mean elevation in Cell 6 is 0.93 m NAVD88 (Figure III-2). Maximum bog surface elevations within the cells generally range between 1.7 and 2.2 m NAVD88 with minimums generally ranging between 0.4 and 1.7 m NAVD88. Project staff also determined the total volume of each cell; this was completed using the minimum and maximum bank elevations and resulted in a large range of volumes. Bank elevations have large ranges with differences between minimum and maximum elevations averaging 1.3 m.

Comparison of the bog surface elevations to the peat depths developed by HGI in 2012 (see Figure II-6) shows that the bottom of the peat deposition in Cells 2, 3, and 5 are very similar at -1 to -1.5 m NAVD88. This finding means that prior to the peat deposition, these depressions likely functioned like separate, small ponds along the flow path of Cold Brook. Peat deposition can have a wide range of rates (1.4 to 15 cm/100 years).[25] Since peat is formed from partially decayed plant materials and the continental ice sheets that formed Cape Cod left the region 15,000 to 17,000 years ago, peat deposition could not have started in the deepest depressions until ice sheets left and wetlands had formed. Based on the range of deposition, the depth of peat in the deepest depression (>2.5 m) and what is known about peat formation in this region, it is likely that peat deposition would likely have occurred between 5,000 and 10,000 years ago. .

Elevations and depths were also determined within the former irrigation pond, which is located along the western edge of Cell 6. The pond had a surface area of 4,098 sq m (~1 acre) and a maximum depth of 2.6 m (elevation of -2.1 m NAVD88). The deepest portion is located in its southern portion across a relatively flat bottom (Figure III-3). Based on the bathymetry, the pond volume was 5,874 m^3. At the same time as elevation data was collected, project staff also measured sediment thickness in the pond. Maximum sediment thickness was ~1 m with the thickest deposits in deeper portions of the pond with the largest area at the northern extent of the main basin (Figure III-4).

[25] Martini, I.P., A. Martinez Cortizas, and W. Chesworth. 2007. *Peatlands: Evolution and Records of Environmental and Climate Changes*. Elsevier Science. 606 pp.

Table III-1. Bank Street Bog Elevation Summary. Elevations were collected between October and December 2015 using a Leica Viva GNSS/GPS with RTK enabled. All elevations are in NAVD88 with accuracies on the order of +/-10 mm. Cell volumes are based on both minimum and maximum bank elevations. The minimum and maximum bank elevations are generally defined as the spot along a bank where the rate of elevation change decreases to near zero. Slight variations in cell area also are listed that were the result of alterations in the selection of the bank height.

Cell	Cell Volume		Cell Area		Bog Surface Elevation			Creek/Channel Elevation			Bank Elevation		
	Min Bank	Max Bank	Min Bank	Max Bank	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean
	m3	m3	m2	m2	m	m	m	m	m	m	m	m	m
1	3,900	15,225	8,715	9,458	2.25	1.73	2.01	1.76	1.23	1.49	3.63	2.00	2.74
2	12,043	31,300	27,608	27,913	2.01	1.00	1.65	1.39	0.61	1.04	2.70	1.39	2.31
3	14,413	52,509	34,783	37,219	1.97	1.03	1.41	1.04	-0.15	0.68	2.72	1.35	2.07
4	6,951	18,456	15,125	15,675	1.67	1.48	1.59	1.30	1.25	1.27	2.74	2.09	2.30
5	9,068	31,735	16,881	17,004	1.83	1.06	1.30	1.01	0.25	0.72	2.97	1.50	1.88
6	12,306	71,233	38,862	41,245	1.67	0.40	0.93	1.37	-0.27	0.26	2.52	1.15	1.70

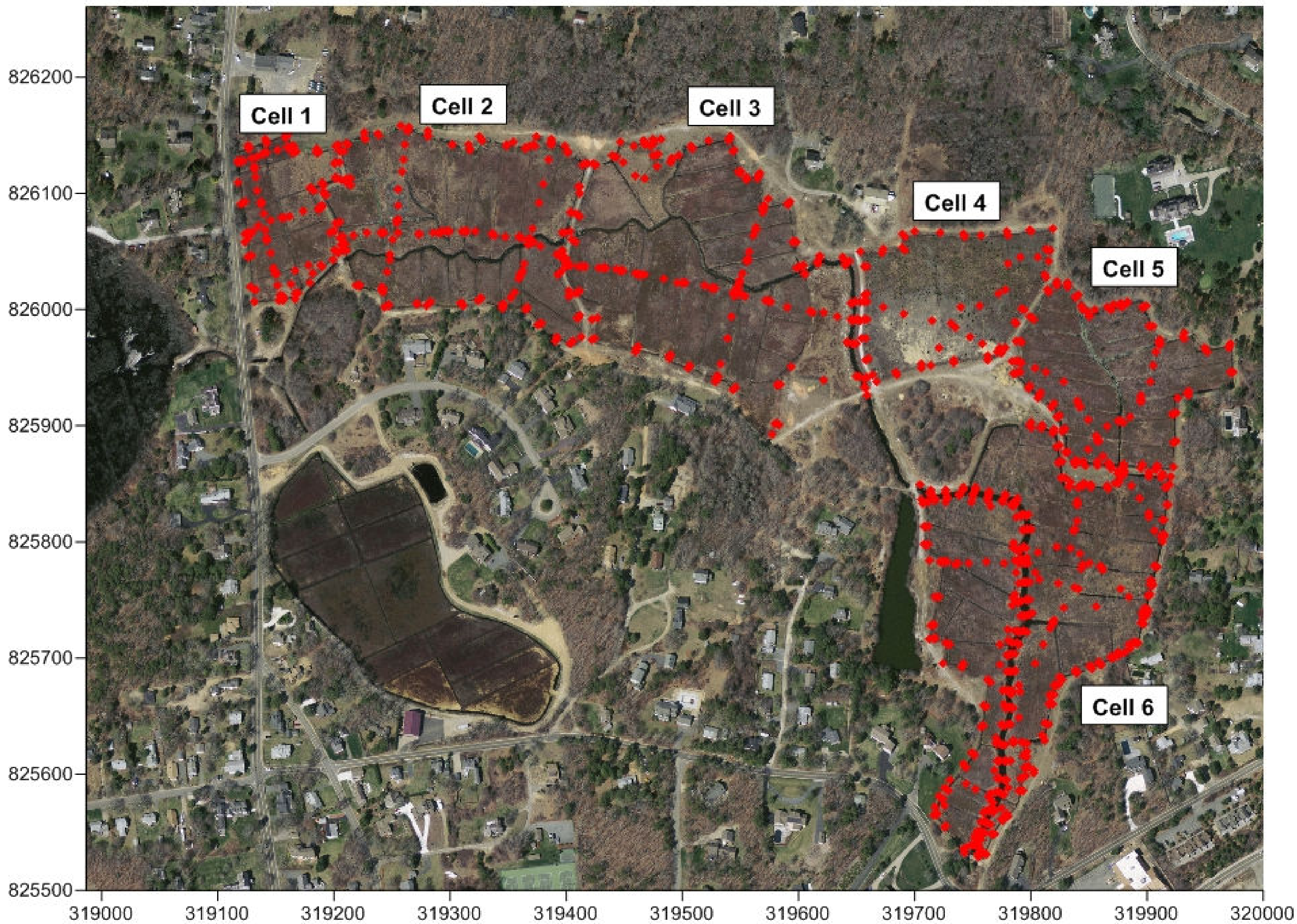

Figure III-1. Bank Street Bogs/Cold Brook Elevation Survey. Elevations were collected at each indicated point between October and December 2015 using a Leica Viva GNSS/GPS with RTK enabled.

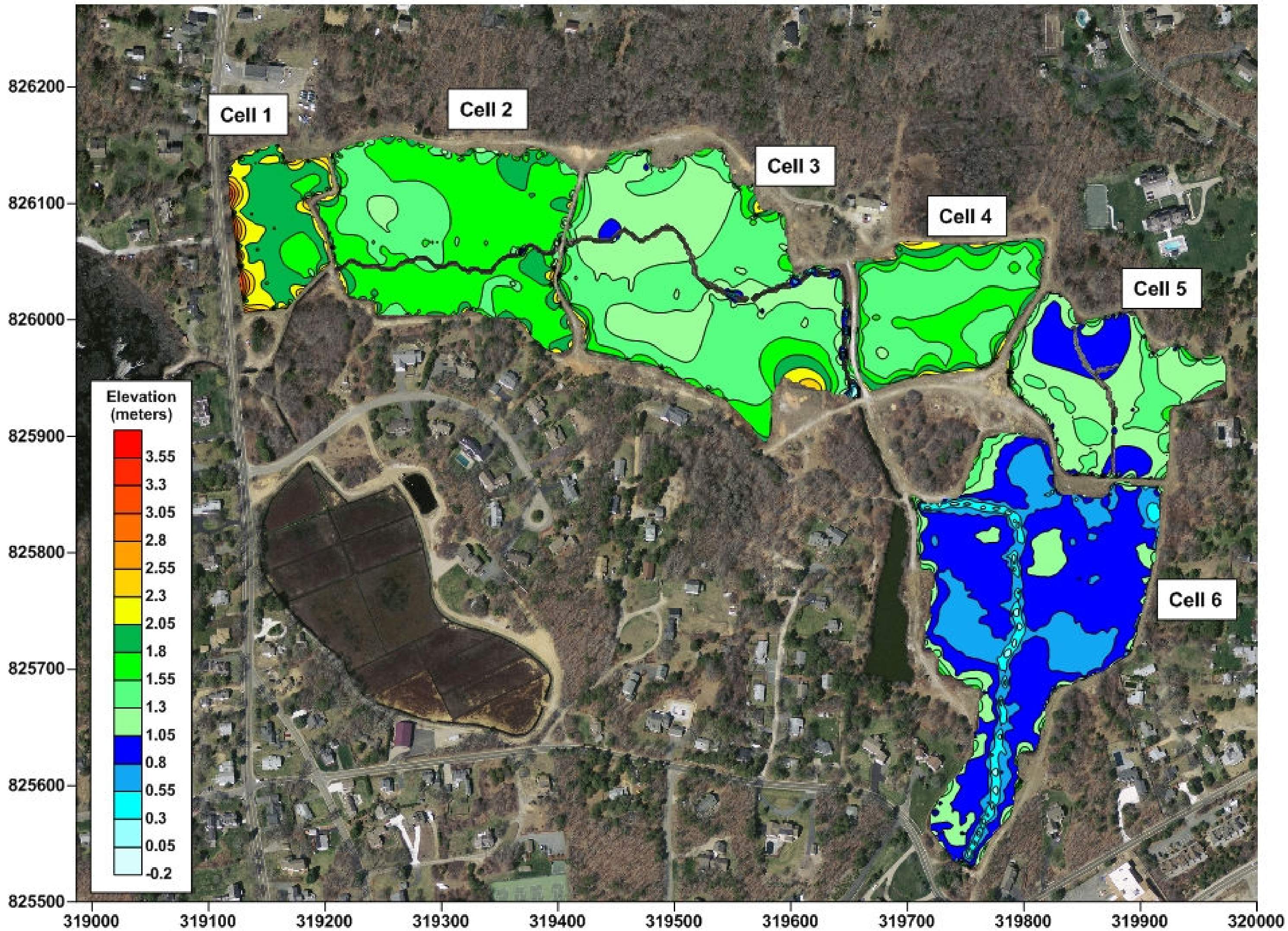

Figure III-2. Bank Street Bogs/Cold Brook Elevations. All elevations are in NAVD88 with an accuracy of +/-10 mm. Mean bog surface elevations begin at 2.01 m in Cell 1 and gradually decrease to 0.93 m in Cell 6.

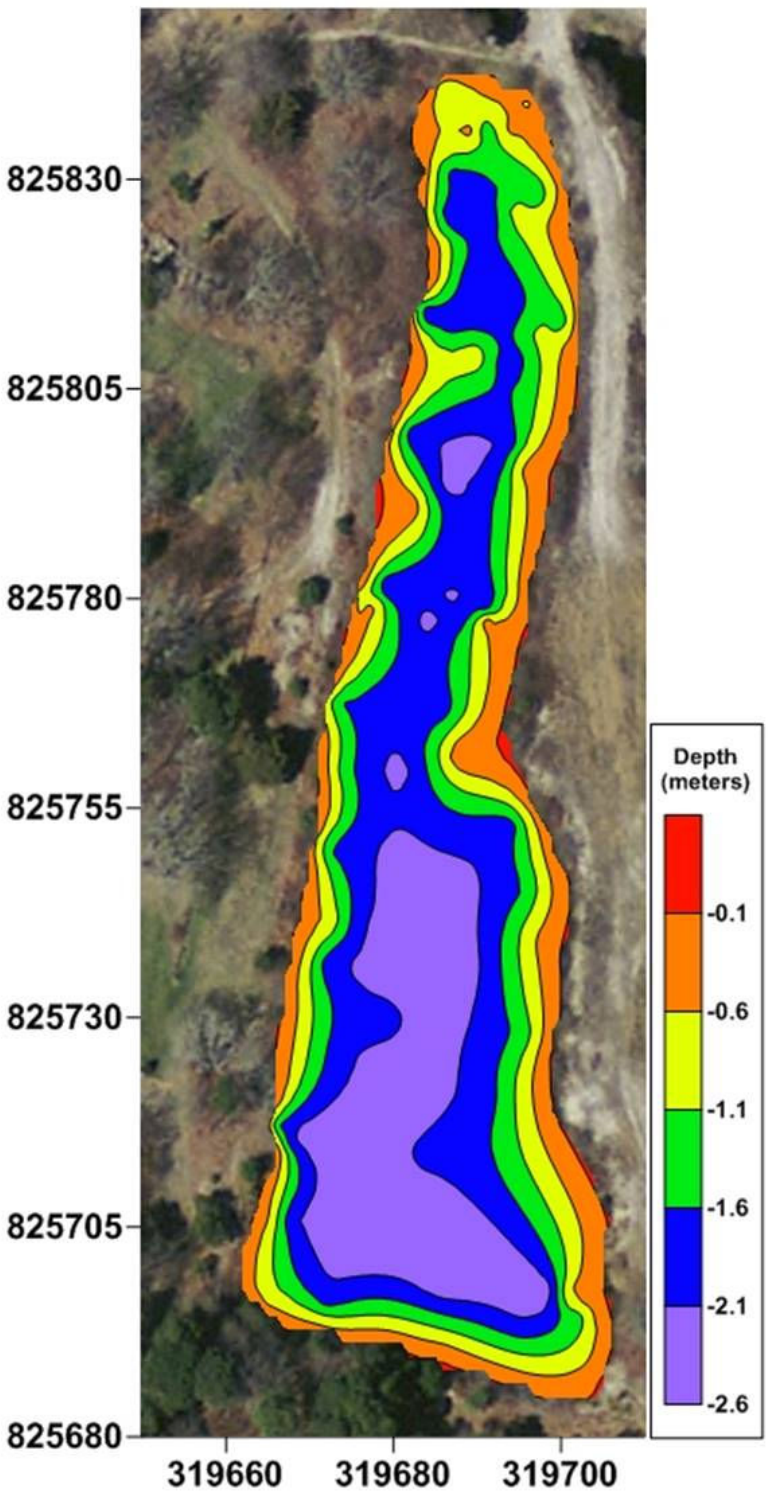

Figure III-3. Bathymetry of former Irrigation Pond. CSP-SMAST staff collected bathymetric data on July 21, 2015 and August 21, 2015 using a RTK GPS unit and depth rod (a depth rod with cm increments was used due large amounts of aquatic vegetation). All depth and position data were recorded into a laptop computer using hydrographic software (HYPACK) integrating the dGPS position (NAD83) and depth measurements into a single data set.

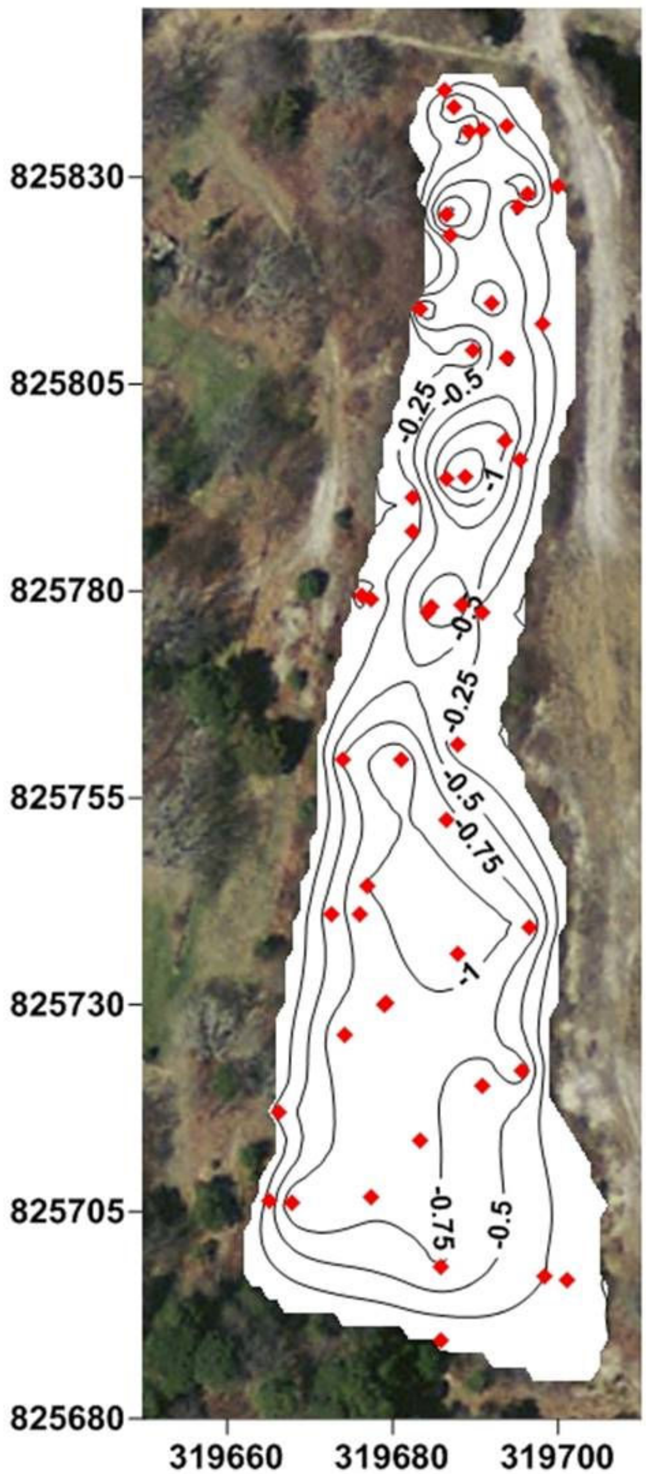

Figure III-4. Sediment depth in former Irrigation Pond. Soft sediment thickness is presented in meters below pond bottom. Sediments were measured on July 21, 2015 by pushing a depth rod (cm increments) to depth of refusal following a modified grid with more extensive readings in selected areas. Locations were recorded using a RTK GPS unit and contoured using hydrographic software (HYPACK) integrating the dGPS position (NAD83) and sediment depth measurements into a single data set.

IV. Water Flows: Flow Measurements, Watersheds, and Water Budget

In order to assess water flows and nutrient loads, CSP/SMAST staff developed and implemented a refined monitoring program, which included annual time-series measurements of water flows and nutrient concentrations throughout the bog system. Water flows were measured at eight stations and were supplemented with stream gauges at four stations (Figure IV-1). Instantaneous flow measurements were collected at all stations between July 8, 2014 and July 7, 2015. Measurements continued at stations CB-1, CB-6, and CB-8 were extended until September 21, 2015 as part of the assessment of the irrigation pond. Flow measurements and water quality samples were collected on a schedule of: a) weekly during warmer months (four events per month, May thru September), b) biweekly during temperature transition months (two events per month for October, and April), and c) once per month during colder temperature months (November thru March). A minimum of 30 instantaneous flow measurements and water quality samples were collected at all stations and 35 were collected at the "extended" stations (CB-1, CB-6, and CB-8). Stream gauges for continuous measurements were located at the inflow of Cold Brook to the Bank Street Bog system (CB-1), at the inlet/outlet of the connected, active cranberry bog (CB-2), as flow exited Cell 3 (CB-5), and as Cold Brook flowed out of the Bank Street Bog system (CB-8). Stream gauges recorded water levels every 10 minutes.

