SAVERY POND
2018 WATER LEVELS & STREAMFLOW

Monitoring Water Levels on Savery Pond

June 2019

Friends of Ellisville Marsh, Inc.

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1.0 INTRODUCTION

Savery Pond is a groundwater-fed, 28.4-acre pond[1] in Plymouth, Massachusetts that discharges via Herring Brook to the Ellisville Marsh estuary. The pond has experienced increasing occurrence of cyanobacteria blooms in recent time. Public health advisories associated with blooms were issued by Massachusetts Department of Public Health (MDPH) in 2011, 2014, 2015, 2016 and 2017; and high levels of algae have been observed by local residents in other years. Friends of Ellisville Marsh (FoEM), in conjunction with the Town of Plymouth Department of Marine & Environmental Affairs (Town) and their consultants have worked diligently to collect data to better understand pond conditions, nutrient concentrations, algal blooms, and related factors. Ultimately, FoEM and the Town plan to work with specialists in the field to develop a pond assessment and a pond management plan. The assessment will include a water budget and a nutrient budget for the pond. This report presents key information regarding pond hydrology and groundwater flow patterns that is relevant to developing the nutrient and water budgets. Ongoing data collection will further contribute to the nutrient and water-budget analyses.

Under its Savery Pond Initiative (SPI), FoEM has been collecting hydrologic data on Savery Pond since August 2016 under the guidance of a licensed hydrogeologist[2]. This report covers data collected over a 2.3-year period through November 2018. Data include time-series water-level elevations (WLE's) for the pond and an adjacent well, a synoptic ("snapshot") measurement of WLE's at 18 hydrologic monitoring points (wells and surface-water features), and continuous flow data from the pond outlet at Herring Brook (collected since early May 2018). The monitoring network is shown on **Figure 1-1**. The data have been interpreted to better understand hydrologic functions associated with Savery Pond and how they relate to upcoming water-budget and nutrient budget analyses.

2.0 SUMMARY OF FINDINGS & CONCLUSIONS

The following bullets summarize the key findings and conclusions of this report:

1. Savery Pond is hydraulically connected to a regionally-extensive water-table aquifer. The pond partially penetrates the aquifer and the pond surface is an expression of the regional water-table. Groundwater flows both into and out of Savery Pond, with inflows predominantly occurring on the west side of the pond and outflows on the east. The pond also discharges to Herring Brook through an outflow control structure, which holds the pond at a relatively stable elevation.
2. The regional aquifer is recharged by precipitation, which also falls directly on the pond. Recharge is seasonally reduced during the growing season when precipitation is largely lost to evapotranspiration. Although pond levels remain relatively stable year-round, groundwater level monitoring in a nearby well shows seasonal variations on the order of 2.2-2.9 feet. Seasonal high groundwater levels were observed in spring (April-June) and seasonal lows were observed in early winter (November-January).
3. Over the 2.3-year monitoring period, annual precipitation showed a rising trend. Relative to a 47.1 in/yr long-term average, precipitation increased from 71 percent of average (2016) to 98 percent (2017) to 129 percent (2018). 2018 was the wettest of the 20-year record and is reflected by relatively high groundwater levels. Resulting 2018 streamflow measured in Herring Brook is therefore expected to be higher than average.

[1] Classified as a "Great Pond" under Massachusetts criteria.

[2] Peter Schwartzman, Principal Hydrogeologist at Pacific Groundwater Group (Seattle WA) and FoEM board member.

