MEMORANDUM

TO: **Donald Ware, P.E., Pennichuck Corporation**
FROM: **Comprehensive Environmental, Inc.**
SUBJECT: **Harris & Bowers Supply Pond In-Fill & Storage Volume Estimates**
JOB NUMBER: **131-61**

This memo summarizes description of methods used to calculate active and dead storage volumes for Harris and Bowers Ponds over several different years; comparisons between CEI's data with previously collected 2011 multi-beam data; results of those calculations; and conclusions from this GIS based effort.

As part of this effort, CEI completed multiple sonar collection efforts in 2016, 2017 and 2018 to supplement historical bathymetric data that was collected in 2010 and in 2011 using various other mapping methods. This data was used to calculate volumes in both active and dead storage for the different time periods in order to identify a potential in-fill rate for the supply ponds. This work was completed using GIS software and extensions that can create bathymetric surfaces and compare those surfaces to determine volumes between.

<u>Description of Methods</u>

CEI began the current project with the following GIS-related objectives:

1. Calculate active and dead storage volumes from CEI's sonar data compiled through 2018
2. Calculate active and dead storage volumes from the 2011 multi-beam sonar data
3. Extrapolate a 2018 bathymetric surface from shore to shore in Harris and Bowers Ponds
4. Estimate additional storage volumes based on pond levels and local topography

1. CEI merged its sonar bathymetric point data collected in the 2016, 2017, and 2018 field seasons in Harris, Bowers, and Holt Ponds. Any 2017 data points within 40' of a 2018 data point were omitted, and any 2016 data points within 40' of a 2017 or 2018 data point were omitted. The purpose was to replace older data with newer wherever possible. It was found that a distance of 40' allowed a smooth interpolation between points in most areas, while still preserving existing detail as much as possible. However, there were still not enough points to interpolate a surface that could be compared with the 2011 multi-beam sonar data in any meaningful way. Additional data were needed to fill in some of the gaps.

   CEI has older bathymetric data in the form of contour polygons, dating from 2010 and earlier, which extend closer to the pond shorelines in many areas. This older data was combined with the newer sonar data by the following method. An array of points was extracted from the 2010 polygons with 3' spacing in the x and y directions, and merged with the newer data by omitting any 2010 points within 40' of any newer point. The resulting array of points represent CEI's most recent bathymetric data in any given area. Spline interpolations tend to be more effective on unevenly-spaced data points such as these, so a spline was made through the points and smoothed slightly by running focal statistics on it, averaging the depth values over a moving circle of 5 cells (15') radius. The purpose of the smoothing is to reduce artefacts produced by the interpolation algorithm where it encounters neighboring points of substantially different values. This occurred where the 40’ separation was not sufficient. The relatively small size of the moving circle minimizes the loss of resolution.

The purpose of this integration of CEI’s data was to create a surface that could be used to calculate active and dead water storage volumes and compare them with those from the 2011 multi-beam data. But the CEI data and the 2011 multi-beam data have different footprints, neither of them extending from shore to shore in each pond. Thus CEI’s integrated 2010-to-2018 data surface had to be trimmed to match the footprint of the 2011 multi-beam sonar surface, and vice versa.

2. The 2011 multi-beam sonar data was received from Pennichuck Water Works (PWW) in the form of text files containing x, y, z data for an array of points with 3’ spacing in the x and y directions. The z values were recorded as elevations referenced to NAVD88. CEI converted them to water depths referenced to NGVD29, in order to match all of CEI’s current and historic bathymetric data and the plans and drawings for the dams. (In this location, a given elevation in NGVD29 is 0.694’ higher than the same elevation in NAVD88.) Because these points are uniformly distributed, a surface was interpolated from them using inverse distance weighting which tends to be more effective on evenly-spaced data points. As stated above, the footprint of the resulting surface was trimmed to match that of CEI’s bathymetric data.

   A number of other surfaces also had to be created to make volume calculations possible. A lake surface with water depth of 0 was created, along with two separate threshold surfaces for Bowers and Harris Ponds. The threshold surfaces were set to water depths of 10.12’ (Bowers) and 26’ (Harris), the depths to spillway or low-flow pipe invert. Then an “active” surface was created for each pond, where the z value reflects the water depth where it is less than the threshold depth, and the threshold depth everywhere else. Finally, cut-fill operations were made on these surfaces to find active water storage, dead water storage, and volume of sediments occupying space in active storage, as follows:

   - Cut-fill lake surface to active surface => active storage
   - Cut-fill threshold surface to bathymetry => dead storage and sediments in active storage

   These volumes were calculated for CEI’s integrated 2010-2018 dataset and for PWW’s 2011 multi-beam sonar data, in order to estimate sediment influx or redistribution over the years between 2011 and 2018.

3. CEI then wished to extrapolate a bathymetric surface for the complete, shore-to-shore extent of Bowers and Harris Ponds. CEI’s point data from the 2016, 2017, and 2018 field seasons were combined with PWW’s 2011 multi-beam sonar points in the manner outlined above, where older points within 40’ are replaced by newer points. Additionally, points were extracted at 3’ intervals along the pond shorelines, assigned a water depth of 0’ and added to the dataset. Then a spline surface was interpolated through all the points. The spline was smoothed slightly using focal statistics on a moving circle of 5 cells (15’) radius. New active and threshold surfaces were created which extend to the pond shorelines, and volume calculations were made as described above.