Both instantaneous and continuous stream gauge flow readings at CB-1 and CB-2 were generally highly variable due to the regular manipulation of the Bank Street dam flow control structures just upstream of CB-1 and the boards at the cranberry bog just upstream of CB-2. Field observations at CB-1 and CB-2 often found still water at the gauges with little or no movement, so flow readings at the two sites are less frequent than at the other measurement stations. Both gauges were found to have been manipulated and sometimes buried by sediments due to work on up-gradient culverts. As such, the gauges had to be moved during the period of deployment, with gauge elevation surveyed for each placement. Mean flow at CB-1 among available instantaneous readings where flow was observed was 1,062 m^3/d (n=19), while the mean flow at CB-2 was 168 m^3/d (n=11) (Figure IV-2). Stream gauge readings were also impacted by the changes in the control structures, but there were periods when flow did not appear to be subject to significant impacts. During these periods, flows at CB-1 and CB-2 generally moved in tandem; for example, between 8/1/14 and 12/28/14, before a large water release from the Bank Street dam upstream of CB-1, the relationship between stage readings at CB-1 and CB-2 had an R^2 of 0.95. The subsequent perturbations in flow impacted the stream gauge readings and a reliable annual stage-discharge relationship could not be developed from the available readings (Figure IV-3).

The CB-3 and CB-4 stations were downstream of CB-1 and located at the boundary between cranberry bog cells; CB-3 was between Cell 1 and Cell 2, while CB-4 was between Cell 2 and Cell 3. Both stations had instantaneous streamflow measurements, but did not have stream gauges installed. Mean flow of the instantaneous readings at CB-3 was 987 m^3/d (n=28), while the mean flow at CB-4 was 2,395 m^3/d (n=30) (see Figure IV-2). The mean flow at CB-3 is not statistically different from the mean flow at CB-1 (1,062 m^3/d), indicating little to no increase in flow between the two stations. Given that field observations noted flow into the cranberry bog past CB-2, some of the flow from CB-1 may have been drained off to the bog with only a portion returning to Cold Brook on an annual basis. In order to resolve the relationships between flows at CB-1, CB-2, and CB-3, additional gauge records would be required, along with coordination with bog owner to ensure that instantaneous flows measured water flow into or out of the bog. Mean flow at CB-4 is 2.4 times higher than mean flow at CB-3.

CB-5 was located where Cold Brook flows out of the upper cells of the system (bog Cells 1 through 3). Both instantaneous and continuous stream gauge readings were conducted at this site. The mean of the instantaneous flow data at CB-5 was 4,632 m^3/d (n=30), which is 1.9 times higher than mean flow at CB-4 (Figure IV-4). The stream gauge at CB-5 collected 52,421 stage readings between July 8, 2014 and July 7, 2015. This data was adjusted to remove periodic tidal influences. Comparison of stage readings and flow measurements allowed the development of a reliable stage-discharge rating curve ($R^2 = 0.90$). Using this curve, the converted stage readings at CB-5 had a mean predicted flow of 7,321 m^3/d over the complete water year (Figure IV-5). Since the stream gauge continuously collects readings, the mean gauge reading is more representative of average flow conditions at CB-5 than the instantaneous readings.

CB-6 was located at the former irrigation pond inlet, so it was influenced by flows from CB-5, tidal changes from downstream, and flows in and out of the irrigation pond. Instantaneous flow measurements at CB-6 were targeted for periods of ebb flow in the system and had a mean flow of 1,791 m^3/d (n=34) (see Figure IV-4). Mean flow at CB-6 is roughly equivalent to average flow at CB-4 (2,395 m^3/d).

CB-7 was located downstream and east of CB-6 and on the downstream side of a culvert which was replaced on 4/18/16. Mean instantaneous flow at CB-7 was 6,771 m^3/d (n=29), which is roughly additive of the mean flows at CB-5 and CB-6 (see Figure IV-4). As with flows at CB-5 and CB-6, flows were collected during periods to minimize or avoid tidal influences. Instantaneous flows generally were low at the beginning of the monitoring period in July 2014 (mean of first four readings = 4,424 m^3/d), rose in late winter and spring to a peak in March 2015 (max 16,791 m^3/d), and decreased in the following months but remained higher than seen in the previous year (mean of last four readings = 10,312 m^3/d).

CB-8 was located just upstream of Hoyt Road where Cold Brook flows out the Bank Street Bogs system and had both instantaneous readings and continuous stream gauge readings. Mean instantaneous flow at CB-8 was 11,193 m^3/d (n=35), which is 1.7 times higher than mean flow at CB-7 (see Figure IV-4). The stream gauge at CB-8 collected 62,642 stage readings between July 8, 2014 and September 21, 2015. This data was adjusted to remove tidal influences. Comparison of stage readings and flow measurements allowed the development of a reliable stage-discharge rating curve ($R^2 = 0.91$). Using this curve, the converted stage readings at CB-8 had a mean predicted annual freshwater flow of 13,004 m^3/d based on a complete water year (Figure IV-6). Since the stream gauge continuously collects readings, the mean gauge reading is more representative of average flow conditions than the instantaneous readings.

The average CB-8 flow of 13,004 m^3/d was slightly higher than the average 10,329 m^3/d measured between September 1, 2004 and August 31, 2005. The CB-8 gauge was at nearly the same location as the Cold Brook gauge during the MEP assessment of Saquatucket Harbor.[26] The MEP assessment compared the measured annual flow and the watershed necessary to support that flow using the MEP subwatersheds delineated by the US Geological Survey based

[26] Howes B., H.E. Ruthven, J.S. Ramsey, R. Samimy, D. Schlezinger, and E. Eichner. 2010.

on the regional groundwater model[27]. The analysis showed a good fit with only a 13% difference in the modeled and measured freshwater flows. Review of annual precipitation shows that the 2014/2015 water year (September to August) was ~8% higher than the prior 15 year average; similar comparison of the MEP 2004/2005 sampling period was ~6% lower than the 15 year average. Review of groundwater levels also confirm higher than average elevations beginning in January 2015 and preceded by a rapid increase from below average levels in December 2014 (Figure IV-7). Above average levels were sustained through June 2015. Instantaneous flow readings at most the stream stations peaked in March, which would be consistent with groundwater levels.

The MEP watershed to Cold Brook also included subwatersheds to Grass Pond and Paddocks Pond (see Figure II-1). The Cold Brook watershed area is bordered by watersheds to: a) Herring River to the north and west, b) East Saquatucket stream to the east, and c) Wychmere Harbor to the west. MEP stream measurements within the Herring River and the East Saquatucket stream confirmed the USGS subwatershed modeling as reasonable and within likely variations of the groundwater model. The USGS model estimated that a flow of 4,431 m3/d would flow to the Bank Street outlet at the head of the Bank Street bogs (CB-1). Measurements collected in this project generally show that flow at CB-1 significantly impacted by board manipulation, but flow was usually a fraction of the estimated, modeled flow. However, flow at the outlet of the Bank Street bog system (CB-8) was still a reasonable match for the USGS modeled flow given the model variability and year-to-year variability in precipitation and groundwater levels. Since flows are based on the contributing area and recharge within that area, the measured flow data at CB-1 and CB-8 suggests that large portions of the subwatershed to CB-1 should more correctly be assigned to CB-8.

Comparison of flow rates between stations reinforces this conclusion. Average flow between stations CB-3 and CB-4 was 6.4 m^3/d per m of stream bed, while average flow between stations CB-4 and CB-5 was a similar 5.7 m^3/d/m. However, between CB-5 and CB-7 the rate increases to 20 m^3/d/m and then decreases to 10.2 m^3/d/m between CB-7 and CB-8. This increase in flow as Cold Brook flows to the east and toward the outlet supports the idea that the subwatershed area feeding this portion of the Brook is larger than has been conceptualized, is consistent with observed lower flows at CB-1, and the on-going difficulties in maintaining adequate flow for herring to reach Grass Pond.

Another consideration is the seasonal effect on flow. Summer (June to September) flows at all stations except CB-6 are less than winter (October to May) flows (Figure IV-8). Summer flow reductions are significant ($\rho<0.05$) at CB-2, CB-3, CB-4, CB-5, and CB-8; seasonal reductions at CB-1 and CB-7 are significant at a $\rho<0.1$ level. Mean flow out of the former irrigation pond (CB-6) was statistically the same in summer (1,824 m^3/d) and winter (1,562 m^3/d). These flows suggest that the retention time in the pond and its connection to surrounding groundwater system maintain a relatively stable pond elevation even when the rest of the streamflows decrease during the summer. Mean summer decreases from winter flows at the other stations were: 77%/78% at CB-1/CB-3, 64% at CB-4, 45% at CB-5, 28% at CB-7 and 35% at CB-8.

[27] Walter, D.A. and A.T. Whealan. 2005. Simulated Water Sources and Effects of Pumping on Surface and Ground Water, Sagamore and Monomoy Flow Lenses, Cape Cod, Massachusetts. U.S. Geological Survey Scientific Investigations Report 2004-5181.

Review of the measured outflow at CB-6 suggests that much of this flow results from tidal water introduced during high tides returning to Cold Brook during the ebb portion of the tide. Review of the tidal prism at CB-5 (the closest continuous stream gauge) has a tidal range that would result in an estimated flow of 2,100 m^3/d out of the irrigation pond when the tide ebbs. This flow is reasonably close to the summer and winter flow averages of 1,824 m^3/d and 1,562 m^3/d, respectively. If the measured flows were sustained by freshwater, the recharge area to sustain these flows would be approximately 200 acres or approximately 20-25% of the overall Cold Brook watershed. Since the average salinity in the CB-6 samples is 3.3 ppt, it further suggests that the water pushed into the irrigation pond during high tides is mostly Cold Brook water backed up by the rise of the tides in the lower portion of the Bank Street Bogs system.

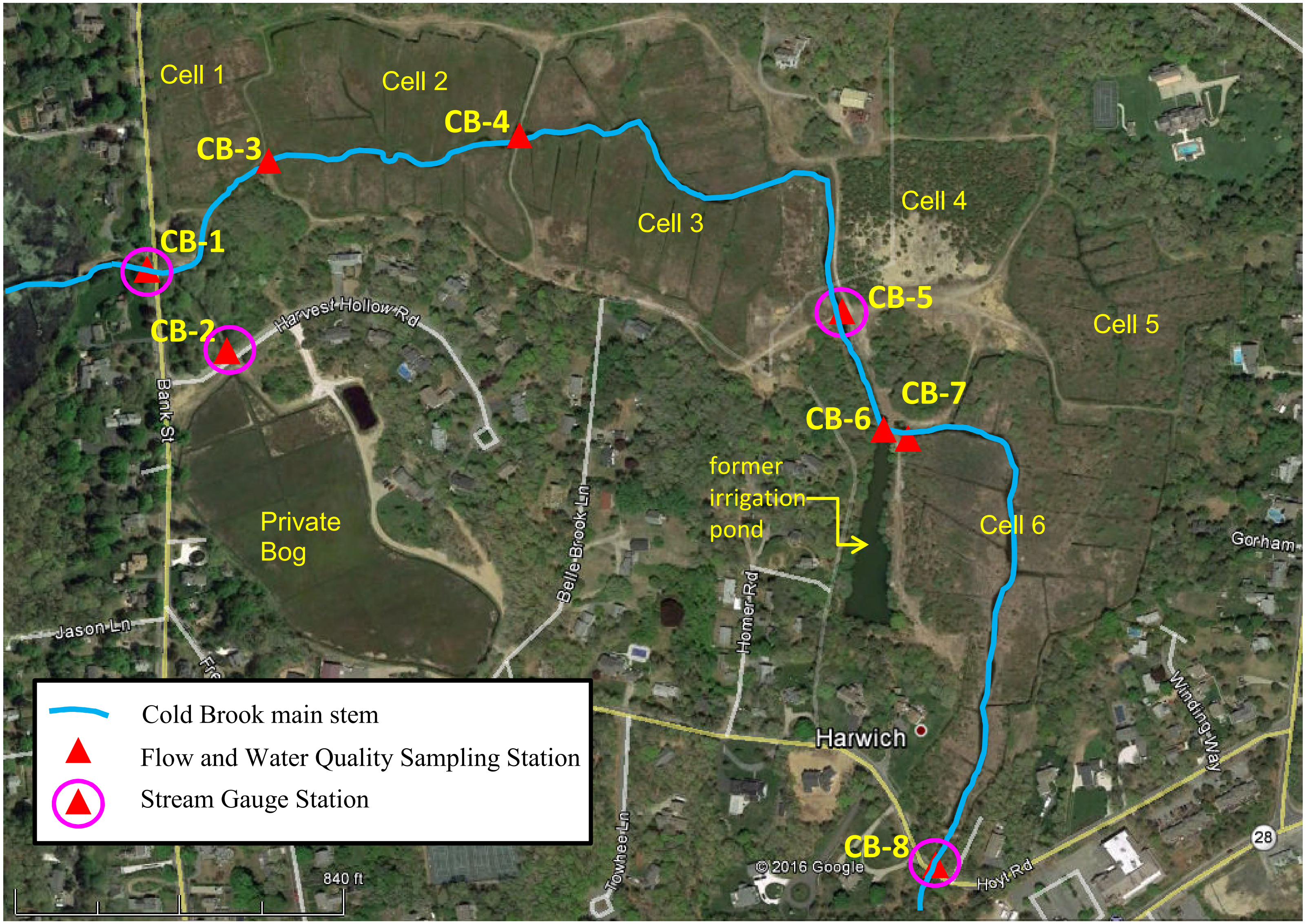

Figure IV-1. Bank Street Bogs/Cold Brook Flow, Water Quality and Stream Gauge Stations. Stream gauges recorded stage readings every 10 minutes between July 2014 and September 2015, while other sampling stations had instantaneous flow readings and water quality samples collected at least monthly with weekly frequency during the summer and biweekly during spring and fall.

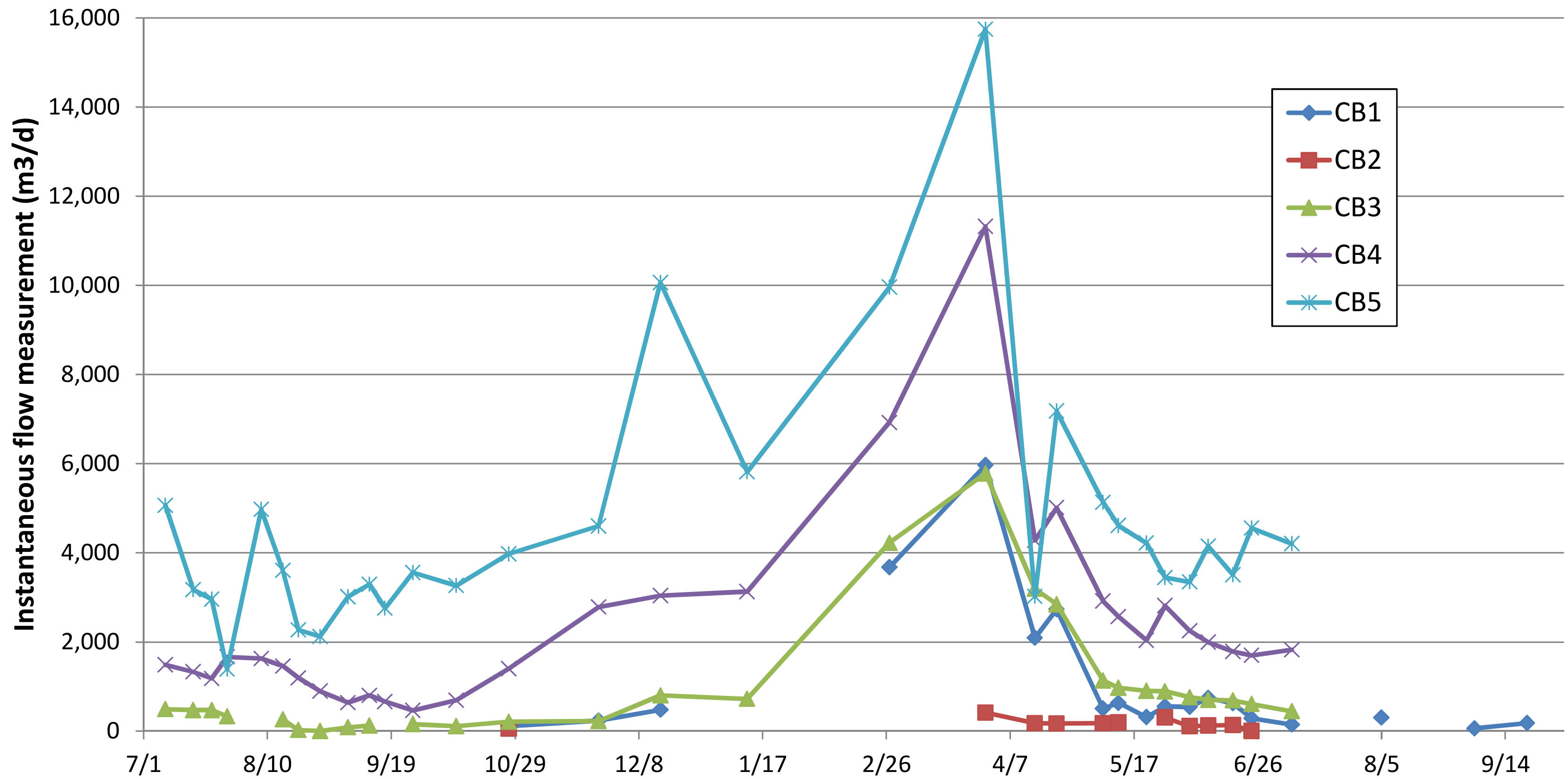

Figure IV-2. Bank Street Bogs Instantaneous Flow at Stations CB-1 through CB-5 (July 2014 to September 2015). Flow readings were recorded at least monthly with weekly frequency during the summer and biweekly during spring and fall. Water quality samples were collected each time flow readings were measured. Readings at CB-1 and CB-2 were often limited by lack of flowing water on sampling dates; these readings and data outliers have not been included in this figure. Readings at CB-1, CB-2, and CB-8 continued from July 2014 until September 2015, while CB-3 and CB-4 were recorded between July 2014 and July 2015. Number of instantaneous readings ranged from 11 (CB-2) to 35 (CB-8).

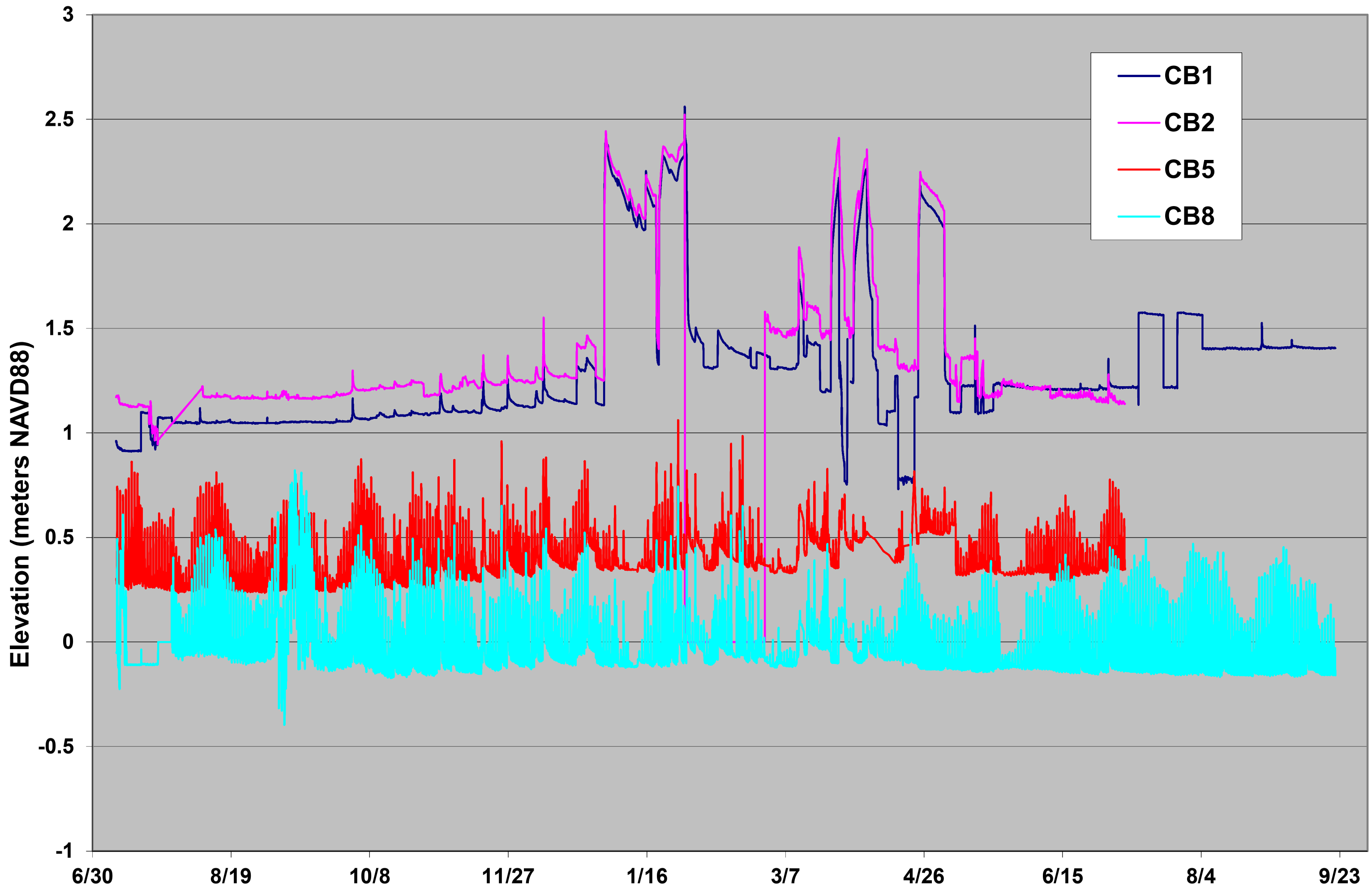

Figure IV-3. Stream gauge stage recordings: CB-1, CB-2, CB-5, and CB-8. The overall inconsistency of the readings at CB-1 and CB-2 did not allow construction of reliable stage-discharge relationships. The inconsistent readings were likely due to the regular manipulation of the Bank Street dam flow control structures just upstream of CB-1 and the boards at the cranberry bog just upstream of CB-2. Readings at CB-5 and CB-8 were adjusted to remove tidal influences and comparison of stage readings and flow measurements allowed the development of reliable stage-discharge rating curves that had mean predicted flows of 7,321 m^3/d and 13,004 m^3/d, respectively, based on complete water years.