4. Water-table mapping by FoEM confirms prior interpretation by the U.S. Geological Survey that groundwater flows towards the coast (roughly west-to-east), gently converging on Savery Pond on its upgradient (west) side and diverging from the pond on its downgradient (east) side. Local mapping also suggests that the small “Bog Pond” (directly east of Savery Pond) locally influences water-table elevations, and that a “perched” aquifer (shallow groundwater “perched” on a clay layer that overlies the regional aquifer) occurs at the East Bog (southeast of Savery Pond).
5. Interpreted groundwater flow directions also illustrate that areas supplying groundwater inflow to the pond have relatively low residential development, with only 5 homes located on the upgradient side of the pond. However, out of 3 septic-related facilities at the Indianhead Resort (2 group bathrooms and a trailer-refuse dumping station), one bathroom occurs in an area where groundwater *may* be flowing towards the pond. This information should be incorporated into the nutrient balance for the pond, along with the fact that background phosphorus concentrations in the regional aquifer appear to be very low (composite sampling of multiple regional-aquifer wells west of the pond showed no detectable ortho-phosphate).
6. Over the 2018 data period, Savery Pond outflows in Herring Brook varied from about 0.5 cfs in the late spring, to low flows on the order of 0.2 cfs during summer months, to values between 0.6-2.0 cfs after October 27th (a particularly wet period). Pond outflows include a baseflow component (supported by groundwater discharge) and short-term responses to individual precipitation events. Baseflows ranging from 0.2 to 0.6 cfs correspond to pond “flushing” times of 450 to 150 days (respectively), however perfect flushing is never achieved because perfect mixing of pond inflows into the pond volume does not occur. Calculation of flushing should also include groundwater flowing through the pond, which would decrease flushing times. Pond flushing is expected to increase with higher groundwater levels and diminish with lower groundwater levels. Pond flushing during 2018 may have been higher than prior years due to above-average precipitation.
7. Key recommendations resulting from this study include:
    - Collection of precipitation, groundwater-level, pond-level and streamflow data should continue over the next several years. Barometric pressure trends should be monitored with an improved-accuracy transducer and applied to future stream-stage monitoring data. This report should be updated to reflect a larger range of climatic conditions.
    - The hydrology of Savery Pond should be interpreted based on the observed range of water-levels and streamflows along with consideration of trends in precipitation (recharge) and groundwater pumping. The recent USGS groundwater flow model (in its current form or up-dated with higher resolution near Savery Pond) could be used to assess how these factors affect groundwater flushing through Savery Pond, with model results incorporated into pond water budget and nutrient budget.

3.0 HYDROGEOLOGIC OVERVIEW

Savery Pond is a shallow "kettle pond" formed at the end of the last ice age, when a remnant block of glacial ice melted away, leaving a cavity in the surrounding glacial sediments that filled with groundwater. Kettle ponds are ubiquitous in Plymouth Township and often occupy topographically "closed” depressions; how-ever, Savery Pond has an outflow stream that connects to the Ellisville Marsh Estuary ("Herring Brook"). The pond level is an expression of the local groundwater table, and the pond is spring fed by the water-table aquifer. A bathymetric survey of the 28.4-acre pond[3] shows an average depth of 6.3 feet, a maximum

[3] GIS digitization for the bathymetric analysis showed a pond surface area of 28.4 acres. The Plymouth Pond and Lake Atlas (SMAST, 2015) reports 29.4 acres.

depth of 12.5 feet, and an associated pond volume of 179 acre-feet (FoEM, 2019a). Three former commercial cranberry bogs surround the pond (**Figure 1-1**):

- The "East Bog" is a fallowed 6.5-acre bog that was commercially managed through October 2016, when it was acquired by the Town of Plymouth for conversion to a grassland preserve. Discontinued nutrient applications due to Town acquisition presumably benefit water quality in Savery Pond. Hydrogeologic reconnaissance at the bog showed that 1-2 feet of sandy fill is underlain by about 5 feet of peat deposits over a dense clay layer (FoEM, 2019b). The clay layer appears to locally "perch" shallow groundwater above the elevations of the regional water table and Savery Pond[4].
- The "West Bog" is a 4-acre bog (comprised of three adjoining small bogs) under private ownership. The bog was converted to "organic" in 2004 and sold in 2008. Under its current ownership, the bog is reportedly no longer irrigated, applied with fertilizers or pesticides, or commercially harvested; however, it is sometimes flooded during winter/spring months. The bog is also reported to be fairly "leaky" due to high permeability soils.
- The "Bog Pond" is a 2-acre natural depression that is relatively wet, sometimes exhibiting saturated soils and other times exhibiting standing water. Herring Brook passes through the Bog Pond, and the Bog Pond has a downstream control structure installed to manage standing-water conditions. Due to the near-constant wet conditions, the Bog Pond was reportedly abandoned for agricultural operations long ago.