4. Another objective was to determine if any additional active storage was possible given the pond surface levels and the surrounding topography. For the sake of consistency,

for all its calculations CEI has used pond outlines taken from the National Hydrography Dataset (NHD), published and maintained by the USGS. However, a shoreline is a dynamic feature and can vary horizontally by a considerable distance. It is likely that the NHD shoreline is not completely accurate, and that "normal pond elevations" may expand the shoreline in some places. To find where these potential expansions might be, CEI downloaded LiDAR elevation data from GRANIT and drew 1 ft. contours. The LiDAR data references the NAVD88 datum and thus is 0.694' lower than the pond bathymetric data, so the "normal pond elevation" of 178' for Bowers corresponds to a LiDAR elevation contour of 177', while the "normal pond elevation" of 168.17' for Harris corresponds to a LiDAR elevation contour of 167'. The 177' elevation contour is mostly above the Bowers Pond shoreline used for these and earlier calculations. The 167' contour is at or below the Harris Pond shoreline as identified by LiDAR. CEI measured the additional surface area between the Bowers Pond shoreline used for these calculations and the 177' contour derived from LiDAR, and estimated an average of 1' water depth over the area to reach a volume of additional, theoretically possible, active storage.

GIS Calculation Results

1. The numbers below come from CEI's 2016-17-18 point data superimposed on a background of the CEI 2010 bathymetry contours and turned into a grid. It has been clipped to match the PWW 2011 sonar data footprint.

CEI'S 2018 DATASET

Water Volumes in Active and Dead Storage

	Active (cu. ft.)	Active (gal.)	Dead (cu. ft.)	Dead (gal.)
Bowers	19,794,584	148,073,782	7,832,581	58,591,779
Harris	46,101,017	344,859,580	362,155	2,709,108

Sediment Volumes Occupying Active Storage Space

	Active (cu. ft.)	Active (cu. yd.)
Bowers	2,290,588	84,837
Harris	25,309,553	937,391

2. The numbers below are the PWW 2011 sonar data only. It has been clipped to match CEI's data as of 2018.

2011 MULTIBEAM SONAR DATASET

Water Volumes in Active and Dead Storage

	Active (cu. ft.)	Active (gal.)	Dead (cu. ft.)	Dead (gal.)
Bowers	19,045,056	142,466,922	6,023,607	45,059,713
Harris	42,509,376	317,992,237	68,254	510,575

Sediment Volumes Occupying Active Storage Space

	Active (cu. ft.)	Active (cu. yd.)
Bowers	3,026,112	112,078
Harris	28,908,153	1,070,672

3. The numbers below come from CEI's 2016-17-18 point data superimposed on a background of the PWW 2011 sonar data and turned into a grid. The grid has been extended from shore to shore by assigning a water depth of 0 to the pond outlines.

Water Volumes in Active and Dead Storage

	Active (cu. ft.)	Active (gal.)	Dead (cu. ft.)	Dead (gal.)
Bowers	25,410,107	190,080,814	8,270,368	61,866,653
Harris	47,153,399	352,731,942	170,935	1,278,680

Sediment Volumes Occupying Active Storage Space

	Active (cu. ft.)	Active (cu. yd.)
Bowers	13,025,893	482,440
Harris	33,955,444	1,257,609

4. The numbers below refer to the additional area between the mapped pond outlines and the LiDAR-derived contour that corresponds to "normal pond elevation". For Bowers, that contour is mostly beyond the mapped pond outline. For Harris, that contour is within the bounds of the pond, so there is no additional space between the pond outline and the LiDAR-derived contour.

	Mapped pond area (sq. ft.)	Additional area to LiDAR contour (sq. ft.)	Additional active storage, assuming 1' depth everywhere (cu. ft.)
Bowers	3,799,940	516,732	516,732
Harris	3,147,710	0	0

<u>Conclusions</u>

Based on the resulting volumes, it was determined that storage volume estimates appeared to increase in 2018 compared to the 2011 data sets and the volume of sediment occupying active storage decreased. However, those sediment volumes were relatively close between 2011 and 2018 and the discrepancies could be due to accuracy of measurement equipment. It was concluded that an accurate in-fill volume or storage loss could not be determined based on this data, as different collection methods and different sonar collection footprints were used between the 2011 multi-beam and 2018 sonar efforts. The 2011 methods were very accurate for very deep sections of the ponds, but could not collect or reach all of the potential bathymetry and thus, underestimated the storage volumes of the ponds. The methods used in 2017 and 2018 could reach more locations, but the data collected in the deeper sections were not as accurate as the 2011 data set because of the type of collection equipment used. The 2018 effort was able to reach most of the bathymetric footprint, however, very shallow reaches still could not be collected and an interpretation results in approximately 500,000 cubic feet of storage that is not represented in the 2018 mapping of Bowers Pond.

It is recommended that the 2018 data set be used as a baseline for future in-fill estimates. Subsequent collection efforts should utilize similar collection methods and sonar collection footprints to determine accurate in-fill or potential storage loss.

These calculations are supported by the GIS data, which are provided as electronic files to this memo.