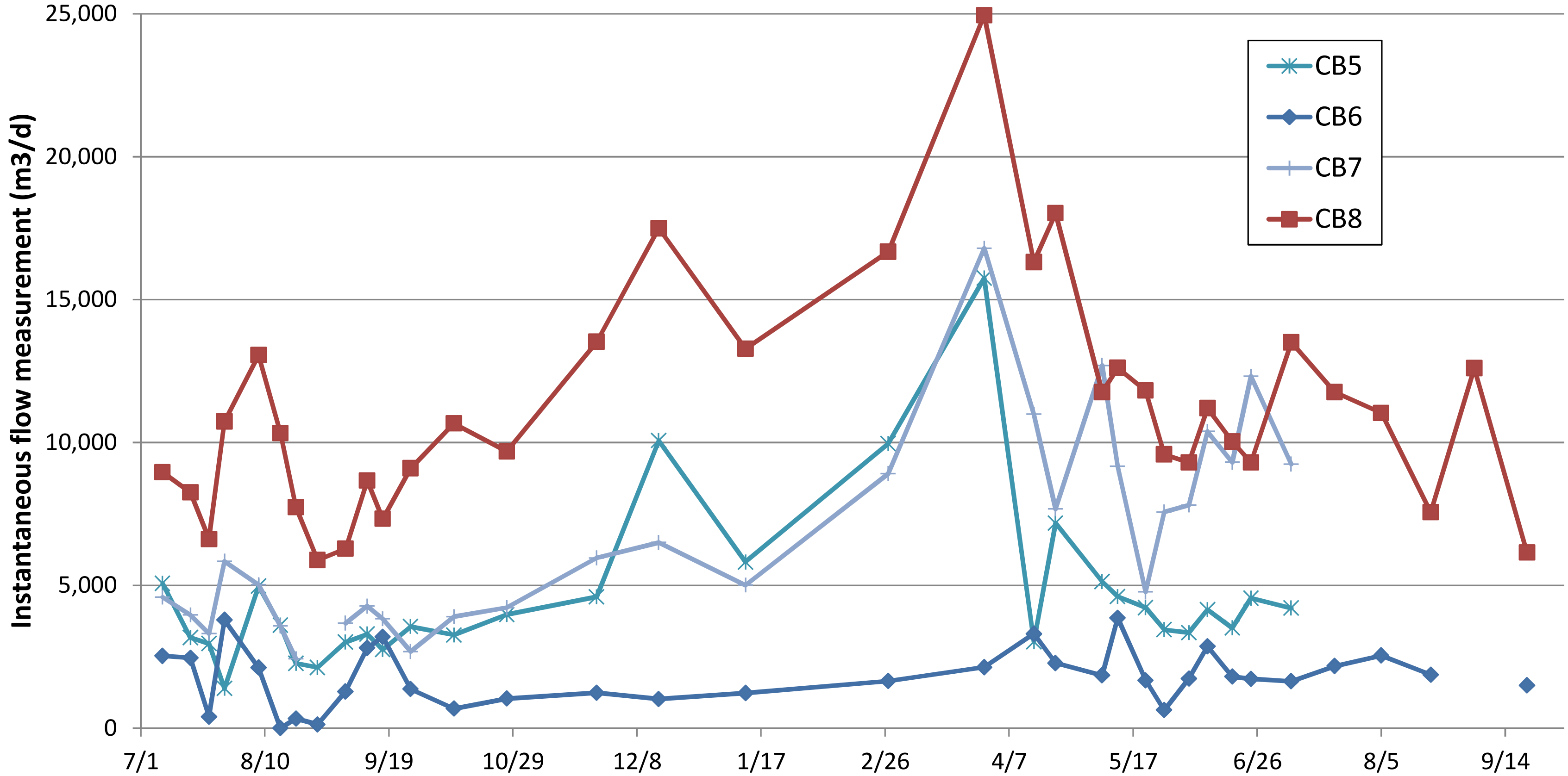

Figure IV-4. Bank Street Bogs Instantaneous Flow at Stations CB-5 through CB-8 (July 2014 to September 2015). Flow readings were recorded at least monthly with weekly frequency during the summer and biweekly during spring and fall. Water quality samples were collected each time flow readings were measured. Readings at CB-6 and CB-8 continued from July 2014 until September 2015, while readings at CB-5 and CB-7 were recorded between July 2014 and July 2015. Number of instantaneous readings ranged from 29 (CB-7) to 35 (CB-8). CB-6 is at the inlet to the pond and is not in the main channel.

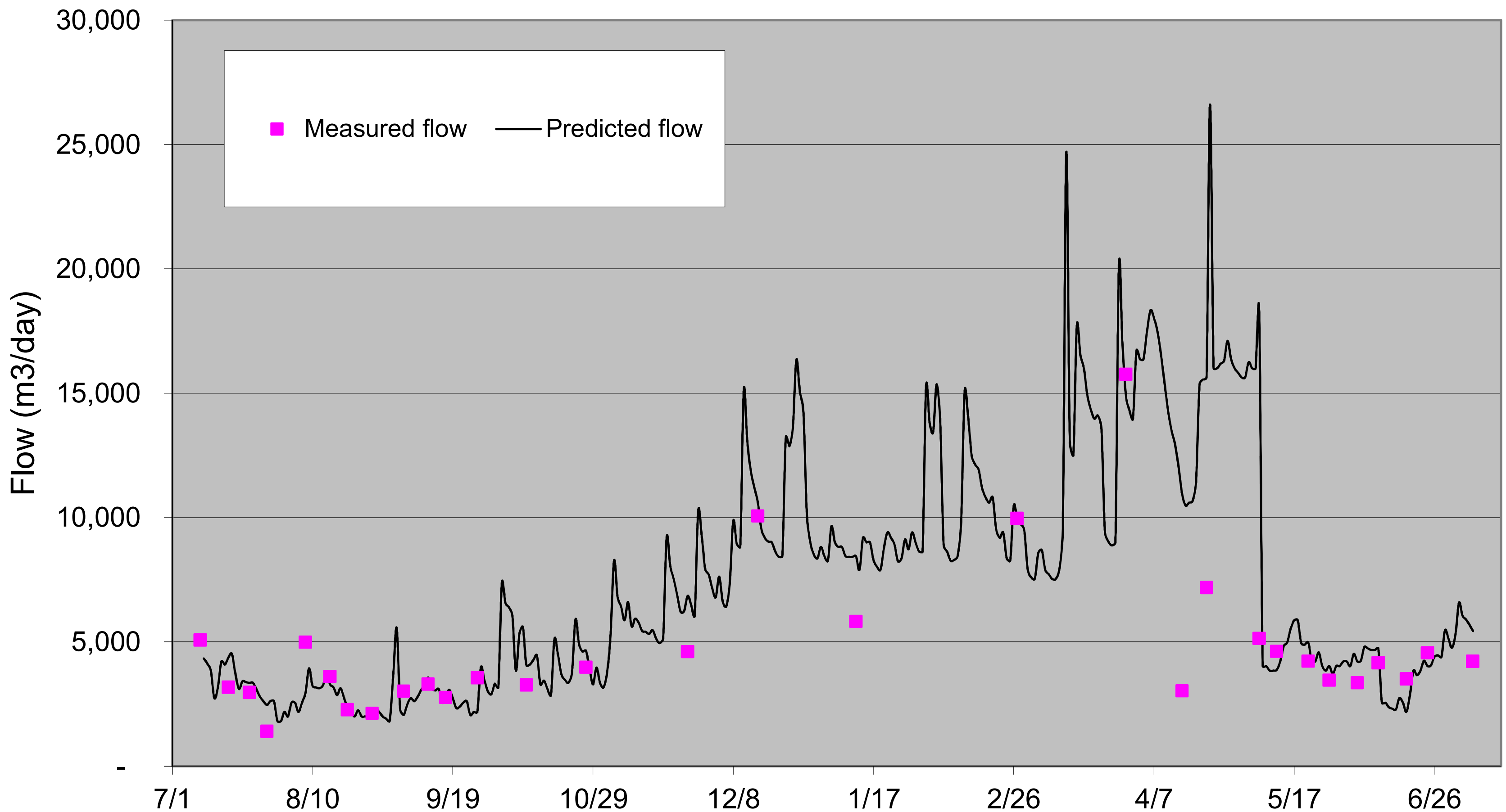

Figure IV-5. Predicted flow at CB-5 based on stage data. The stream gauge at CB-5 was programmed to collect a stage reading every 10 minutes and collected 52,421 stage readings between July 8, 2014 and July 7, 2015. This data was adjusted to remove tidal influences and comparison of stage readings and flow measurements (shown as point measurements in the figure) allowed the development of a reliable stage-discharge rating curve ($R^2 = 0.90$). This curve was used to develop the predicted stream flows shown in the figure; the mean predicted flow based on a complete water year was 7,321 m^3/d.

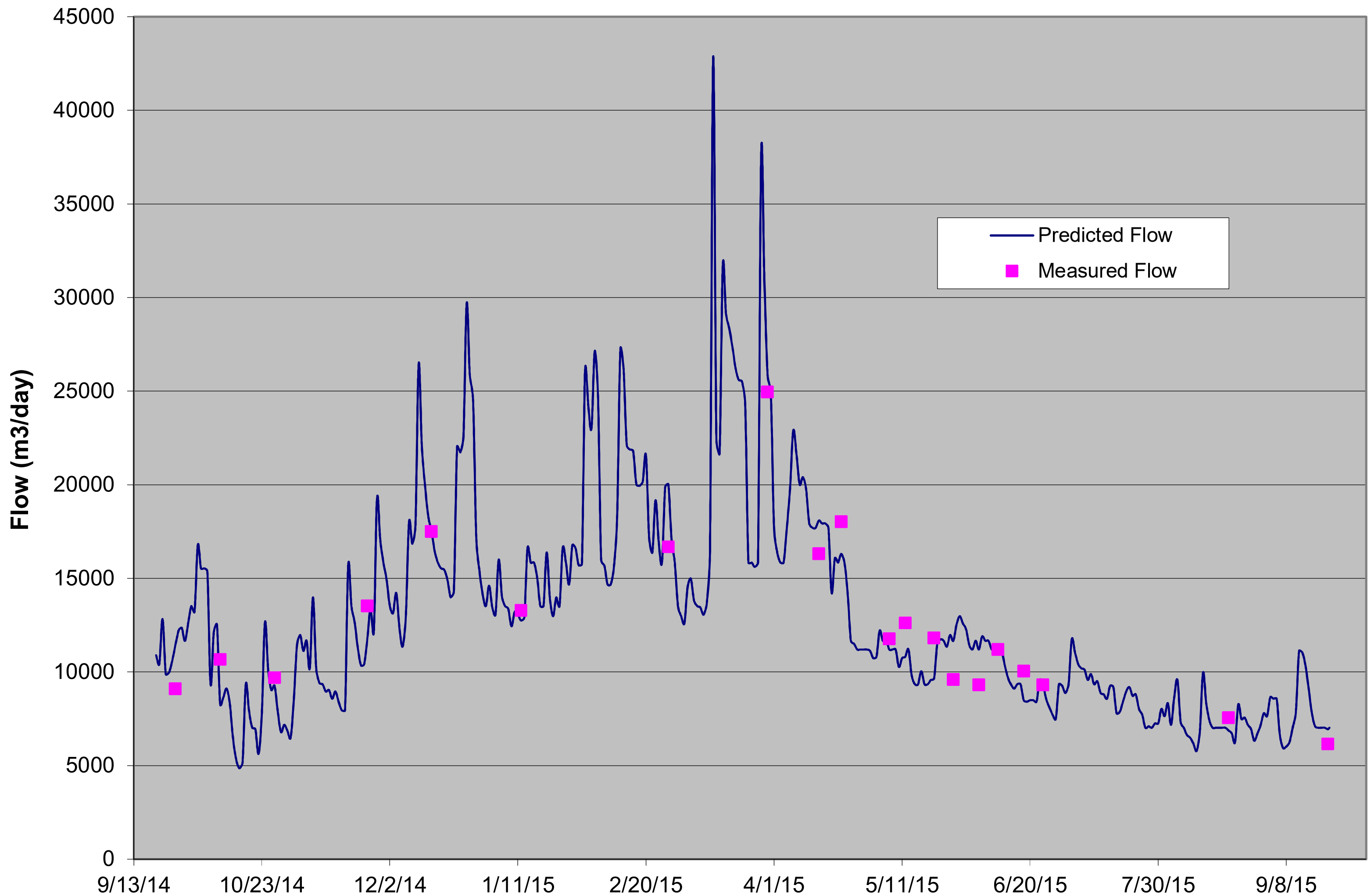

Figure IV-6. Predicted flow at CB-8 based on stage data. The stream gauge at CB-8 was programmed to collect a stage reading every 10 minutes and collected 62,642 stage readings between July 8, 2014 and September 21, 2015. This data was adjusted to remove tidal influences, targeted for a September/September water year, and comparison of stage readings and flow measurements (shown as point measurements in the figure) allowed the development of a reliable stage-discharge rating curve (R^2 = 0.91). This curve was used to develop the predicted stream flows shown in the figure; the mean predicted flow based on a complete water year was 13,004 m^3/d.

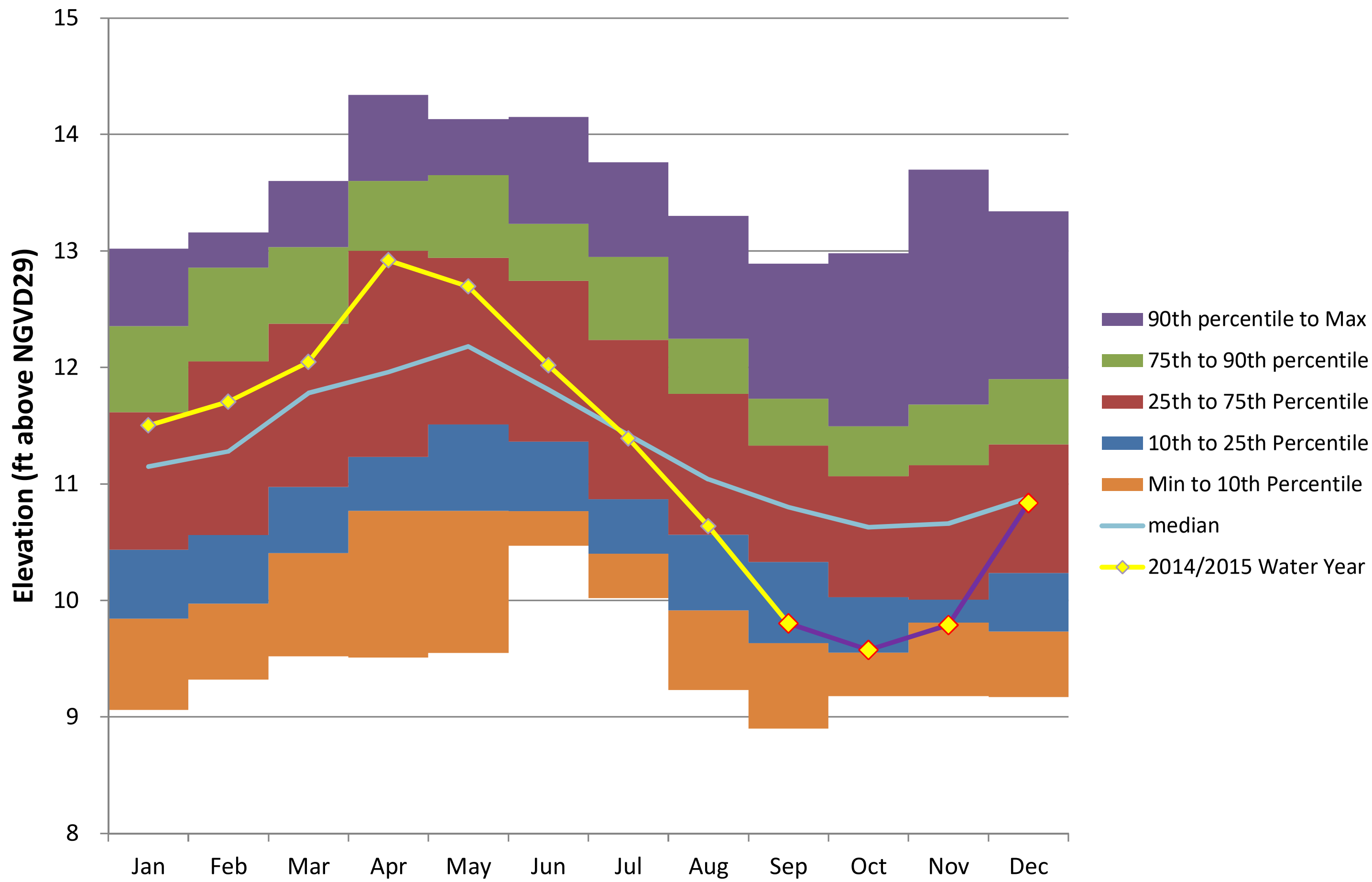

Figure IV-7. Groundwater Elevations during 2014/2015 Water Year (CGW138). CGW138 is a groundwater well where water levels have been measured mostly monthly for more than 50 years. Project staff developed monthly percentile ranges and median elevations and compared these to monthly readings during the 2014/2015 water year when flow readings were collected in Cold Brook. Water levels in September and October 2014 began near the 10th percentile before recovering to approximately median levels in December (purple line and red outlined datapoints). Between January and May, groundwater elevations were near the 75th percentiles for each month before declining to median levels in July and near the 25th percentile in August (yellow line and datapoints). Stream flow readings at all stations reached maximum flows in late March, which coincides with the maximum groundwater levels during the water year.