Regional hydrogeologic conditions in the Plymouth-Carver area have been characterized by the U.S. Geological Survey (Hansen & Lapham, 1992 and Masterson et al, 2009). Both USGS studies also included regional-scale groundwater models. The following narrative incorporates direct quotes from the Masterson report *in italics*:

> Regarding the regional aquifer: *The unconfined aquifer that underlies this region is composed mostly of glacially deposited sediments ranging in size from clay to boulders and is the second largest aquifer system in Massachusetts. It ranges in thickness from less than 20 to more than 200 ft. Groundwater discharge from the aquifer supports numerous kettle ponds and coastal streams. The aquifer was designated as a Sole Source Aquifer by the U.S. Environmental Protection Agency, recognizing that groundwater is a vital source of drinking water for many of the communities in the area*. In the southern Plymouth-Carver area, *the predominant glacial features are outwash plains and moraines*.
>
> **Figure 3-1** (excerpted from the Masterson Report) shows that Savery Pond (added to the map) occurs within the "Ellisville Moraine" which is largely surrounded by adjacent outwash deposits ("Carver Pitted Plain" and "Wareham Pitted Plain"). *Unlike the outwash plain sediments that were deposited by meltwater streams flowing from the retreating ice sheets, moraine deposits were formed by the collapse of unstable ice-block slopes along the margins of the retreating ice sheets. This process created debris-flow sediments of gravel, sand, silt, and clay. These deposits mark the recessional positions of the retreating ice sheets and therefore have a very hummocky topography of hills and depressions. Whereas outwash sediments generally are well sorted and show some stratigraphic continuity, moraine deposits have a more variable lithology, given the mechanism by which they were formed.*

[4] Common vernacular refers to the saturation of shallow soils above an underlying low-permeability layer as "perched". The formal definition of a perched aquifer, however, includes an unsaturated zone between the bottom of the perching layer and the underlying water table. For the purpose of this report, "perched" refers to shallow groundwater separated from the regional water table by an underlying low-permeability unit.

Masterson et al describe the sedimentary texture of surficial geologic units shown on **Figure 3-1** as "*loose, unstratified, unsorted sandy silty gravel (sandy till); poorly stratified and poorly sorted coarse sandy boulder gravel containing some well stratified, well sorted sandy gravel*" for the moraines and "*medium to coarse sand*" for the outwash plains. Despite these textural differences, differences in estimated permeability are noted to be minor. FoEM notes that anecdotal accounts derived from septic-system excavations and communications from drillers suggest that subsurface sediments near Savery Pond are predominantly sandy, although pockets of finer-grained materials have been observed.

Hansen & Lapham developed a regional water-table elevation map with arrows showing interpreted groundwater flow directions (**Figure 3-2**). Groundwater in the Ellisville area flows roughly west-to-east towards Cape Cod Bay. *Water-table contours and groundwater-flow patterns… are affected by the numerous kettle-hole ponds in the region. These ponds are surface-water expressions of the water table because, like streams, they are hydraulically connected to the groundwater flow system. Kettle-hole ponds are a unique hydrologic feature in this groundwater-flow system because they receive groundwater discharge and are a source of groundwater recharge. Groundwater flow paths converge in areas upgradient of the ponds, where groundwater discharges into the ponds, and diverge in downgradient areas, where pond water recharges the aquifer. Some ponds have surface-water outlets where ponds drain into freshwater streams, and therefore changes in pond levels can affect streamflow downgradient of the pond.*

Groundwater flows from recharge areas towards groundwater discharge features such as marine water and various ponds and streams. Recharge to the water-table aquifer is predominantly derived from precipitation. *The portion of precipitation that is not lost to evaporation or the transpiration of plants (herein referred to as evapotranspiration) and reaches the water table is referred to as aquifer recharge. All of the water that flows through the aquifer and discharges to ponds, streams, coastal areas, and pumping wells is derived from aquifer recharge. Groundwater flows away from regional water-table divides towards natural discharge boundaries at streams and coastal water bodies; some water flows through kettle-hole ponds prior to discharging and some water is removed from the system for water supply.* **Figure 3-3** presents estimated monthly precipitation and recharge for East Wareham MA, which has similar average annual precipitation as Plymouth (47 in/yr). Although average month-to-month variation in precipitation is relatively minor, estimated recharge is greatly diminished between May and October due to higher losses to evapotranspiration.