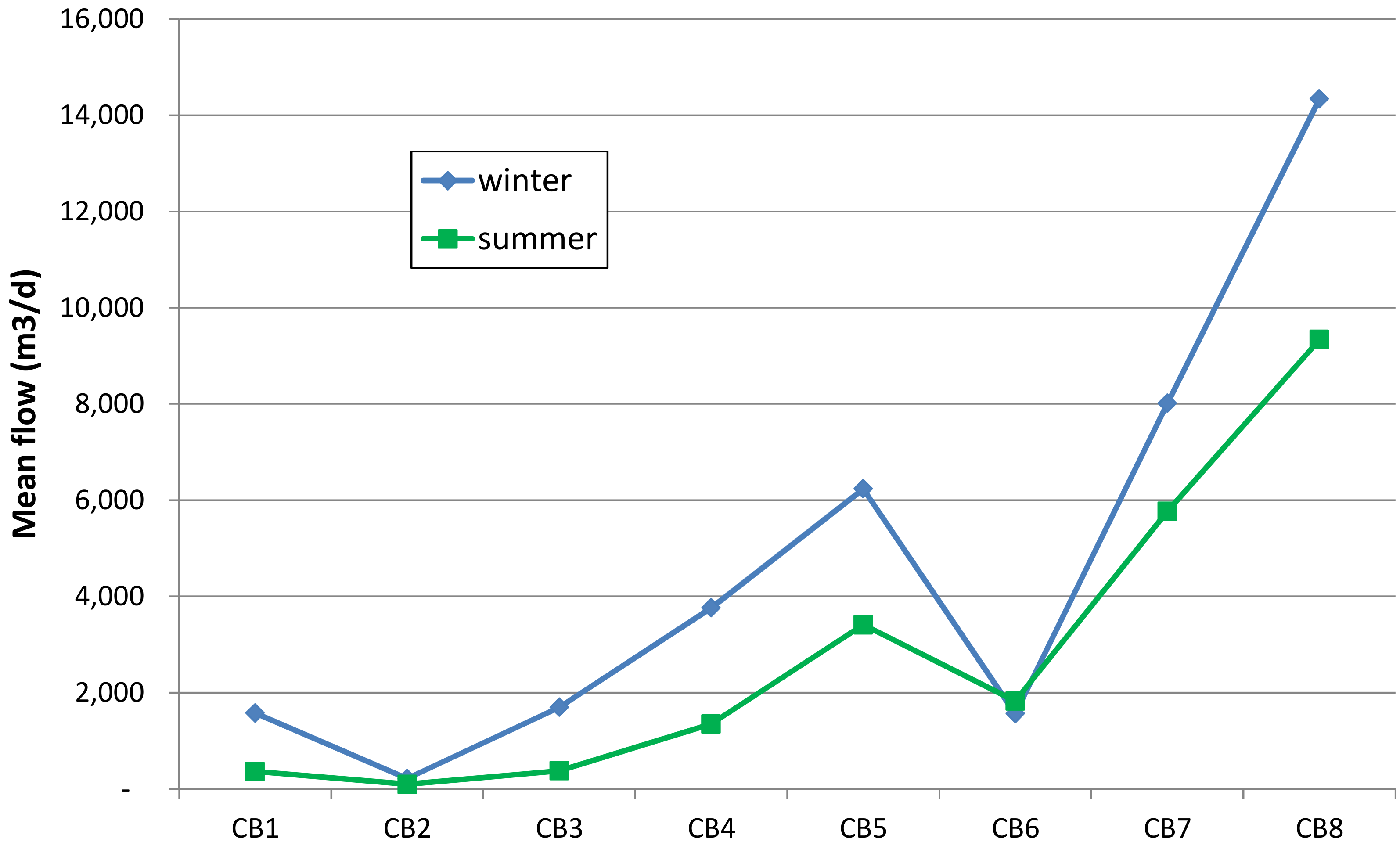

Figure IV-8. Seasonal Discharge Flows at Bank Street Bog Stations (2014/2015). Mean summer (June to September) flows at stations CB-2, CB-3, CB-4, CB-5, and CB-8 are significantly less ($\rho<0.05$) than winter (May to October) means. Seasonal reductions at CB-1 and CB-7 are significant a $\rho<0.1$ level. There is no significant difference between mean flows out of the former irrigation pond (CB-6): summer (1,824 m^3/d) and winter (1,739 m^3/d). Differences between summer and winter mean flows generally decrease as flows move downstream.

V. Water Quality

Water quality samples were collected at each of the stream flow sampling stations, as well as within the irrigation pond. Water quality samples were collected on the same schedule as the instantaneous flow measurements. A minimum of 30 samples were collected at all stations between July 8, 2014 and July 7, 2015 with an additional five samples collected until September 21, 2015 at stations CB-1, CB-6, and CB-8 to support the assessment of the irrigation pond. Irrigation pond sampling procedures followed the standard Cape Cod Pond and Lake Stewards (PALS) procedures with samples collected from shallow/surface and deep (1 m off the bottom) depths plus field measurements of dissolved oxygen, temperature, and clarity. Pond samples were generally collected twice a month: July 7, July 21, August 5, August 21, September 4, September 21, and Oct 8. All collected water quality samples were analyzed at the Coastal Systems Analytical Facility (SMAST) under QA/QC procedures approved by MassDEP and USEPA and used for the present and prior MEP freshwater assays for the following constituents: total phosphorus, ortho-phosphate, ammonia-nitrogen, nitrate/nitrite-nitrogen, organic nitrogen (both dissolved and particulate), total nitrogen, particulate organic carbon, salinity and pheophytin and chlorophyll (pigments were only assayed for irrigation pond samples).

V.A. Cold Brook Water Quality

V.A.1. Concentrations

Table V-1 shows average concentrations, standard deviations and number of samples for the measured constituents. Data outliers in the record have been removed for the calculations of these averages and the record has been assessed for seasonal differences. Mean concentration for summer (June to September) and winter (October to May) are presented for those constituents that had statistically significant seasonal differences ($\rho<0.05$). Means were also assessed for a slightly longer summer period (May to September), but the seasonal differences were generally consistent with the June to September summer, so these are not presented.

Mean total nitrogen concentrations were generally comparable between all stream stations, which ranged between 77 and 101 µM (Figure V-1). CB-2, which is the inlet/outlet for the active adjacent cranberry bog, had the highest mean concentration, as well as highest portion as particulate organic nitrogen. Dissolved organic nitrogen (DON) mean concentrations generally were significantly highest ($\rho<0.05$) in the lowest flow settings (*i.e.*, CB-1, CB-2, and CB-6). Similarly, particulate organic nitrogen (PON) mean concentrations were also highest in the lowest flow settings (*i.e.*, CB-1, CB-2, and CB-6), but saw some increases at the most downstream stations (*i.e.*, CB-7 and CB-8). In contrast, dissolved inorganic nitrogen (DIN) levels were significantly higher in the highest flow settings (*i.e.*, CB-4, CB-5, CB-7, and CB-8). DIN (nitrate+nitrite-N and ammonia-N) generally accounted for the largest fraction of the TN pool (range: 41% to 76%) with the highest percentages at the highest flow settings (*i.e.*, CB-4, CB-5, CB-7, and CB-8). DIN concentrations were generally composed of mostly of nitrate-N at all stations except CB-1 which had high ammonium levels in waters entering from upstream.

Mean TN concentrations at CB-1 and CB-2 were significantly ($\rho<0.05$) higher in summer versus winter with concentrations of 101 and 147 µM during the summer, respectively, and 63 and 70 µM during the winter, respectively. Seasonal mean TN concentrations at the other stations showed no significant differences. Mean PON and DON concentrations had similar seasonal patterns with significant seasonal difference at CB-1 and CB-2. PON was also significantly higher during the summer at CB-6 (17.8 and 11.6 µM, respectively) and DON was significantly higher during the summer at CB-8 (24.5 and 18.1 µM, respectively). DIN, which composed most of the TN pool at all stations except CB-2, generally did not show a significant seasonal difference except at CB-2, CB-6, and CB-8. At each of these stations, winter mean concentrations were significantly higher than summer. DIN would be higher in the winter due to less plant uptake, while during the summer DIN is taken up and incorporated into plant material (mostly phytoplankton and algae) and converted into PON and DON, which is consistent with the higher level of these nitrogen species in the summer months.

Mean total nitrogen concentrations were higher during the 2014/2015 water year than during 2004/2005 in the MEP analysis. Mean TN concentration in 2014/2015 at CB-8 was 86.8 µM (1.22 mg/L) while the mean TN concentration in 2004/2005 was only 68.6 µM (0.961 mg/L). DIN was also higher in 2014/2015 at 52 µM with 60% of the TN pool, while in 2004/2005 DIN was 48 µM or 70% of the TN. The changing proportion of DIN to TN results from more organic nitrogen in 2014/2015 and may indicate that the bog is taking up and transforming more inorganic to organic nitrogen at this time.

Mean total phosphorus (TP) concentrations generally showed no statistically significant differences ($\rho<0.05$) between stations except for CB-2, which is higher than all other stations, and CB-4, which is higher than CB-5 and CB-6 (Figure V-2). CB-2 had a mean TP concentration of 5.8 µM, while the rest of the stations averaged between 1.64 and 2.27 µM. Most of the total phosphorus was organic forms with inorganic ortho-phosphate ranging between 10% and 43% of the total phosphorus pool. Mean ortho-phosphate (PO4) concentration at CB-2 (1.05 µM) was significantly ($\rho<0.05$) higher than the means at all the other stations, while the mean at CB-6 (0.16 µM) is significantly lower than all other stations. The ortho-phosphate mean concentrations at CB-4 and CB-5 are not significantly different (0.71 and 0.72 µM, respectively), but are significantly higher than means at all other stations other than CB-2.

Seasonal differences were seen in the TP levels at the upper stations (CB-1, CB-2, CB-3, and CB-4), where summer levels were consistently higher than in winter Similarly, ortho-phosphate concentrations also had higher summer concentrations, but the difference was shifted slightly lower in the bog system to the middle stations: CB-3, CB-4, and CB-5. TP and ortho-phosphate would be mobilized in summer conditions as temperatures rise and bacterial populations in the organic rich bogs create lower oxygen conditions and release ortho-phosphorus from iron:phosphorus solids.

Mean alkalinity and pH increased as water moves downstream in Cold Brook to CB-8 (Figure V-3). Mean alkalinity concentrations at CB-1 and CB-2 were 22.2 and 21.2 mg/L $CaCO_3$, respectively, increasing to 28.0 and 28.8 mg/L $CaCO_3$ at CB-4 and CB-5, respectively. Alkalinity continues to increase to an average of 46.4 mg/L $CaCO_3$ at the outlet from the irrigation pond (CB-6) and was 34.6 and 40.1 mg/L $CaCO_3$ at CB-7 and CB-8, respectively. Average pH levels followed a similar pattern increasing from 5.9 at CB-1 and CB-2 to 6.6 at CB-8.

Significant seasonal differences in mean pH were only seen at one station (CB-1), while significantly higher summer mean alkalinity concentrations were measured at four stations (CB-2, CB-4, CB-5, and CB-8). Higher summer pH is generally associated with greater photosynthesis during the summer; when aquatic plants photosynthesize they take hydrogen ions and carbon dioxide out of the water causing pH to increase. The higher summer alkalinities are likely related to the mobilization of carbon in the bogs; as noted in Table V-1, four of the stations have significant increases in summer particulate organic carbon concentrations.

Plant growth in ecosystems is typically governed by availability of nutrients and light. In freshwater systems, phosphorus is usually the nutrient that determines the amount of plant growth and this is confirmed by comparing nitrogen and phosphorus concentrations. As a rule of thumb, if the ratio between nitrogen and phosphorus is greater than 16 (also known as the Redfield ratio), phosphorus is the nutrient which stimulates algae growth and should be the nutrient that is managed to maintain or restore water quality. Phosphorus-limited pond systems generally have N to P ratios that are 2-5 times the Redfield ratio of 16. Review of N to P ratios at stations within the Bank Street Bogs system generally showed that average ratios are phosphorus limited; ratios at all stations except CB-2 are 2.8 to 3.3 times the Redfield ratio. Ratios at CB-2, which drains the adjacent active bog, are likely influenced by phosphorus fertilization of the bog. Significant seasonal decreases in average summer ratios at CB-3 and CB-4 are likely due to the summer phosphorus releases from wetland sediments resulting from organic matter decay and chemical release of inorganic phosphorus under low oxygen conditions.

V.A.2. Loads

Concentration data provides insights into how nutrients enter and are transformed within the Bank Street Bog system, but this information needs to be combined with water flow information to understand the mass or load of these nutrients that is transferred downstream, naturally attenuated, and/or, ultimately, discharged to Saquatucket Harbor.

Since nitrogen is not the limiting nutrient with the Bank Street Bog system, it would be expected that changes in nitrogen loads would largely follow changes in water flows and removal in transport. Mean daily total nitrogen loads generally match with the changes in water flow; relationships between loads at stations are not significantly different from the relationships between flows at stations (Figures V-4, V-5). For example, flow at CB-4 was on average 4.3 times greater than the flow at CB-3. The accompanying increase in nitrogen load was a similar 3.9 times increase. This finding generally matches with the small variation in the total nitrogen concentration from CB-3 to CB-8; since the concentration was largely the same, changes in flow are the predominant causes of the changes in load. Loads at CB-1 and CB-3 were not significantly different, but loads at each subsequent downstream station were significantly higher ($\rho<0.05$) than the preceding station, except for CB-6, which was lower than CB-5 (3.5 kg/d vs. 5.4 kg/d). CB-7 (8.47 kg/d) was significantly higher than CB-6, but it was also significantly higher than CB-5.

Winter total nitrogen loads were significantly higher ($\rho<0.05$) than summer levels at all stations except CB-1 and CB-6. CB-6 had summer (June to September) and winter (October to May) loads that were not significantly different (Figure V-6). Summer reductions in winter loads were highest at CB-3 (73%) and gradually decreased at each subsequent downstream station with a minimum of 39% at CB-8. These reductions generally closely tracked the seasonal flow reductions except for CB-1, CB-6, and CB-7. The seasonal load reduction at CB-7 was greater than the seasonal flow reduction (44% and 28%, respectively) and was likely due to proximity to the relative constant loads entering at CB-6. As noted above, flows out of the irrigation pond were relatively stable throughout the year with higher, but not significantly higher, mean flows during the summer. CB-1 saw a smaller reduction in mean seasonal TN load (20%) compared to the mean seasonal flow reduction (77%), which is likely related to higher summer TN concentrations offsetting the flow reduction (observed at only CB-1 and CB-2, see Table V-1).

The annual TN load discharged out of the Bank Street Bog system at CB-8 in the 2014/2015 water year was 15.8 kg/d with an average flow of 13,004 m^3/d. This loading rate is 59% greater than measured over the 2004/2005 MEP water year. Even accounting for fluctuations in precipitation and groundwater levels, the higher TN concentration in 2014/2015 and the mean flow from the MEP water year would still result in a 26% increase in loading or a 13% reduction in the natural nitrogen attenuation within the Cold Brook watershed. Since the MEP stream monitoring was designed to measure stream flows and loads just upstream of the estuaries, the only point comparison available is at CB-8, so it is unclear what other changes within the Cold Brook watershed may have led to the nitrogen loading increase to Saquatucket Harbor.

Mean daily total phosphorus loads have many of the same relationships as total nitrogen, but appear to be more limited in the magnitude of potential seasonal reduction. In much the same way as TN loads, mean TP loads based on a whole year were not significantly different ($\rho<0.05$) at CB-1 and CB-3, but each subsequent downstream station, save CB-6, had a significantly higher mean load than the adjacent upstream station. Seasonal reductions in mean TP loads generally are in the 50 to 60% range, except for CB-6 and CB-7 (Figure V-7). These are not as closely tied to the seasonal reductions in flow as in the TN loads; most of the seasonal mean TP reductions are less than the seasonal mean flow reductions. At CB-6, no significant seasonal change in TP load was observed, just as for TN loads. The irrigation pond appears to help maintain relatively consistent TP concentrations at CB-6; as an example, the average summer 2015 TP concentration in the pond was 1.69 μM, while the average summer TP concentration at CB-6 was 1.67 μM. As with the TN loads, the relatively stable pond load likely stabilized loads at CB-7 as well, which had a seasonal TP load reduction of only 15% compared to a 28% reduction in the seasonal mean water flow. In contrast, the seasonal reduction in mean TP load was 52% at CB-8.

The near constancy of the seasonal TP reduction along most of Cold Brook combined with phosphorus limitation suggests that water has a similar residence times within each of the bog cells; if the residence times were significantly different between cells it would be reasonable to expect significant differences between TP reductions in each of the cells. Given the differences in the sizes of cells and the area of the channels within each cell, these differences should alter residence time and seasonal TP reductions in each of the cells. The nearly constant seasonal TP reductions suggest that TP reductions are largely occurring within the main stem of Cold Brook.

V.B. Irrigation Pond

As mentioned above, an assessment of the former irrigation pond was integrated into the Bank Street Bog sampling protocols in 2015. Dissolved oxygen and temperature profiles, clarity/Secchi readings, water quality samples, and sediment cores were collected and assayed. Dissolved oxygen and temperature profiles, Secchi readings, and water quality samples were collected over the deepest portion of the pond (~2.5 m) (Figure V-8). In addition, four sediment cores were collected at locations indicated in Figure V-8 and were incubated using standard CSP/SMAST protocols.

Dissolved oxygen and temperature profile readings were collected at 0.5 m increments throughout the water column on six dates in 2015: July 7, July 21, August 5, August 21, September 4, September 21, and October 8 (Figure V-9). Temperature readings showed some sufficient resistance to thermal mixing to isolate deeper waters during the July and August profiles, but subsequent profiles indicate that available wind energy would mix the entire water column. Dissolved oxygen concentrations were generally above the MassDEP regulatory minimum of 5 mg/L for warm water fisheries[28] except for the deepest readings in September and October. These low concentrations were likely due to a significant phytoplankton bloom creating water column and sediment oxygen demand that overwhelmed atmospheric mixing of oxygen into the water column. Review of dissolved oxygen saturation levels showed that levels in July were generally in balance with atmospheric inputs (90% to 110%), but shallow concentrations at 0.5 m on August 21, September 4, and September 21 were all above 125% of air equilibration with the August 21 level spiking at 172% (see Figure V-9). These supra-atmospheric levels are only attainable by a bloom of photosynthesizing phytoplankton; the average chlorophyll-a concentrations on the three later sampling dates were about 5X higher than those earlier in the summer. This late summer period was also when the deepest dissolved oxygen concentrations decreased below the MassDEP minimum. Clarity in the pond averaged 31% of the water column with a range of 24% to 40%; a pond this shallow should generally have light reaching the bottom (*i.e.,* clarity = 100%).

Review of water quality concentration data is consistent with an impaired pond system (Table V-2). Surface total phosphorus (TP) concentrations averaged 52 µg/L (1.7 µM), which is more than 5 times the Cape Cod ecological guideline of 10 µg/L for freshwater ponds (Figure V-10).[29] Deep samples averaged 135 µg/L (4.4 µM) TP, indicating significant sediment regeneration. The ratios of TP and TN concentrations showed that the pond was generally phosphorus-limited with an average ratio 2.8 times the Redfield ratio; this is consistent with ratios at the stations within the main stem of Cold Brook. TN concentrations were relatively consistent in shallow and deep waters, which indicate little sediment release of nitrogen; shallow and deep TN concentrations averaged 1.0 mg/L and 1.1 mg/L, respectively (see Figure V-10). Shallow and deep salinity concentrations indicated periodic stratification with a mean surface concentration of 6.1 ppt and a mean bottom water concentration of 10.6 ppt (ρ=0.08). This salinity difference suggests that the more dense brackish water that flows into the pond during higher tides settles into the bottom of the pond. This higher salinity water also likely accentuates the sediment oxygen demand since higher salinity water has a lower capacity for dissolved oxygen. Other factors with significant differences between shallow and deep mean concentrations were: particulate organic carbon (POC), particulate organic nitrogen (PON), alkalinity, and the ratio between chlorophyll and total pigments. POC, PON, and alkalinity mean concentrations are all higher in the deep waters, which is likely a combination of regenerated materials from the sediments and settling of the phytoplankton from the bloom beginning in late August. The lower ratio of chlorophyll to total pigments in the deeper water compared to the shallow average is also related to settling of phytoplankton, as pheophytin, which is the other portion of the total

[28] 314 CMR 4.05(b)1

[29] Eichner, E.M., T.C. Cambareri, G. Belfit, D. McCaffery, S. Michaud, and B. Smith. 2003. Cape Cod Pond and Lake Atlas. Cape Cod Commission. Barnstable, MA.

pigments concentration, is the initial degradation product of chlorophyll and is elevated in senescing or decomposing phytoplankton.

Sediment cores were collected at four locations on October 8, 2015 by SCUBA diver (see Figure V-8). 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 and chemical constituents were assayed. Rates of sediment nutrient release/uptake were determined from linear regression of analyte concentrations through time. Cores were incubated to first sustain aerobic conditions (~7 days), matching conditions when oxygen conditions are near atmospheric equilibrium throughout the water column and at *in situ* temperature (15°C). Dissolved oxygen was then removed and sediment conditions were gradually moved to anoxia, which begins with an initial chemical release of phosphorus (severing of weak chemical bonds), where water column dissolved oxygen concentrations drop to less than 1 mg/L. The anaerobic incubation of the irrigation pond cores lasted between 38 and 49 days depending on the individual core. The laboratory followed standard methods for analysis and sediment geochemistry as currently used by the Coastal Systems Analytical Facility at SMAST-UMass Dartmouth.

Nitrogen release from the intact cores showed a gradient down the main axis of the pond with net release from the sediments near the inlet/CB-6 and a large net removal from the overlying water in the southernmost pond area. The two cores furthest from the inlet (C1 and C2) were removing nitrogen from the water column under aerobic conditions at a rate ≥20X the release of nitrogen under anaerobic conditions (Table V-3). The middle pond, C3 core showed a reduced removal rate (~50% of C1/C2) and the C4 core, closest to the inlet was adding nitrogen to the water column under both aerobic and anaerobic conditions.

Phosphorus results showed that phosphorus was being removed from the water column to the surface sediments at all sites under aerobic conditions, but under anoxic conditions, chemical release and anaerobic decomposition processes yielded net phosphorus release at all sites. TP release under anoxic conditions is almost entirely as inorganic P and was large in comparison to aerobic rates. The field phosphorus levels from shallow and bottom waters suggest that sediment phosphorus was regularly released during the warmer months (see Figure V-10).

Since the actual contribution of nutrients from the sediments is a balance between release from sediments and nutrients settling in particulates to the sediments from the water column, project staff also reviewed net sediment release. This analysis reviewed pond water quality conditions when the sediments were collected (10/8/15) and compare those to core incubation results. Water column conditions of October 8 showed some prior sediment release, but this was largely confined to the deepest waters, which represent a relatively small portion of the overall volume of the pond. Using this information, staff determined that the net potential aerobic sediment TP release was -0.02 kg/d (into the sediments), while net potential chemical release was +0.03 kg/d (out of the sediments). The net potential aerobic TN release is -1.5 kg/d with a net potential anaerobic release of +0.02 kg/d. Net potential TP release from decay under anaerobic conditions was negligible. These rates are potential rates because anaerobic conditions in the pond would need to be sustained for a prolonged period (weeks) to attain the full measure core release rates. In small ponds like the irrigation pond, bottom water oxygen conditions fluctuate and anaerobic conditions are unlikely to be consistently attained. Water column mixing and regular tidal influence and outflows from the irrigation pond will make prolonged anoxia unlikely. Review of the mass of TP within the pond shows that increases generally are an order of magnitude smaller than the potential chemical release under prolonged anoxia, but do reach a maximum of +0.015 kg/d during the phytoplankton bloom. This rate is ~50% of the potential net chemical release rate,

In order to evaluate a potential management strategy of removing sediment buildup within the pond, project staff also collected pond sediment samples for analysis of: metals (arsenic, cadmium, chromium, lead, and mercury), polychlorinated biphenyls (PCBs; 7 compounds), volatile organic compounds (VOCs; 64 compounds), polycyclic aromatic hydrocarbons (PAHs, 17 compounds) and total petroleum hydrocarbons (TPH). Sediment samples were collected January 4, 2016 near the core collection sites for the incubations and assayed at the Barnstable County Health Laboratory. Sample results were compared to MassDEP guidance for Massachusetts Contingency Plan (MCP) ecological risk assessment limits,[30] lined and unlined landfill soils reuse limits,[31] and MCP health risk limits.[32] Among these standards, landfill reuse standards are the most applicable for sediment removal, but the others are presented should other reuse plans be considered. Among the metals, only arsenic at C3 exceeded any of the limits, exceeding both reuse limits for landfills and the freshwater screening limit (Table V-4). PCBs, VOCs, and PAHs were below limits at all sampling locations. TPH concentrations at C3 and C4 exceeded direct human contact limits (S-1 MCP limits), but were less than other standards. Presumably the sediments would be brought into direct human contact if excavated and the excavation plan would have contingencies for proper sediment handling. The sediment contaminant results suggest that pursuit of management strategies that involve removal of sediments can focus on the deepest portions of the pond (C1 and C2 sites) without further regulatory concerns about reuse, but removal of sediments in the shallower portions of the pond (C3 and C4 sites) should include additional testing and/or restrictions on reuse.

Given the small size and depth of the pond, the estimated residence time of water in the pond is relatively short. Using the volume of 5,874 m3 determined from the bathymetric survey (see Figure V-8), the water residence time was between 3.2 and 3.8 days based on average summer and winter outflows at CB-6, respectively. If it is assumed that average sediment depth in the pond is 0.5 m (see Figure III-4) and all soft sediment deposits are removed, the volume of the pond would increase by 35% and water residence times would increase to 4.3 to 5.1 days. This calculation is somewhat complicated by the estimation that CB-6 flow is likely composed of a large portion of tidal water. Review of the tidal prism at CB-5, the nearest upstream station with a stream gauge, shows that a flow based on the tidal prism would closely match the measured flows at CB-6. This comparison would suggest that the residence time of water in the pond is likely less than one day after accounting for the temperature and salinity stratification effects.

[30] Massachusetts Department of Environmental Protection, Office of Research and Standards. January, 2006. Revised Sediment Screening Values.

[31] Massachusetts Department of Environmental Protection. August 15, 1997. Reuse and Disposal of Contaminated Soil at Massachusetts Landfills, MassDEP Policy # COMM-97-001.

[32] 310 CMR 40.0000: Massachusetts Contingency Plan

Table V-1. Water Quality Concentrations at Bank Street Bog Stations. Means, standard deviations, and number of measurements are shown. Concentrations are also shown for analytes that had significant (ρ<0.05) differences between summer and winter means.

			pH	ALK	Salinity	PO4	TP	NH4	NOx	DIN	DON	TDN	POC	PON	C/N ratio	TON	TN	N:P
			s.u.	mg/L CaCO3	ppt	µM	µM	µM	µM	µM	µM	µM	µM	µM	µM	µM	µM	µM
CB1	Overall	MEAN	5.88	22.24	0.10	0.41	2.07	30.27	3.60	35.11	34.25	72.68	167.02	15.52	11.16	49.99	85.95	44.46
		STDEV	0.28	4.05	0.02	0.22	1.10	17.83	3.60	19.89	7.57	18.80	107.59	11.22	2.02	17.85	26.49	16.81
		N	18	18	32	34	33	35	33	35	32	33	33	33	35	33	33	29
	Summer	mean	5.74				2.35	35.41			39.89	78.43	216.60	20.58		58.86	100.61	
	Winter	mean	6.05				1.65	21.56			28.60	55.65	90.75	7.74		36.34	63.39	
CB2	Overall	MEAN	5.92	21.16	0.10	1.05	5.84	3.60	5.68	9.11	39.79	52.45	489.85	46.05	13.18	86.37	101.10	18.86
		STDEV	0.13	5.37	0.00	0.49	3.86	2.20	7.21	8.20	10.89	8.35	586.88	66.28	2.80	73.72	67.52	6.10
		N	13	14	27	28	28	27	26	26	28	27	27	27	29	27	27	26
	Summer	mean		24.77			7.59		3.20	6.38	44.09		754.59	94.36	11.92	139.99	146.67	
	Winter	mean		18.45			3.51		18.74	24.67	34.04		158.92	10.90	14.97	44.94	69.61	
CB3	Overall	MEAN	5.99	24.23	0.10	0.59	1.71	14.52	26.80	43.68	25.11	70.63	101.32	8.98	12.33	34.46	82.47	50.44
		STDEV	0.17	4.58	0.02	0.21	0.66	7.33	7.08	13.86	6.14	13.62	56.68	5.56	1.74	9.40	17.14	16.54
		N	14	14	29	29	27	30	27	29	28	29	28	29	28	28	30	26
	Summer	mean				0.68	2.13						128.80					39.71
	Winter	mean				0.47	1.25						64.68					62.95
CB4	Overall	MEAN	6.27	28.05	0.10	0.71	2.10	3.54	71.03	74.70	14.91	90.43	90.97	6.88	13.00	21.46	97.84	50.69
		STDEV	0.12	3.14	0.00	0.17	0.84	1.37	18.58	19.14	6.95	16.22	45.83	2.95	2.74	7.66	15.70	13.81
		N	14	13	30	29	29	29	29	29	29	29	29	28	30	28	29	27
	Summer	mean		29.94		0.80	2.42											45.98
	Winter	mean		26.86		0.61	1.70											56.58
CB5	Overall	MEAN	6.31	28.85	0.10	0.72	1.68	3.07	60.41	63.60	16.71	81.84	51.69	4.14	12.85	21.08	86.23	53.18
		STDEV	0.10	3.10	0.00	0.23	0.39	1.45	14.17	15.13	5.89	11.91	15.34	1.46	2.39	6.67	11.27	10.31
		N	14	13	30	29	28	29	30	30	29	29	29	29	29	29	29	27
	Summer	mean		31.06		0.83												
	Winter	mean		27.48		0.58												
CB6	Overall	MEAN	6.56	46.42	3.28	0.16	1.64	2.17	32.42	34.78	21.87	60.48	130.45	15.39	8.46	38.85	76.58	51.21
		STDEV	0.18	10.03	3.02	0.11	0.71	2.18	10.98	12.12	6.93	16.25	49.96	6.71	1.41	11.49	14.80	21.06
		N	19	18	33	33	33	33	33	33	32	35	34	34	33	34	34	31
	Summer	mean							29.88	31.94			146.31	17.76				
	Winter	mean							36.88	39.74			104.84	11.58				
CB7	Overall	MEAN	6.40	34.56	1.27	0.49	1.89	3.19	48.44	51.99	19.94	72.61	84.71	8.42	10.80	28.70	83.15	44.39
		STDEV	0.07	6.25	1.21	0.16	0.49	1.66	9.29	10.14	5.40	9.99	27.92	3.12	2.12	7.35	10.06	7.90
		N	13	14	29	28	28	28	30	30	28	29	28	29	30	28	29	26
	Summer	mean							45.32						10.02			
	Winter	mean							52.52						11.81			
CB8	Overall	MEAN	6.60	40.12	2.19	0.38	2.27	3.33	47.54	51.48	22.02	72.84	116.83	11.66	9.99	34.66	81.97	49.64
		STDEV	0.15	12.07	2.50	0.21	2.11	2.09	12.76	13.39	11.41	11.30	101.73	8.07	1.41	14.94	10.94	15.49
		N	19	19	35	34	35	34	33	33	34	33	33	33	34	33	32	32
	Summer	mean		45.23	2.95				43.16	46.84	24.46				9.63			
	Winter	mean		33.10	0.92				54.27	58.62	18.07				10.64			

Table V-2. Water Quality Data at Former Irrigation Pond. Pond was sampled on seven dates during the 2015 summer. Samples were collected at shallow and deep depths on each date. All analytes were assayed at the Coastal Systems Analytical Facility (SMAST) under QA/QC procedures approved by MassDEP and USEPA. Dissolved oxygen concentrations are corrected for salinity concentrations. Chlorophyll-a and pheophytin concentrations on August 5 sampling event (cells colored green) may have been altered by the sampling device hitting the bottom sediments.

Date	Depth	Total Depth	Secchi Depth	Sample Depth	Temp	DO	pH	ALK	Salinity	PO4	TP	NH4	NOx	DIN	DON	TDN	POC	PON	TON	TN	Chl-a	Phaeo
		m	m	m	°C	mg/L	s.u.	mg/L CaCO3	ppt	µM	µM	µM	µM	µM	µM	µM	µM	µM	µM	µM	µg/L	µg/L
7/7/15	S	2.52	0.6	0.5	20.1	9.40	6.44	67	6.7	0.1	1.45	0.3	27.25	27.51	12.78	40.29	237.70	26.60	39.39	66.90	4.68	2.79
7/21/15	S	2.3	0.55	0.5	21.5	9.61	6.66	76	6.9	0.1	1.74	0.2	47.34	47.51	20.08	67.58	208.33	28.91	48.98	96.49	6.6	1.0
8/5/15	S	2.5	ND	0.5	ND	ND	6.82	86	9.6	0.1	1.16	0.2	30.10	30.28	21.52	51.80	ND	ND	ND	ND	4.15	2.30
8/21/15	S	2.5	0.7	0.5	21.8	14.77	6.81	66.8	3.7	0.6	1.70	0.8	9.95	10.73	21.01	31.74	197.82	28.30	49.31	60.04	25.89	6.24
9/4/15	S	2	0.8	0.5	22.8	10.07	6.57	91.7	10.7	0.1	2.79	0.5	25.52	26.04	20.16	46.20	177.10	24.27	44.43	70.47	17.38	2.92
9/21/15	S	2.05	ND	0.5	18.1	15.59	6.88	58.80	2.6	0.4	1.85	1.2	11.49	12.64	40.34	52.98	248.00	36.57	76.91	89.55	32.03	29.31
10/8/15	S	2.3	0.9	0.5	19.2	6.15	ND	ND	2.7	0.1	1.11	2.2	28.47	30.69	15.50	46.20	78.69	12.57	28.08	58.77		NS
7/7/15	D	2.52	0.6	1.5	17.3	6.93	6.65	98.2	10.6	0.1	2.39	1.3	16.47	17.79	16.01	33.80	264.48	38.00	54.01	71.80	7.95	3.82
7/21/15	D	2.3	0.55	1.8	19.2	7.35	6.74	102.3	10.8	0.1	4.89	10.6	50.95	61.57	9.70	71.27	271.22	34.24	43.94	105.51	8.9	7.1
8/5/15	D	2.5		2	ND	ND	7.15	124.4	16.15	0.5	5.10	24.8	12.41	37.18	31.88	69.06	ND	ND	ND	ND	53.91	129.34
8/21/15	D	2.5	0.7	2	18.3	5.63	6.7	96.1	5.7	0.5	3.91	1.6	0.16	1.72	23.32	25.04	289.11	35.93	59.25	60.97	14.65	10.86
9/4/15	D	2	0.8	1.7	22.8	3.29	8.28	133.40	17.9	0.4	5.22	5.6	7.86	13.42	25.40	38.82	597.99	62.81	88.21	101.63	20.04	32.35
9/21/15	D	2.05		1.5	17.8	3.20	6.57	86.40	4.2	0.5	5.40	1.2	0.60	1.79	24.14	25.93	399.09	45.16	69.30	71.08	26.93	18.52
10/8/15	D	2.3	0.9	1.75	14.7	3.04	ND	ND	8.5	0.2	3.69	0.7	8.94	9.66	11.02	20.67	241.46	38.31	49.33	58.99		NS

Table V-3. Sediment Core Incubation Results: Former Irrigation Pond in the Bank Street Bogs.

Sediment cores were collected at four sites on October 8, 2015. Cores were incubated at temperatures consistent with water temperatures at the time of core collection (15°C). Cores were incubated to measure nutrient release under both aerobic and anaerobic conditions; phosphorus anaerobic release also focused on the initial chemical release phase. Sediment release rates below represent averages of multiple (3 to 20) samples during each incubation phases. Note that cores were collected at sites along a north/south axis with the southernmost C1 located in the deepest basin and northernmost C4 located near the pond inlet. Net pond-wide phosphorus sediment transfers, which incorporate settling of measured phosphorus from the 10/8 water column were: -0.02 kg/d (into the sediments) under aerobic conditions, while net potential chemical release was +0.03 kg/d (out of the sediments). Net pond-wide nitrogen sediment transfers were: -1.5 kg/d (into the sediments) under aerobic conditions and a net potential anaerobic release of +0.02 kg/d. Anaerobic incubation of individual cores was continued for between 38 and 49 days.

Sediment Sample Site	Sediment Oxygen Demand	Aerobic Flux Rate				Chemical Release	Anaerobic Flux Rate	
		Ammonium	Nitrate	Total Dissolved Nitrogen	Phosphorus	Total P	Nitrogen	Phosphorus
	$mM/m^2/d$	$\mu Moles/m^2/d$	$\mu Moles/m^2/d$	$\mu Moles/m^2/d$	$\mu Moles/m^2/d$	$\mu Moles/m^2/d$	$\mu Moles/m^2/d$	$\mu Moles/m^2/d$
C1	78	-183	-13,545	-20,141	-100	46	566	11
C2	45	1271	-14,432	-21,813	-48	366	711	35
C3	104	-244	-5,986	-7,113	-61	167	698	89
C4	40	1929	2,071	4,387	-30	515	1,040	130

Table V-4. Irrigation Pond Sediment Contaminant Assay Results. Sediment samples were collected on January 4, 2016 in the former irrigation pond within the Bank Street Bogs system. Samples were collected near the sediment core collection sites and delivered to the Barnstable County Health Laboratory for assays of the indicated contaminants. Assay results are compared to various MassDEP standards for a) landfill reuse of the sediments, b) freshwater screening criteria for ecological risk, and c) Massachusetts Contingency Plan standards for hazardous waste spills. Among these standards, landfill reuse standards are the most applicable for sediment removal, but the others are presented should other reuse plans be considered.

Contaminant	Irrigation Pond Sediment Sample Results					Sediment Standards					
						Landfill reuse		Freshwater Screening Criteria	MCP (GW-3 standards)[e]		
	C1	C2	C3	C4	Method	Lined	Unlined		S-1[b]	S-2[c]	S-3[d]
Metals	mg/kg	mg/kg	mg/kg	mg/kg		mg/kg	mg/kg	mg/kg dry			
Arsenic	0.65	11	58	29	6010C	40	40	33	20	20	50
Cadmium	ND	0.32	1.9	ND	6010C	80	30	5	70	100	100
Chromium	3	6.1	27	6.7	6010C	1,000	1,000	110	100	200	200
Lead	1.6	7.4	62	30	6010C	2,000	1,000	130	200	600	600
Mercury	ND	ND	ND	ND	EPA 7470A	10	10	0.18	20	30	30
Organics	µg/kg	µg/kg	µg/kg	µg/kg		mg/kg	mg/kg				
PCB (7 compounds)	ND	ND	ND	ND	EPA 8082	2 (total)	2 (total)	60 (total)	1 (total)	4 (total)	4 (total)
Volatile Organics (64 compounds)	ND	ND	ND	ND	EPA 8260C	10 (total)	4 (total)	-	-[a]	-[a]	-[a]
PAHs 17 compounds	ND	ND	ND	ND	EPA 8270D	100 (SVOC)	100 (SVOC)	-	-[a]	-[a]	-[a]
TPH by GC/FID	35	260	2,000	2,200	8100	5,000	2,500	-	1,000	3,000	5,000

Notes:

a. Standards exist for individual compounds
b. S-1 soils are accessible and high contact or high frequency of human contact or current or foreseeable use for growth of crops for human consumption
c. S-2 soils are accessible and high contact or frequency of contact by adults, but only low contact by children
d. S-3 soils are accessible and low human contact or frequency of contact or soils are isolated
e. GW-3 standards are the least restrictive of the MCP standards for groundwater (MCP is detailed in 310 CMR 40).