Regarding groundwater withdrawals, Masterson et al note: *Withdrawals of groundwater from the aquifer system change water levels, flow directions, and the rate of groundwater discharge into streams and coastal areas. Although most pumped water (about 85 percent) is returned to the aquifer at the water table, the effects of pumping and redistribution of water on the hydrologic system are greatest near pumping wells where there is a local net loss of water. Transient changes in natural recharge and pumping rates in the aquifer system cause the effects of pumping to be largest during the summer months. Effects of pumping include water-level declines, which can dry vernal pools; pond-level declines, which can affect pond-shore ecosystems; and streamflow depletions, which can affect fish habitats.*

The regional groundwater flow model of the Plymouth-Carver-Kingston-Duxbury (PCKD) aquifer system developed by Masterson et al can be used to estimate groundwater/surface-water interactions. Although the model *does* include Savery Pond and Herring Brook, its regional-scale resolution makes pond-related predictions approximate. Models are good tools to estimate how changes in groundwater levels affect surface-water features. Since the model was developed (2009), new modifications to USGS modeling software have become available that support local refinement of specific focus areas set within a regional groundwater model. The Masterson Report notes: *Although detailed analyses of local-scale hydrologic conditions were beyond the scope of this regional investigation, the flow model may serve as the starting point for more detailed, site-specific investigations where local-scale models may be developed.*

4.0 STUDY METHODOLOGY

The following sections describe the methods used for collecting and managing climate, pond-level, groundwater-level and streamflow data. A map of monitoring locations is provided in **Figure 1-1**.

4.1 CLIMATE MONITORING

Climate data at Savery Pond are currently gathered at a private weather station (PWS) installed above the rooftop at a residence on the west side of the pond. The PWS, an *Ambient Weather* Model WS-2902A, was installed in August 2018. The unit measures wind speed, wind direction, rainfall, outdoor temperature and humidity, solar radiation and UV, and (indoor) barometric pressure. The data are automatically uploaded to Weather Underground using station name "Savery Pond" and are viewable on the internet[5]. Due to the limited period of record for the Savery Pond PWS, FoEM supplemented local precipitation data with two additional sources:

- A second PWS with data available on Weather Underground. "Fred's WS" is located at Harlow Landing in Ellisville, on the east side of Route 3a.
- A plastic outdoor (manual) rain gage maintained by Roger Janson, located 430 feet north of Savery Pond. Accumulated precipitation is recorded from the gage on a near-daily basis.

The three *local* data sources noted above were supplemented (as needed) by data from the Plymouth Municipal Airport, located 10.3 miles north-northwest of Savery Pond. Precipitation trends were assessed based on 20 years of monthly precipitation data downloaded for the Airport[6].

FoEM requires barometric data to perform compensation on non-vented pressure transducers used to monitor water levels in a near-pond well and at the outflow control structure on Herring Brook. Over the 2.3-year data period referenced in this report, several sources of barometric data were employed to create a continuous hourly record of barometric pressure, as shown below:

Station	Start Date	End Date	Duration (days)	Formula
Plymouth Municipal Airport	8/22/2016	8/12/2017	355	P = X
Fred's WS (PWS)	*8/12/2017*	*8/15/2017*	3	P = X - 0.03
Ellisville, Van Essen Diver (10m)	8/15/2017	4/29/2018	257	P = X + 0.15
Fred's WS (PWS)	*4/29/2018*	*5/5/2018*	6	P = X - 0.03
Ellisville, Hobo (9m)	5/5/2018	7/13/2018	69	P = X
Fred's WS (PWS)	*7/13/2018*	*9/1/2018*	49	P = X - 0.03
Savery Pond (PWS)	9/1/2018	ongoing	ongoing	P = X + 0.1

[5] The Savery Pond PWS has an ID number of KMAPLYMO79, and can be accessed at https://www.wunderground.com/personal-weather-station/dashboard?ID=KMAPLYMO79. The "Fred's WS" PWS is no longer active, but prior data can be accessed online at https://www.wunderground.com/personal-weather-station/dashboard?ID=KMAHARLO3.
[6] Downloaded from http://scacis.rcc-acis.org/.