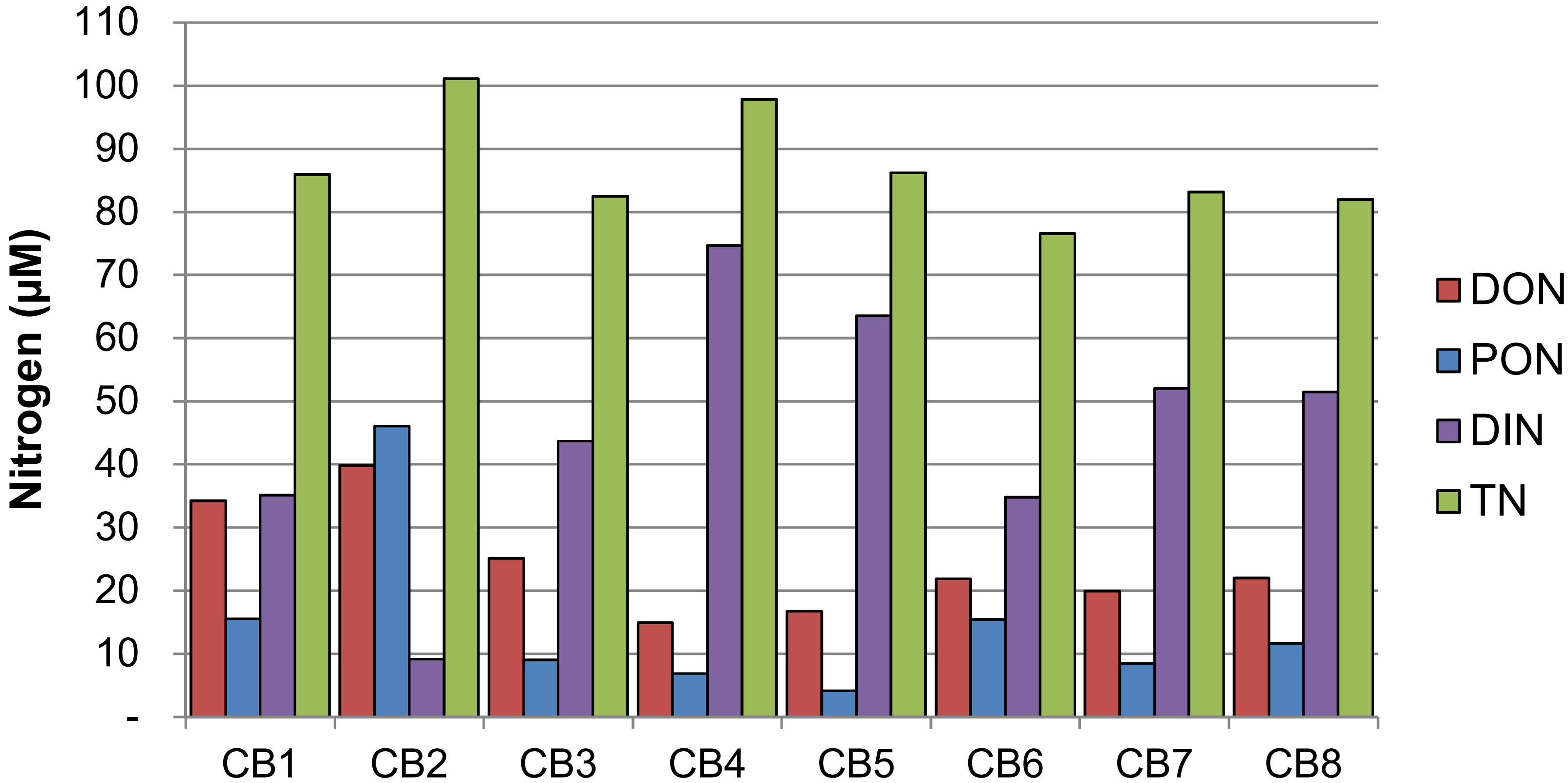

Figure V-1. Mean Concentrations for various nitrogen analytes at Cold Brook monitoring stations in Bank Street Bogs. Total nitrogen (TN) mean concentrations are generally similar except for statistically significant differences ($\rho<0.05$) between CB-4 and all stations except CB-2 and CB-6 and selected higher means (CB-2, CB-5, and CB-7). Dissolved organic nitrogen (DON) mean concentrations generally were significantly highest in the lowest flow settings (*i.e.*, CB-1, CB-2, and CB-6), while dissolved inorganic nitrogen (DIN) were significantly highest in the highest flow settings (*i.e.*, CB-4, CB-5, CB-7, and CB-8). Particulate organic nitrogen (PON) mean concentrations generally were also significantly highest in the lowest flow settings (*i.e.*, CB-1, CB-2, and CB-6), but saw some increases at the most downstream stations (*i.e.*, CB-7 and CB-8). DIN (nitrate-N and ammonia-N) generally was the highest portion of the TN concentrations (range: 41% to 76%) with the highest percentages at the highest flow settings (*i.e.*, CB-4, CB-5, CB-7, and CB-8), indicating that the potential for enhancing nitrogen attenuation is high.

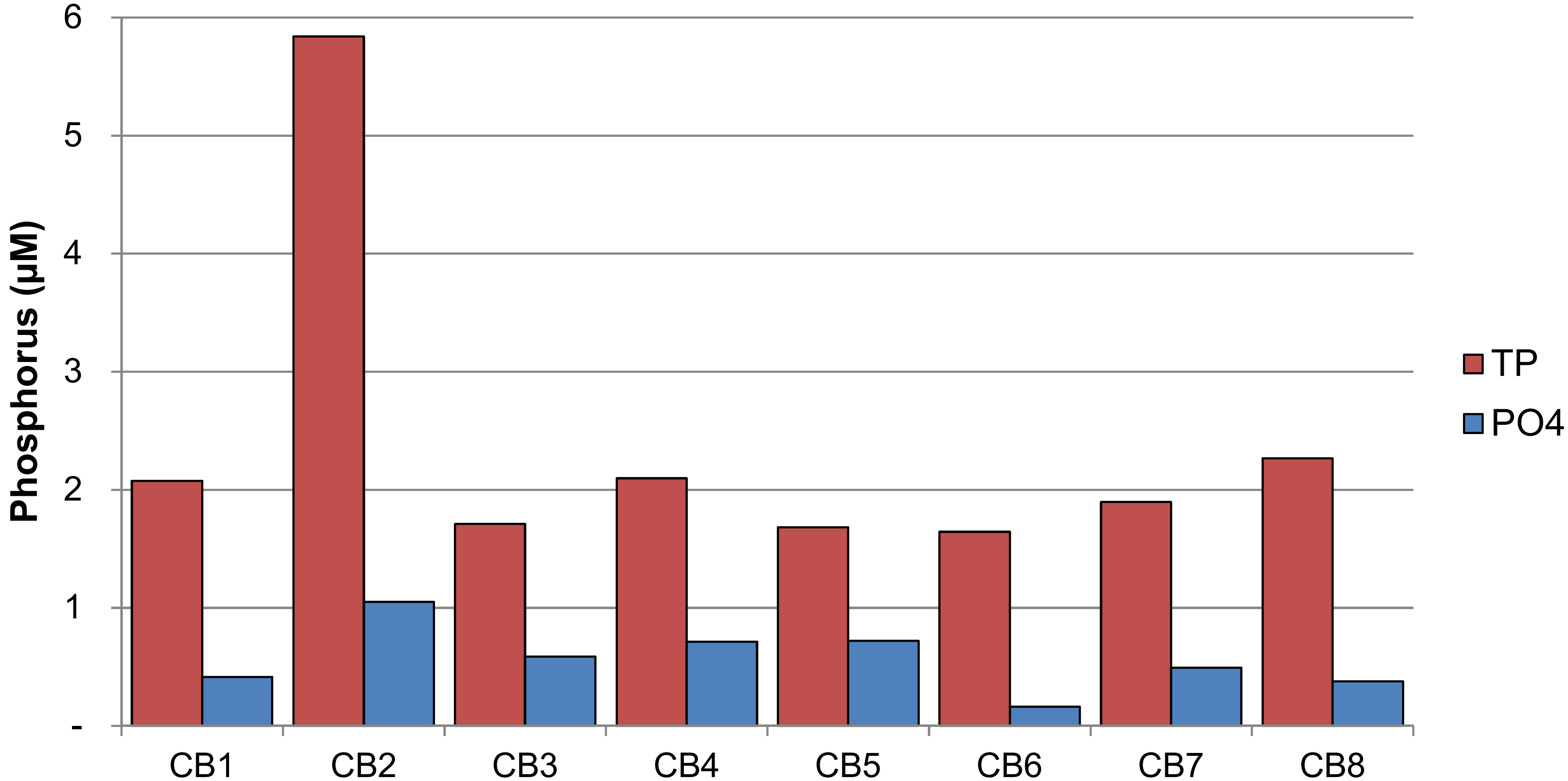

Figure V-2. Mean Concentrations for total phosphorus and ortho-phosphate analytes at Cold Brook monitoring stations in Bank Street Bogs. Total phosphorus (TP) mean concentrations generally have no statistically significant differences ($\rho<0.05$) between stations except for CB-2, which is higher than all other stations, and CB-4, which is higher than CB-5 and CB-6. Mean ortho-phosphate (PO4) concentration at CB-2 is significantly ($\rho<0.05$) higher than the means at all the other stations, while the mean at CB-6 is significantly lower than all other stations, which is typical of pond water. Means of ortho-P at CB-4 and CB-5 not significantly different and are significantly higher than means at all other stations other than CB-2.

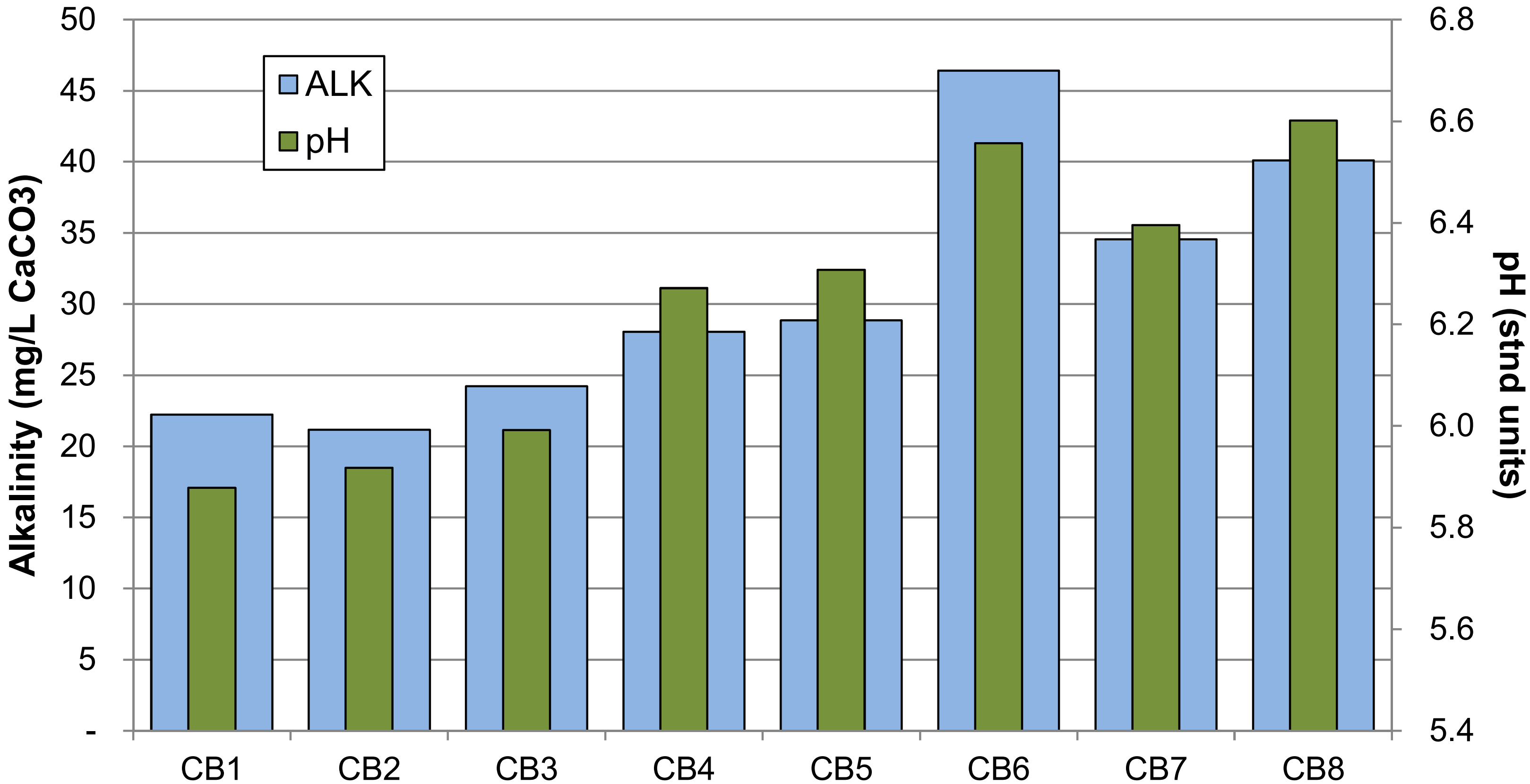

Figure V-3. Mean Alkalinity and pH readings at Cold Brook monitoring stations in Bank Street Bogs. Mean pH readings generally followed a trend of significantly ($\rho<0.05$) higher readings at each downstream station except for CB-6 or occasionally the adjacent station; for example, mean pH at CB-4 and CB-5 are not statistically different, but the mean at CB-4 was statistically lower than the mean at all downstream stations. Mean alkalinity concentrations followed a similar pattern.

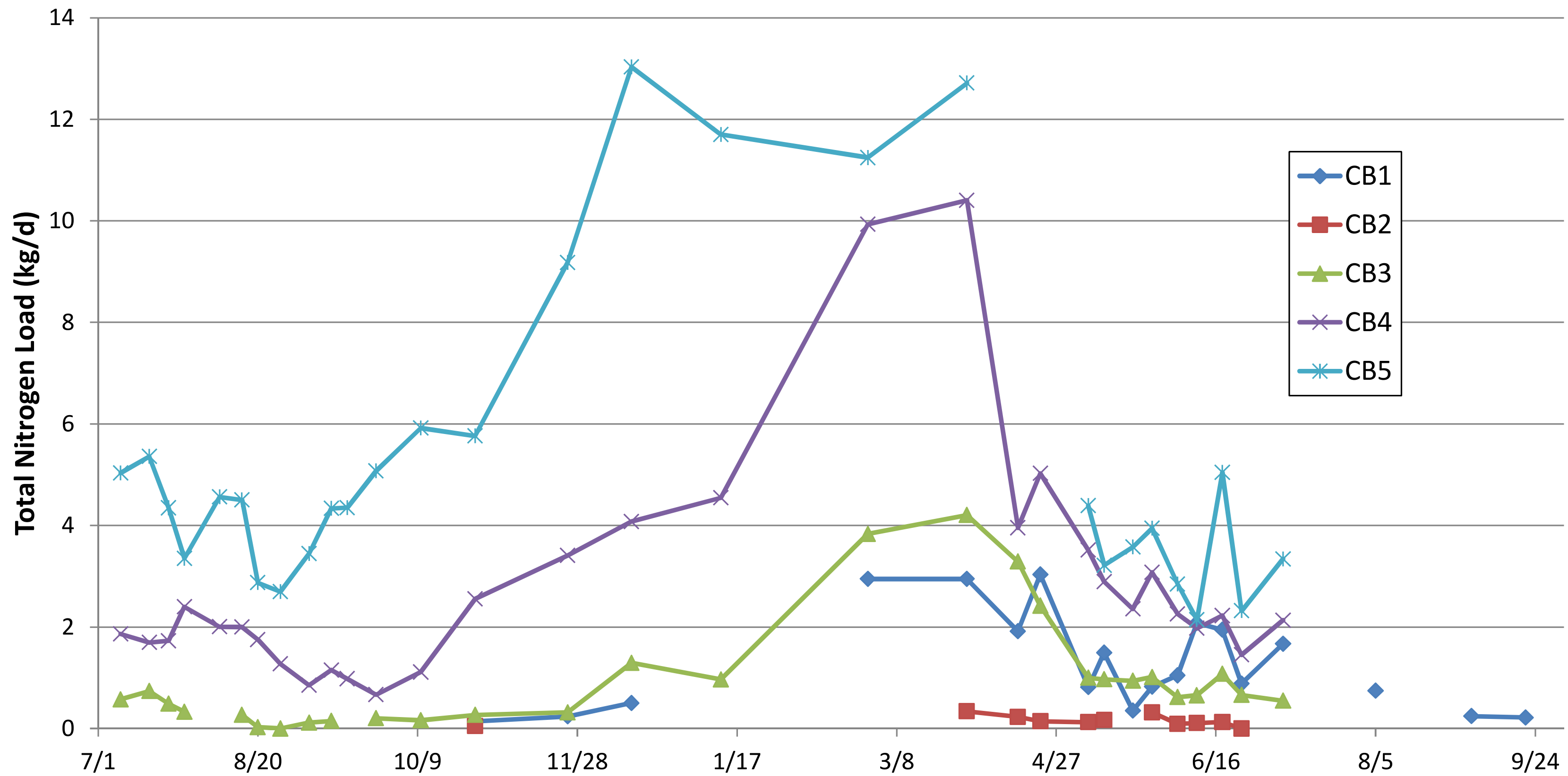

Figure V-4. Bank Street Bog Water Quality Stations: Total Nitrogen Loads (CB-1 to CB-5). Total nitrogen loads are generally lower in summer and higher in winter, moving nearly in tandem with seasonal changes in water flow. Loads at CB-1 and CB-3 were not significantly different, but mean loads at each subsequent downstream station were generally significantly higher ($\rho<0.05$) than the preceding station.

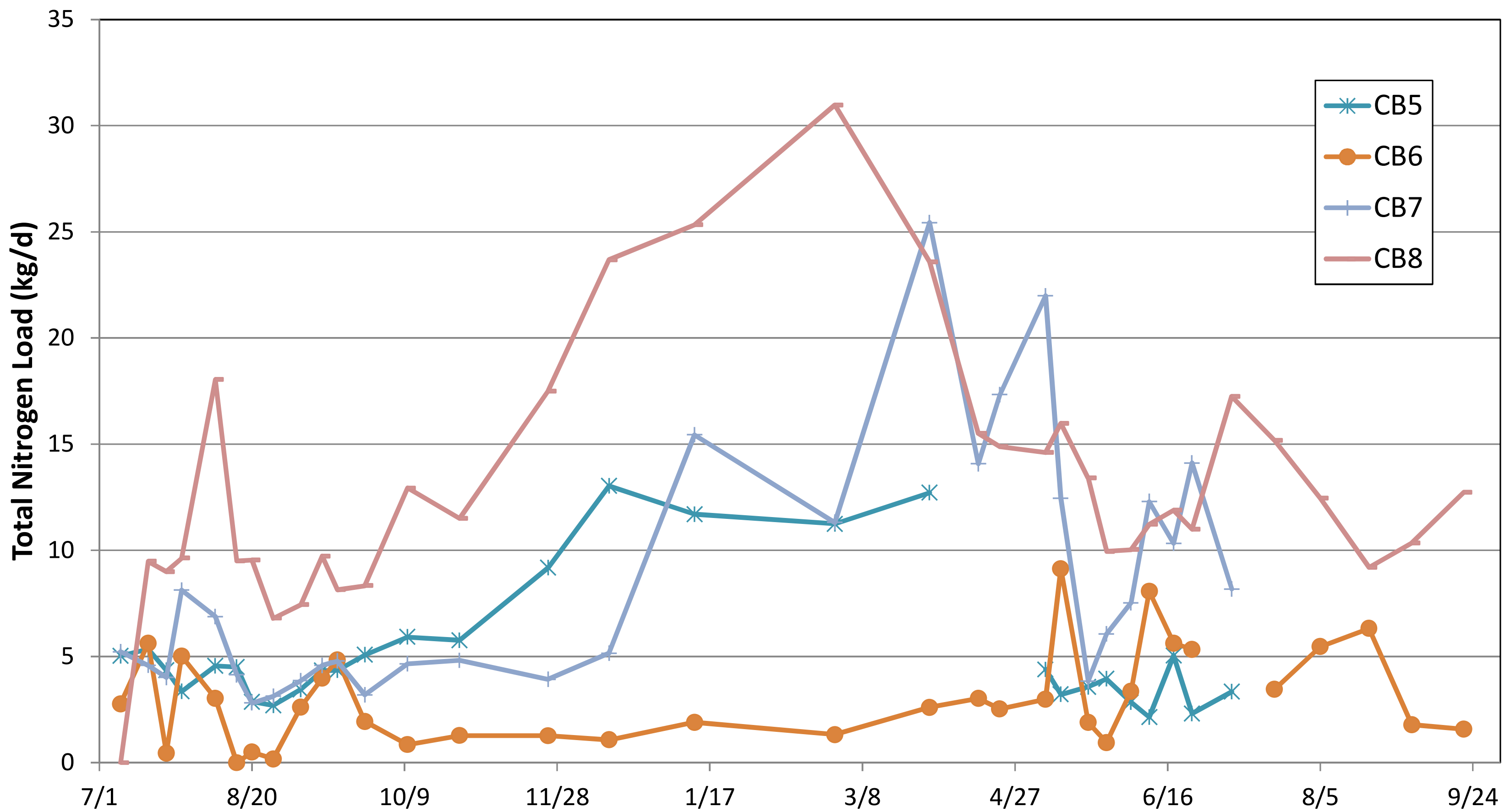

Figure V-5. Bank Street Bog Water Quality Stations: Total Nitrogen Loads (CB-5 to CB-8). Total nitrogen loads are generally lower in summer and higher in winter, moving nearly in tandem with seasonal changes in water flow. Mean loads at each subsequent downstream station were generally significantly higher ($\rho<0.05$) than the preceding station, except for CB-6 which was significantly lower than the mean TN load at CB-5. The former irrigation pond at CB-6 had no significant seasonal change in flow or TN load.

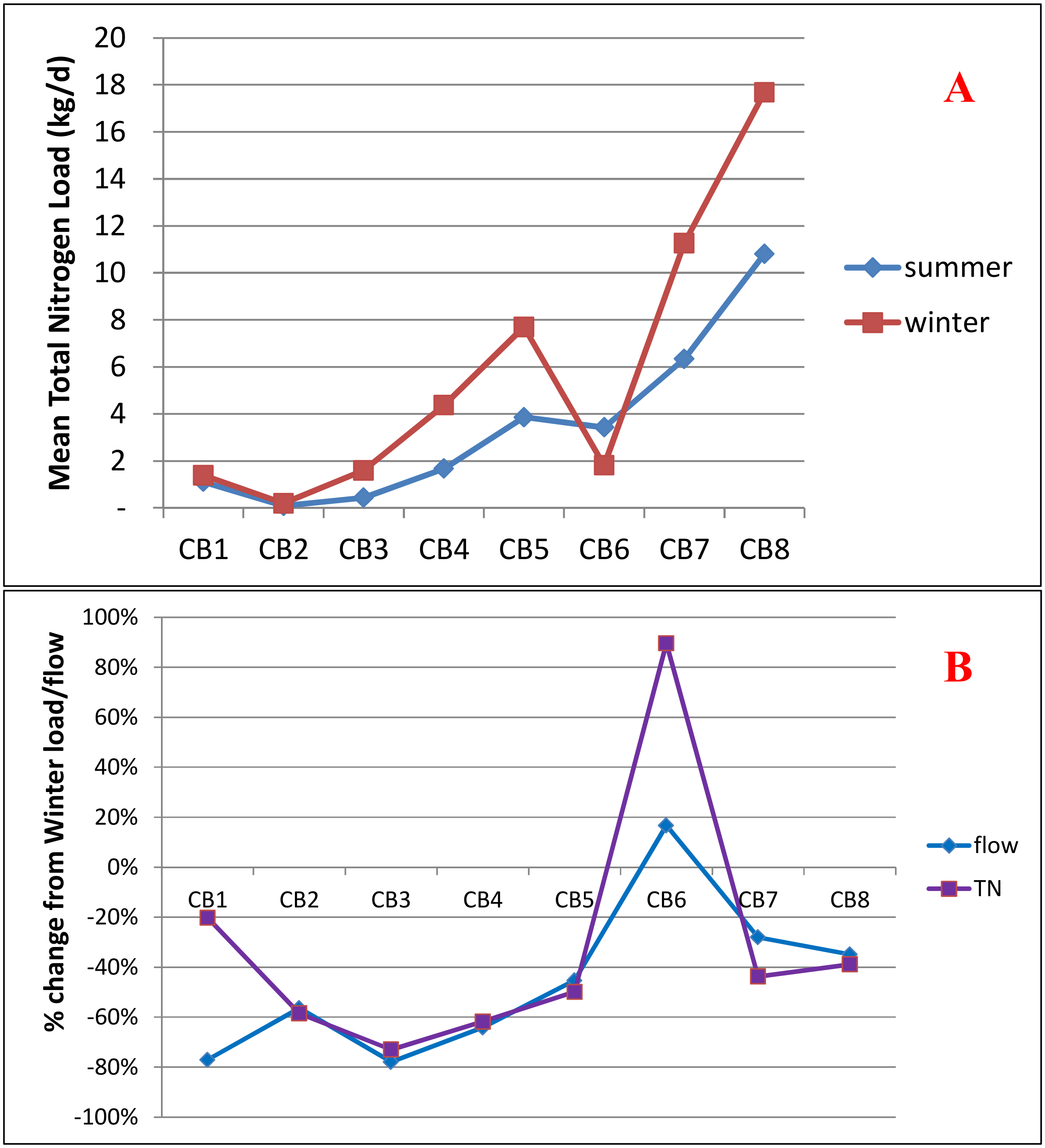

Figure V-6. Bank Street Bog Water Quality Stations: Seasonal Total Nitrogen Loads. Total nitrogen loads are generally lower in summer and higher in winter, except for CB-6 (Plate A). TN changes generally move in tandem with seasonal changes in water flow (Plate B). Summer mean TN loads at CB-6 are significantly higher than winter mean loads and are higher than the increase in flow at CB-6. Since CB-6 was in the outlet from the former irrigation pond, flows are relatively stable across seasons and, on average, slightly higher during the summer.

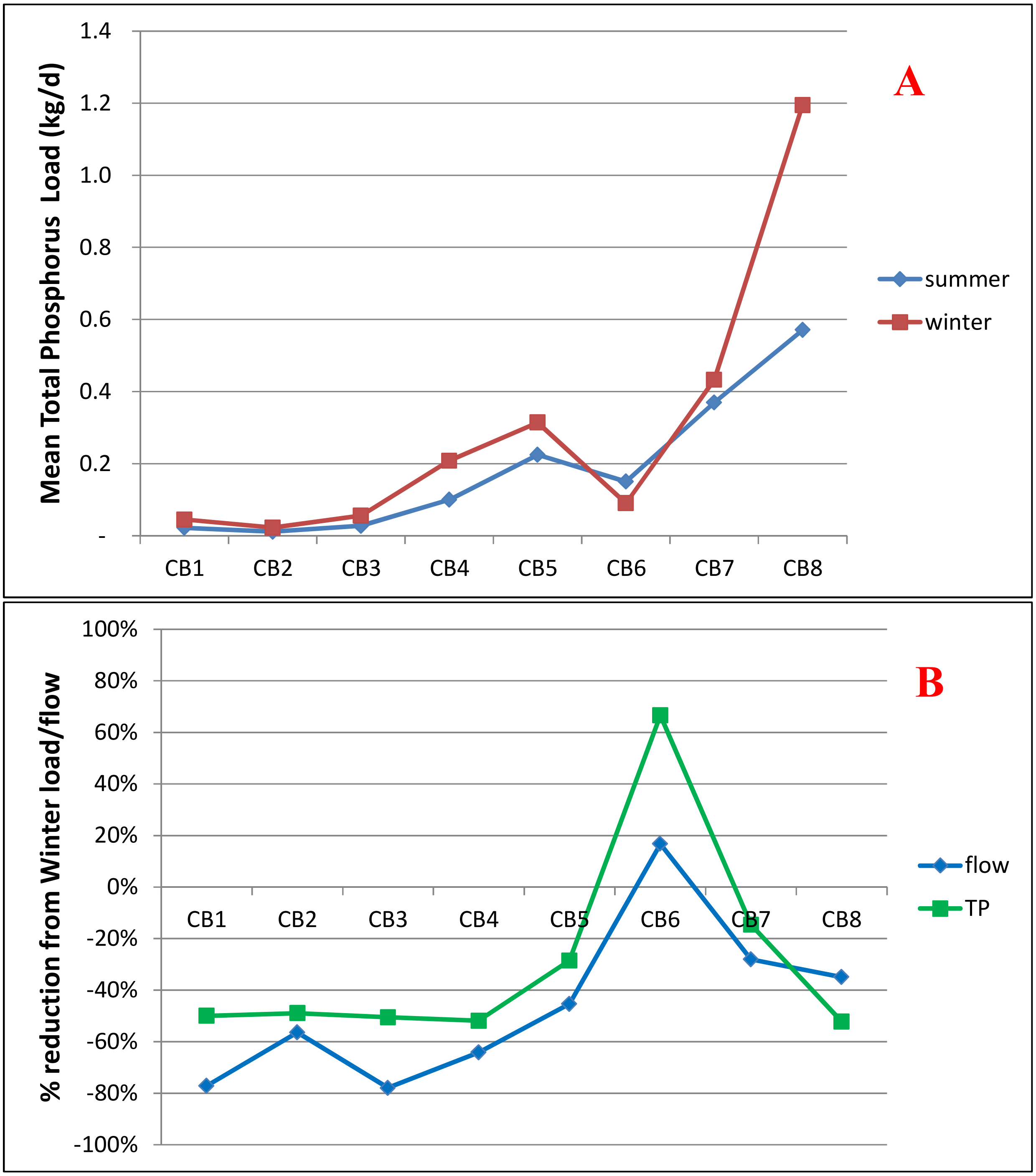

Figure V-7. Bank Street Bog Water Quality Stations: Seasonal Total Phosphorus Loads. Seasonal mean total phosphorus loads did not have as large differences between summer and winter loads as did the TN loads. Mean TP loads based on a whole year were not significantly different ($\rho<0.05$) at CB-1 and CB-3, but each subsequent downstream station, save CB-6, had a significantly higher mean load than the adjacent upstream station (Plate A). Seasonal reductions in mean TP loads generally are in the 50 to 60% range, except for CB-6 and CB-7 (Plate B). Most of the seasonal mean TP reductions are less than the seasonal mean flow reductions. CB-8, which is the station most influenced by tidal flows had a seasonal TP reduction of 52%, which is greater than the summer flow reduction.

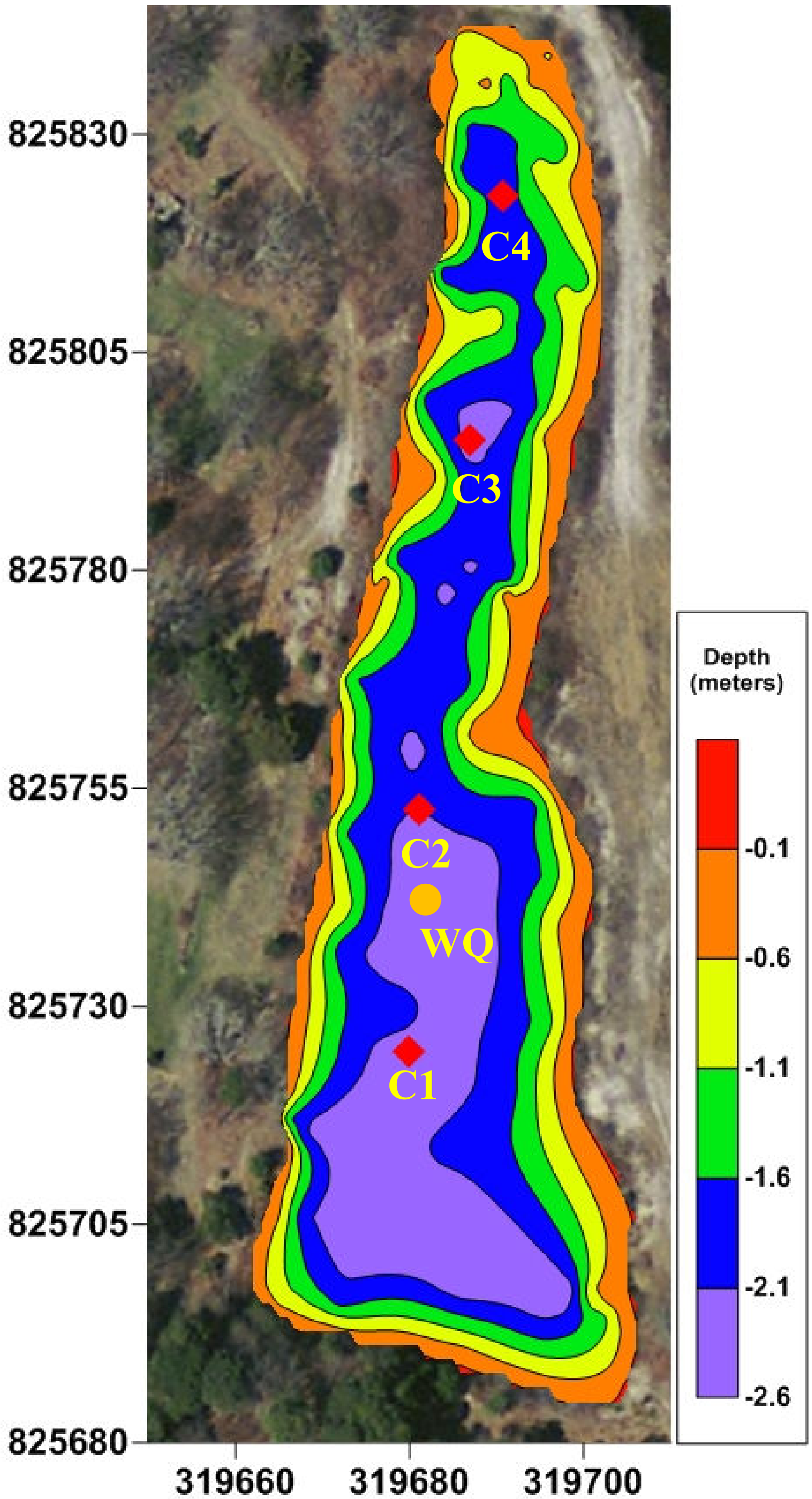

Figure V-8. Former Irrigation Pond Water Quality Station and Sediment Core Locations. The pond water quality station is indicated by the orange circle, while the sediment core locations are indicted by red diamonds. Cores were collected by SCUBA diver and were incubated at *in situ* temperatures (15°C) to evaluate nutrient regeneration from the sediments under oxic and anoxic conditions.

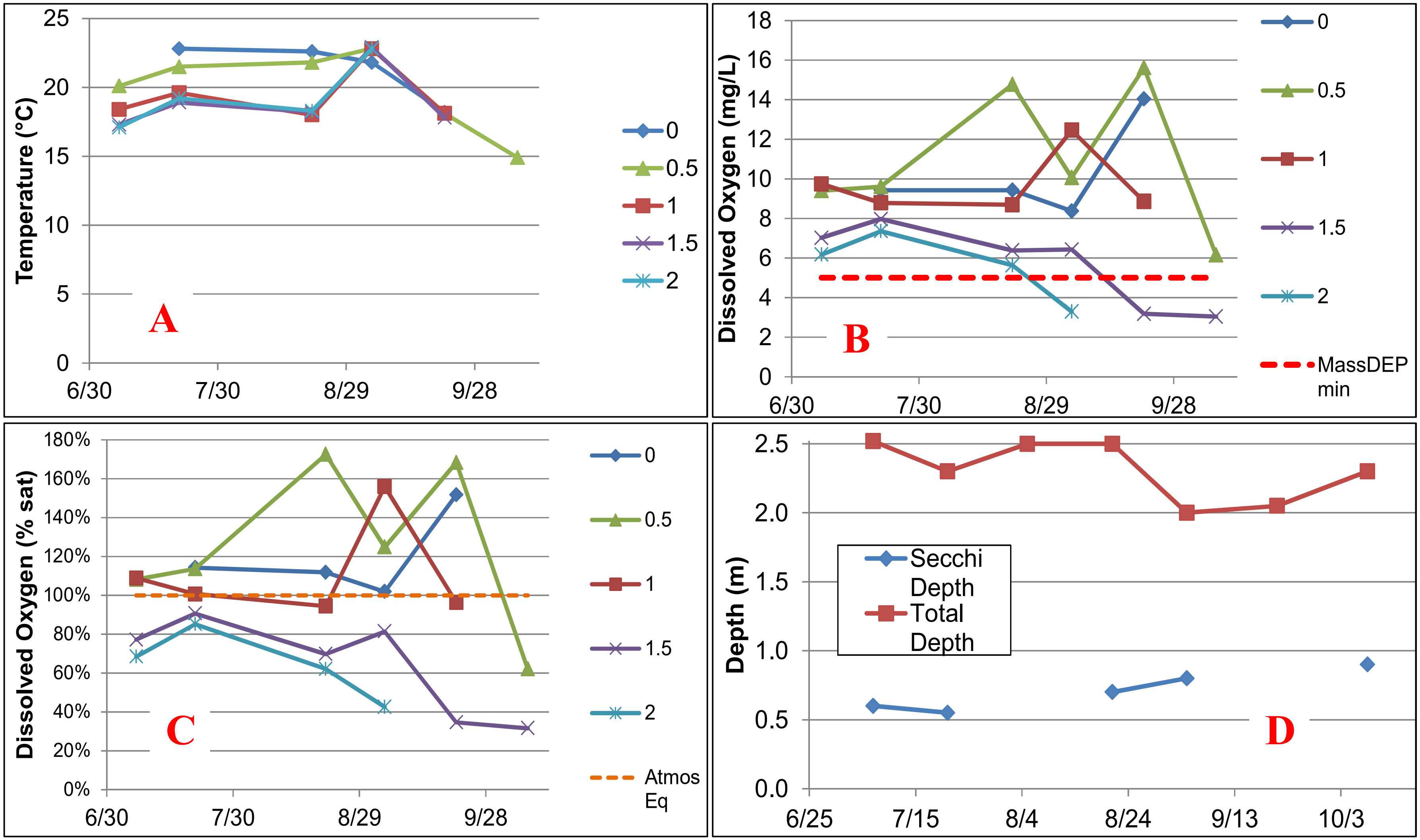

Figure V-9. Former Irrigation Pond: Dissolved oxygen, temperature, and Secchi/clarity. Plate A shows temperature collected at 0.5 m depth increments throughout the water column; readings in early summer would enhance the salinity restrictions of mixing of the water column. Plate B shows dissolved oxygen concentrations; deepest readings beginning in September are less than the MassDEP 5 mg/L minimum. Plate C shows % saturation levels of dissolved oxygen; late August and September surface readings indicate supra-atmospheric concentrations consistent with a phytoplankton bloom. Plate D shows Secchi/clarity readings; average clarity is only 31% of the water column.

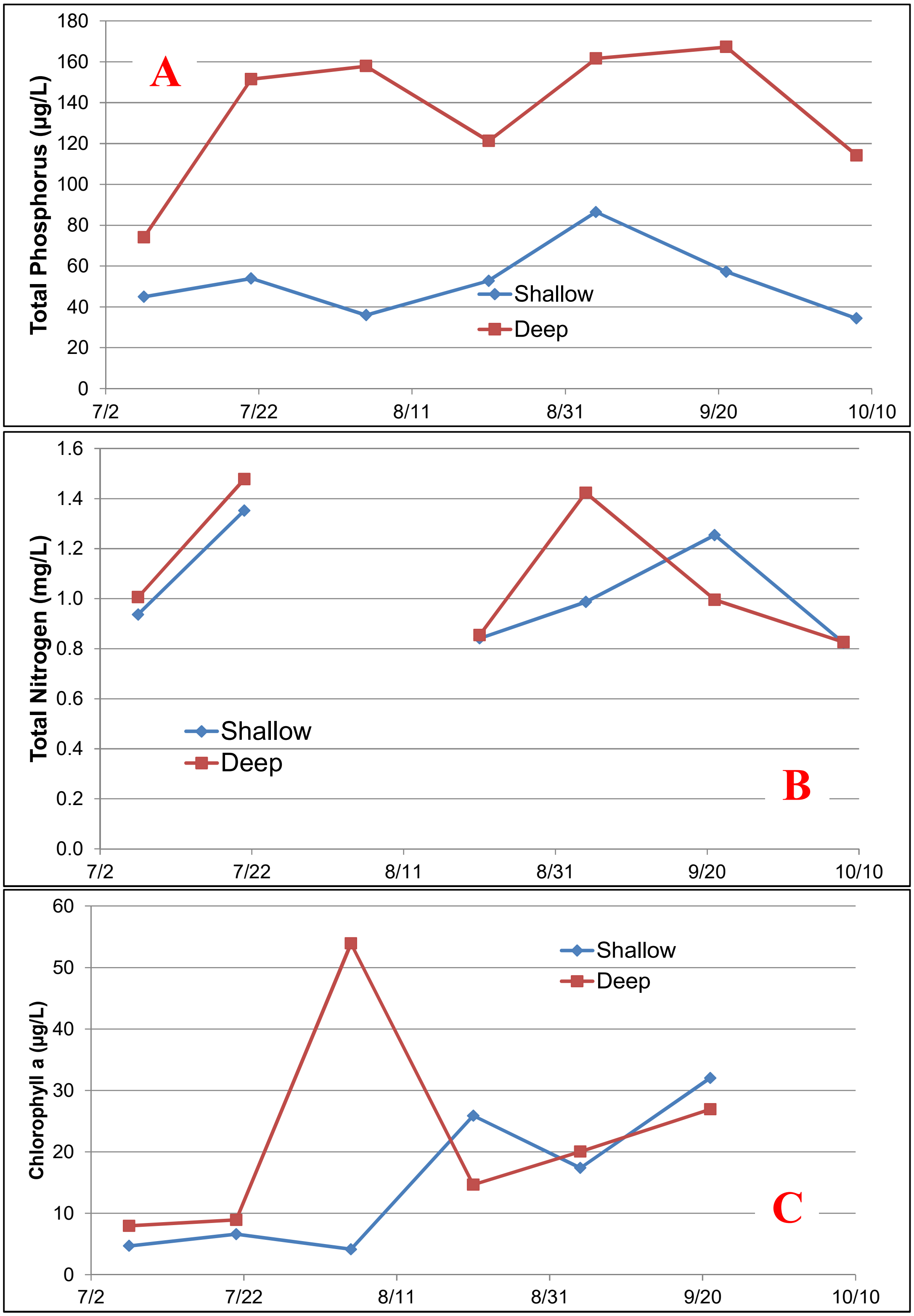

Figure V-10. Former Irrigation Pond: Total Phosphorus, Total Nitrogen, and Chlorophyll a. Plate A shows TP concentrations from samples collected at the pond water quality station at shallow and deep depths; the comparison between depths indicated sediment regeneration of TP. Plate B shows TN concentrations, which are consistent at both depths. Plate C shows chlorophyll-a concentrations, which show a doubling and tripling of early summer concentrations in late September. All TP and chlorophyll-a concentrations exceed respective Cape Cod ecoregion guidance thresholds.