FoEM maintains several datalogging pressure transducers – two of which were deployed for barometric data collection over portions of the data record:

- A non-vented Van Essen "Diver" (S/N L1316) with a 10m range and an accuracy of ±0.5 cm (±0.016 ft).
- A non-vented HOBO water-level logger (P/N U20-001-01) produced by Onset Computer Corporation with a 9-meter range and a typical error of 0.1% (±0.03 feet).

The transducers were programmed to measure barometric pressure every hour, and data from the airport was provided with hourly readings. Data from the PWS sources are recorded several times per hour – but not "on the hour". To create an hourly record, FoEM referenced the closest reading to the top-of-the-hour. The barometric accuracy of an *Ambient Weather* Model WS-2902A is reported as ±0.09 feet of water. Data from local sources were normalized to absolute pressure readings in the "Hobo" pressure transducer by applying formulas that apply an offset to the data gathered by the instrument (labeled as "X" in the formulas above). FoEM's "Diver" transducer was re-assigned from barometric monitoring to monitoring stage at Herring Brook in May 2018. Barometric data from the Plymouth Municipal Airport were used for the first year of the record but were not normalized because local representativeness is expected to be reduced due to the station's distance from Savery Pond. In 2019, FoEM will be deploying a dedicated Hobo or Van Essen transducer on a full-time basis to facilitate 24/7 collection of barometric data.

Other datasets from the Savery Pond PWS may prove to be useful for assessing the causes of algal blooms in the pond. Temperature has significant influence on plant growth and algal activity, and wind can affect thermal stratification in the pond. Although the *Ambient Weather* Model WS-2902A likely provides only moderate-accuracy data, obtaining local data (even on a relative basis) may still prove useful for understanding pond algal dynamics.

4.2 POND-LEVEL MONITORING

FoEM installed a stage gage on Savery Pond at a local residence on the west side of the pond (see "SW-1" on **Figure 1-1** and photo on front cover). The gage is attached to a post that was driven down several feet into the pond bottom until a gravelly resistive layer was encountered. FoEM established a concrete benchmark on the nearby shoreline, and we employ a laser level to track any vertical displacement of the gage that may occur due to settling or movement of winter ice[7]. Pond level is recorded several times a month (in some cases weekly or more frequently) depending on conditions. The absolute elevation of the stage gage was measured during an elevation survey discussed in Section 4.3.

4.3 GROUNDWATER LEVEL MAPPING & MONITORING

FoEM performed a synoptic ("snapshot") survey of water-level elevations (WLE's) in local wells and key surface-water features in August 2018. The survey included 15 wells and surface-water stage at Savery Pond, the Herring Brook headwater control structure and the Bog Pond. All WLE measurements were made over a 3-day period from 8/23 to 8/26. For wells, all depth-to-water (DTW) measurements were made from the rim of the access port on the well cap or the top of the well casing using a calibrated electric well sounder

[7] Comparison of the offset between the benchmark and the gage at installation (9/26/17) and current (12/31/18) shows that the gage has moved upwards by 0.03 feet over 2.25 years. Given that the gage elevation was surveyed recently, this small displacement means that early data could read 0.03 feet higher than recent data. This displacement is insignificant for the purposes of this investigation; however, FoEM has established a protocol to survey twice annually (before and after winter ice) to compensate for any further displacements.

produced by Waterline Envirotech Ltd[8] demarcated at 0.01-foot intervals. DTW measurements were made multiple times over a several-minute interval to ensure that the water level was static in the well, and are conservatively expected to be accurate to within ±0.02 feet.

For the three surface-water features, WLE's were read directly off permanently installed stage gages that are demarcated at 0.01-foot intervals. The gages on Savery Pond and Herring Brook are described in Sections 4.2 and 4.4 (respectively). A third stage gage was installed on an outlet control structure on the west side of the Bog Pond (SW-3 on **Figure 1-1**).