VI. Habitat Assessment
As part of the assessment of the Bank Street Bogs, project staff completed a habitat survey. Staff began the survey by conducting a vegetation survey on October 23, 2015 to determine the current dominant plant communities within each bog cell. The vegetation surveys consisted of two transects through each of the cells (Figure VI-1). Dominant plant species were noted along each survey transect and other relevant observations were also noted.

Cell 1: Vegetation was surveyed along two transects within Bog Cell 1. An east/west survey transect traversed the northern portion of the cell just the southeast of the entrance to the Town of Harwich Harbormaster's Workshop facility. A mixture of vegetation was observed along transect composed of small shrubs and ground plants. Cranberry (Vaccinium) plants interspersed with some moss (Sphagnum) composed most of the ground cover. Greenbriar (Smilax rotundifolia) and denser shrubs were found to be present along the edges of the bog adjacent to the channels. Small wetland shrubs observed included common winterberry (Ilex verticillata), smooth winterberry (Ilex laevigata), red chokeberry (Aronia arbutifolia) and Virginia creeper (Parthenocissus quinquefolia). A few small red maple (Acer rubrum) and cedar trees were also present throughout the bog. A north/south transect had a mixture of different vegetation types similar to the first survey line. Small shrubs observed included winterberry (Ilex) and bayberry (Morella caroliniensis). The southernmost section of the bog contained a large cluster of trees and bushes composed of red maple, white birch, small pine (Pinus rigida) and large bayberry bushes. Groundcover was similar to the east/west transect, but tussock sedges (Carex stricta) were also present sporadically.

Cell 2: Survey of this bog cell also consisted of east/west and north/south transects. The east/west survey line was a mixture of vegetation types, but with larger shrubs and tree clusters (up to 15 ft tall) than seen in Cell 1. Ground cover consisted of cranberry (Vaccinium) and grasses (Carex and Juncus species). The sedges (Carex) and rushes (Juncus) were dispersed throughout the cell. Approaching the main stem of Cold Brook, there were sporadic patches of cattails (Typha), ferns, and bittersweet. Moving in the westerly direction across the bog, the winterberry shrub (Ilex) and chokeberry (Aronia arbutifolia) bush clusters were more common and larger than in Cell 1. Red maple (Acer rubrum) trees also increased in size and frequency. Also found to be growing within the bog were small cedar trees (Chamaecyparis thyoides), but in less frequency than the red maples. Green briars were also observed extensive in this cell. The north/south transect, produced similar observations of vegetation types of red maple stands but also included winterberry shrubs, bayberry bushes and pine trees (Pinus rigida, Pinus banksiana). Evidence of brush cutting, apparently targeting pitch pines (Pinus rigida) was noticed within this cell.

Cell 3: Within Cell 3 a transition in the vegetation community was seen in regards to upland tree species. The east/west transect contained red maple trees as the dominant tree type with large stands throughout the bog, many taller than those seen in Cell 2. Small pine trees and a few small scrub oaks (Quereus ililifolia) were also observed but in less frequency than the red maple. Red chokeberry (Aronia arbutifolia) and arrowwood bushes were also present along this transect as well as some winterberry shrubs. Sedges (Carex species) composed the observed grass vegetation on the bog surface. The north/south transect also contained clusters of red maple and pine trees with sparse small scrub oaks. Groundcover was sedges (Carex species) and rushes (Juncus species). Of particular note in this cell was a large patch of Phragmites and cattails

(Typha) with some ferns (Onoclea species) located along the northwestern edge of the cell (indicated as red circle on Vegetation Map). This area was adjacent to the drainage ditch along the northern edge of the cell and in one of the lowest elevation areas in this cell. Evidence of brush cutting, apparently targeting pitch pines (Pinus rigida) was also apparent within this cell.

<u>Cell 4</u>: This cell contains large stands of pine trees (Pinus) throughout the cell, many 10 to 15 ft tall. This cell does not appear to have been put into extensive cranberry production since the cell surface has extensive patches of exposed sand and additional vegetation was very sparse. The northern and eastern sections of the cell were dominated by dense stands of pine. Toward the southern section, the pine stands became less dense. It should be noted that the northeastern edge of the cell contained a small creek area that held some water. The former creek/channels that bordered the bog cell are now mostly filled in and are not easily definable as generally observed in the other cells.

<u>Cell 5</u>: Observations along the two cell transects generally indicated that the plant community was shifting from bog/wetland toward an upland plant community. As observed in Cell 3, red maple (Acer rubrum) trees increased in number, creating large stands throughout the cell. Cedar trees (Chamaecyparis thyoides) and Juniper shrubs (Juniperus communis) were also present but in much less frequency and density than the maples. Red chokeberry (Aronia arbutifolia) and winterberry (Ilex) shrubs were also observed. Small scrub oak trees (Quereus ililifolia) were also present but largely located along the upland banks of the cell. Pine trees were present but few in numbers. Along the major channels that flow through the bog, cattails (Typha) and ferns (Onoclea) were also present. A section in the northern/central portion with the main cell creek contained a swampy area with a dense stand of cattails. Ground cover generally consisted of cranberry (Vaccinium) and moss (Sphagum species) especially adjacent to the above mentioned wetland area. Sedges (Carex) were also part of the ground cover.

<u>Cell 6</u>: Four survey transects were run through this cell with more concentrated observations in selected areas. The main stem of the brook was used as a natural divide separating the cell into east and west sections. In the northern portion of the cell, red maple (Acer rubrum) predominated as the tree species in both east and west sections, while cedars (Chamaecyparis thyoides) and a few pine trees were also present. Shrub vegetation generally consisted of red chokeberry (Aronia arbutifolia) and winterberry (Ilex). Cranberry and sedges, as well as ferns (Dryopetris), were observed in the ground cover on each side of the brook within the northern portions of the cell. In the southern portion of the eastern section of the cell, a well-defined transition line was observed with significant numbers of red maple trees north of the line and a shift toward eastern false willow (Baccharis halimifolia) shrub and sedge grass (Carex) south of the transition line (indicated in pink in Figure VI-1). Red maples were still present south of the transition line, but sharply reduced in number. The same decline was observed on the western side of the cell, south of the former irrigation pond. This transition line roughly corresponds to a decrease in elevation, which likely provides less unsaturated thickness above the saltier groundwater indicated in the GPR study (see Figure II-6). In the southern sections of the cell, the vegetation consisted almost entirely of sedge grasses (Carex stricta) with some mixing in of eastern false willows. Cattails (Typha) were present along sections of the main brook. On the southwestern edge, small pines (Pinus) and eastern false willow formed the edge of the bog cell and transitioned to sedges approaching the main creek.

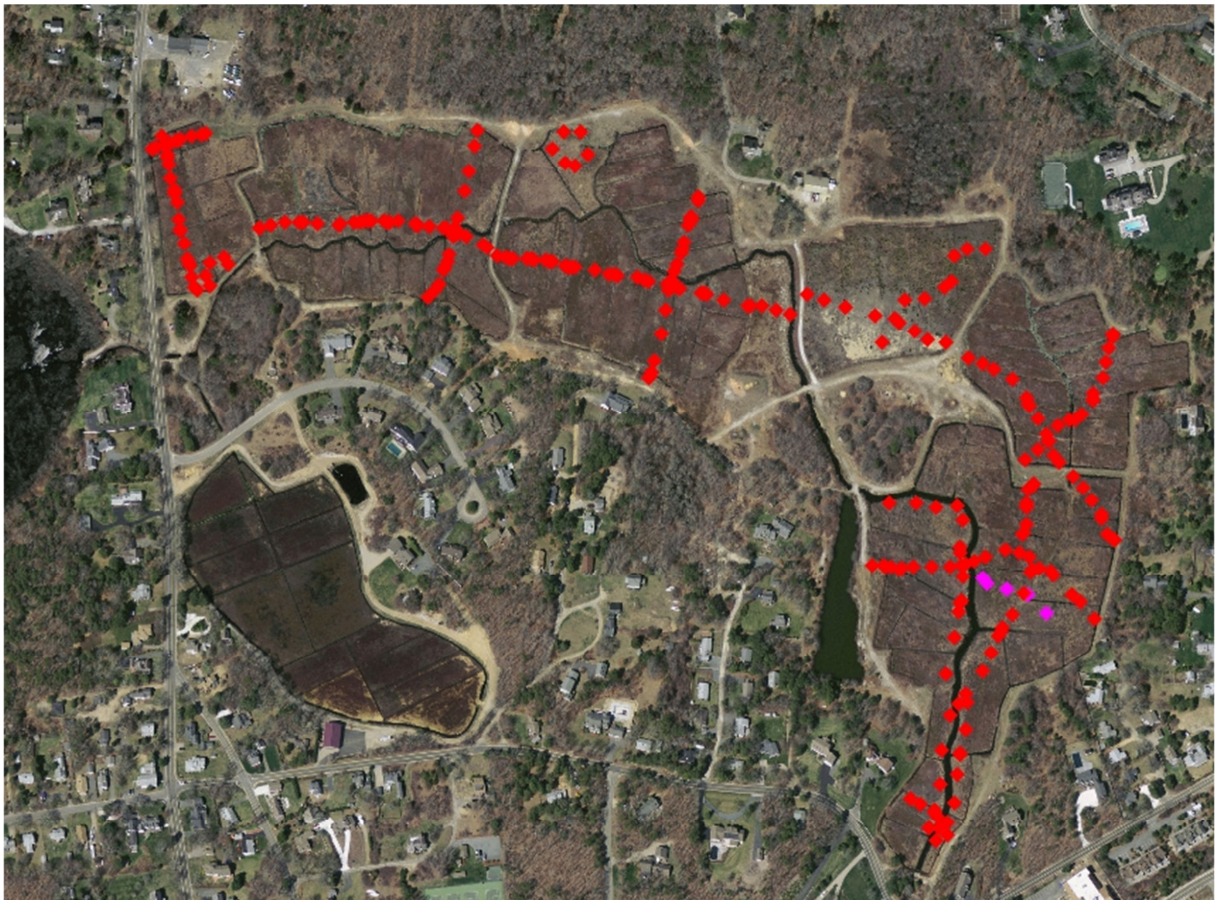

Figure VI-1. Bank Street Bogs: Bog Cell Vegetation Survey Transects. Survey was conducted October 23, 2015. Red diamond points are locations that were collected along transects using a Leica Viva GNSS/GPS with RTK enabled. Vegetation was noted along the transects. Selected locations were surveyed more extensively due to unique vegetative features [*e.g.*, the patch of Phragmites in the northwest portion of Cell 3 or the transition from a tree-dominated collection to a shrub-dominated collection in Cell 6 (indicated by the pink diamonds)].

VII. Management Options and Goals

Management within and around the Bank Street Bogs system involves a number of parties including the Town of Harwich, the Harwich Conservation Trust, the Massachusetts Division of Marine Fisheries, Massachusetts Division of Environmental Restoration and a number of consultants throughout the recent years since the Saquatucket Harbor MEP report was released. The purchase of the Bogs by the Harwich Conservation Trust in 2001 and the Bogs gradual natural reclamation by the surrounding plant communities has raised a number of management issues within and beyond the Bogs, including: a) decades-long discussions relating to maintaining adequate stream flow for passage of eels to Grass Pond and available water for use by the adjacent cranberry bog, b) how the landscape and ecosystems of the bog property might be best managed, and c) discussions about potential opportunities to restoration of freshwater habitats in a manner that also enhances natural removal of watershed nitrogen as part of a plan to restore water quality in Saquatucket Harbor.

MassDER has recently proposed an extensive reworking of the Bogs including excavation of large portions of Cells 2 and 3, a number of alterations and changes to the Cold Brook channel, filling of internal bog ditches, and removal of many of the Brook water control flumes. Project staff reviews of the proposed excavations and topographic survey data suggests that these deepened excavation areas will have standing water for much of the year. For example, MassDER has proposed excavation of approximately 4.8 acres (or 69%) of Cell 2 area by removing up to 4 feet (1.21 m) of surficial sand based on the HGI ground-penetrating radar assessment. Based on the topographic survey data, the mean bog surface in Cell 2 is 1.65 m NAVD88. If the average depth of MassDER excavation is 2 ft, the mean bog surface would be reduced by 0.6 m to 1.05 m NAVD88 with a minimum elevation of 0.40 m NAVD88 (see Table III-1). Water levels at CB-1 fluctuated roughly between 1.1 and 1.5 m NAVD88, while water levels at CB-5 (the next closest continuous stage recorder) fluctuated roughly between 0.4 and 0.5 m NAVD88 (see Figure IV-3). Since the Cell 2 excavation is approximately 70% of the brook distance between CB-1 and CB-5, it is reasonable to assume that the fluctuation in the groundwater levels in the areas of excavation will be roughly similar to the distance change or a groundwater fluctuation range of 0.9 to 1.2 m NAVD88. Since the average depth of the excavated Cell 2 is estimated as 1.05 m, most of the cell will likely have water just at the surface with the proposed deeper hole holding water 0.5 to 0.8 m deep. Further refinement would be necessary through comparison of planned excavation elevations and elevation contours developed for this project, but the projected residence time of water in this basin would be on the order of 5 days based on the average 2014/2015 flow into Cell 2. Similar analysis for Cell 3 would result in a residence time of ~3 days, a groundwater fluctuation range of 0.68 to 0.9 m NAVD88, and a deepest hole holding water 0.25 to 0.5 m in depth.

The greater the water volume created, the longer the residence time and the greater the nitrogen attenuation potential. Evaluation of freshwater ponds on Cape Cod with intensive water quality monitoring and similar residence times has found natural nitrogen attenuation rates of 50 to 80%.[33] Comparable MEP stream attenuation rates have ranged from 10% to 40% generally appearing to be based on the number of ponds within the stream contributing area and

[33] Howes B., S. W. Kelley, J. S. Ramsey, R. Samimy, D. Schlezinger, E. Eichner (2006). Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for Three Bays, Barnstable, Massachusetts. Massachusetts Estuaries Project, Massachusetts, Department of Environmental Protection. Boston, MA.

hydrogeology of the watershed, with higher runoff watersheds having lower attenuation rates than highly permeable sandy soils. The balance between phosphorus and nitrogen is also a factor; Cedar Pond in Orleans was brackish with phosphorus as the nutrient which stimulates plant growth and the Rock Harbor MEP assessment and stream measurements showed it removed 58% of the watershed nitrogen.[34] Through a series of changes to the system that were not reviewed sufficiently, the pond salinity has increased from 7 ppt to 23 ppt and the natural nitrogen attenuation has been eliminated.[35]

With all of this in mind, it is proposed that even deeper excavations within Cell 2 and Cell 3 be evaluated; the depth of the excavations will have to be discussed with the Harwich Conservation Trust and local and state regulators and will have to consider slope stability for the soil types, whether the stream will flow through the ponds, and other details related to potential changes within the Bank Street Bog wetlands. Given the areas of the cells 2 and 3, simple conical ponds of 4 acres/7 m deep and 5 acres/8 m deep, respectively, were evaluated with modest 10% internal bathymetric slope. Deeper, more irregularly shaped ponds will be likely, but more refined design would have to await further details and discussions. As currently proposed and using the measured flows in this project, the deepened MassDER areas in Cells 2 and 3 would have estimated residence times of 3 to 5 days each with a slightly longer residence time in Cell 3 due to the linking of the areas in series. If simple conical ponds were added to the system, the residence times of the MassDER areas would triple (10 to 15 days). If ponds with steeper edges and broader bottoms were created (*e.g.*, 90% of the surface area), residence times would rise to 43 and 29 days, respectively. Longer residence times provide greater nitrogen attenuation.[36] The anticipated attenuation for a reworked Cold Brook/Bank Street Bog system would depend on the configuration of the system (*e.g.*, volume of ponds, whether streams flow through or around ponds, whether the stream flow is altered, etc.).

The addition of larger pools with sustained water throughout these deepened areas would also provide the additional benefit of providing some non-contested spawning habitat for returning eels. Eels currently travel up Cold Brook to try to spawn in Grass Pond, which is upstream of Bank Street and across the Bank Street dam. MassDMF has developed a number of management strategies to get eels past the Bank Street dam including hand transport and installation of a pump. Grass Pond is approximately 20 acres with a measured maximum depth of 3 ft (0.9 m).[37] If the excavation areas in Cells 2 and 3 were deepened slightly to ensure that the entire area was flooded throughout the year, their combined open water area would be slightly greater than 10 acres or a bit more than half of the area of present day Grass Pond. Since Grass Pond is surrounded by wetland, the habitat should be fairly similar. If these areas could be utilized as a "backup" for Grass Pond, it could ensure that eel spawning grounds are always available within the Cold Brook system. This action would also help mitigate natural groundwater fluctuations,

[34] Howes B.L., S.W. Kelley, J. S. Ramsey, R.I. Samimy, D.R. Schlezinger, and E.M. Eichner. 2007. Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Rock Harbor Embayment System, Orleans, MA. SMAST/DEP Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA.

[35] Eichner, E., B. Howes, and D. Schlezinger. 2013. Cedar Pond Water Quality Management Plan. Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth. New Bedford, MA. 54 pp.

[36] Nitrogen attenuation depends on a number of system characteristics, but hydraulic residence time has been shown to be a key factor (*e.g.*, Toet, et al., 2005; Saunders and Kalff, 2001).

[37] CDM Smith. 2016. Final Comprehensive Wastewater Management Plan/ Single Environmental Impact Report, Town of Harwich, Massachusetts. Boston, MA.

and create some additional time for resolving all of the management issues associated with maintaining timely flow for the cranberry grower and passage to Grass Pond.

In addition to the modifications in the proposed excavation areas, staff also proposes that HCT and the Town of Harwich consider creation of a pond in Cell 4. Cell 4 is a mostly sandy sparsely vegetated cell, with relatively large areas that do not have residual wetland/cranberry plants. Ground-penetrating radar has indicated it used to contain the historical a portion of the Cold Brook channel. Flow monitoring during this project has shown that this cell is directly upgradient of the portion of the Bogs receiving 60% of the Brook flow and nitrogen load. Restoring this area and creating a moderately deep isolated pond will capture groundwater providing the opportunity to intercept and focus much of the upgradient watershed before entry into Cold Brook. Given the area of Cell 4, a simple conical pond of 5.1 acres could be installed and with a 10% slope could attain a maximum depth of 6 m. If this cell intercepted a third of the flow headed to CB-8, its residence time would be approximately 5 days. If the pond was flat-bottomed, its volume and residence time would nearly triple (15 days). If the whole cell was used, the residence time would nearly double again (27 days). Longer residence times are associated with greater N removals.

In addition to the modifications within the existing cells, CSP/SMAST staff also proposes that HCT and the Town consider modification of the former irrigation pond to create more nitrogen attenuation. This modification would involve removal of the sediments in the southernmost portion of the pond and installation of a flapper valve or similar structure to allow Cold Brook flow into the pond but prevent tidal waters (and salt) from entering. Reducing the salinity stratification would reduce the sediment nitrogen and phosphorus release in summer and its transport downstream. In addition, reduction of the phosphorus would drive the system toward more consistent nitrogen:phosphorus ratios and reduce the algal blooms and low oxygen events, improving the pond habitat. This would also increase nitrogen removals by enhancing coupled nitrification-denitrification in the pond sediments. The result being a lowering of watershed nitrogen reaching nitrogen impaired Saquatucket Harbor.

Finally, it is clear that the Bank Street Bog system is complex with varying conditions both on a seasonal and year-to-year basis. Implementation of planned and proposed strategies within the Bank Street Bog and overall Saquatucket Harbor watershed could be done in a step-wise fashion with regular assessment of system response. This type of adaptive management approach may offer the opportunity to alter and adapt strategies as the system is reaches a new equilibrium. It is recommended that monitoring, synthesis of data, and regular feedback is part of any program to alter the hydrology and nutrient dynamics of this Bog System. However, it is clear from the synthesis of all available data from the present and previous studies, that the Cold Brook system fulfills the criteria needed to be a candidate for enhancing nitrogen removal as part of aquatic system restoration. A proper managed alteration of this system will not only increase and improve freshwater habitat, but also be a step toward restoring the nitrogen impaired habitats within the receiving basin of Saquatucket Harbor.

Much of these proposals will require more extensive discussions with stakeholders and certainly will require addressing regulatory issues. CSP/SMAST staff is available to assist the Town, HCT, and any of the management partners with those discussions and/or to refine any evaluations and conclusions in this report.

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