All WLE's were mapped to a common vertical datum (NAVD88). Survey of wellhead and stage-gage elevations was accomplished as follows[9]:

- Town of Plymouth ("Town") land-survey engineers surveyed 11 elevations within the geographic range of WLE measuring points on 8/21/18. Surveyed features included well caps (or top of well casings) and benchmarks comprised of spikes, driven rods, and concrete structures. The survey was conducted with a Leica Model GS14 global positioning system (GPS) with an estimated vertical accuracy of ±0.1-0.5 feet – depending on obstructions to the sky (Firth, 2019).
- FoEM used elevations surveyed by the Town as benchmarks to perform a level/transit survey in which all "loops" were closed to within ±0.03-0.05 feet. FoEM rented a Leica Rugby 670 to perform the survey.
- For one distant well on the west side of Savery Pond, FoEM used the pond water surface as a "level" to provide a reference elevation from the pond stage-gage to the shoreline adjacent to the well.
- For the Town's "Ellisville Well", FoEM used the surveyed elevation of the concrete pad outside the wellhouse and an engineer's report that states that the wellhead was cut to 4.0 feet above land surface (Metcalf & Eddy,1980). As discussed in Section 5.3, WLE for the Ellisville Well is based on previously reported static water levels and is therefore considered approximate.

Table 4-1 summarizes the elevation survey results. Overall accuracy of measuring-point elevations depends on the survey method used. Expected data error *between* GPS benchmarks is on the order of several tenths of a foot; however, where groups of measuring points were surveyed by level/transit from a single benchmark, relative accuracy within the group is expected to be <0.05 feet. **Appendix A** provides more detailed survey information, including how groups of measuring points were derived from individual benchmarks. For the purpose of this report, domestic wells were provided generic ID numbers to preserve the privacy of local residents.

Among the 15 surveyed wells, the Janson Well (Well PW-1 on **Figure 1-1**, located 430 feet north of Savery Pond) was equipped with a dedicated Van Essen "Diver" (same model as reported above, S/N N7466). The Diver was suspended approximately 32 feet below the well cap using non-stretching cord. Digital data were lost between 12/2/2016 and 7/1/17 when the Diver got stuck in the well casing as it was pulled up to download data (the Diver was subsequently deployed with a direct-read cable so it could remain set in downhole position). Manual DTW measurements are taken monthly and used to calibrate the digital time-series data. Digital data are downloaded 3-4 times per year and imported to an excel database where they are: compensated for barometric pressure (using the compiled barometric time series described in Section

[8] https://www.waterlineusa.com/
[9] Documentation of the elevation survey can be provided upon request.

4.1); compared to manual DTW measurements; and adjusted to offset any drift in the transducer or probe depth. Measurement drift was generally within ±0.05 feet, which is insignificant with respect to the observed range of WLE variation. The time-series water-level data were translated to WLE (NAVD88 datum) based on the surveyed elevation of the top of the well casing.

4.4 STREAMFLOW MONITORING

FoEM installed a streamflow gaging station at the headwaters of Herring Brook in late April 2018 to measure the surface-water outflow from Savery Pond. The station is positioned at the downstream end of a concrete control structure previously used to control pond levels during cranberry-bog operations. This measurement location was determined to be the best available during a 4/27/18 field visit from a USDA surface-water hydrologist[10]. The station includes a stage gage, a stilling well equipped with a pressure transducer, a permanently mounted graduated scale across the downstream lip of the control structure and a time-lapse camera focused on the stage gage (**Figure 4-1**). The top of the control structure and staff-gauge zero have been surveyed for absolute elevation. The following dedicated equipment is used for streamflow measurement and stage monitoring:

- Flow is measured with a Sontek Flowtracker (original model)[11]. The Flowtracker is a doppler-based velocity meter and was calibrated by Sontek prior to purchase. The Flowtracker self-tests for accuracy on every startup and tracks key parameters for each measurement in order to document accuracy, support the operator in minimizing errors and promote a measurement approach that conforms to established protocols. FoEM staff were trained using the Flowtracker by the USDA hydrologist. The Flowtracker generates data files that calculate flow and document errors, noise and uncertainties.
- The pressure transducer installed in the stilling well is a Van Essen, non-vented “Diver” (S/N L1316) with a 10m range and an accuracy of ±0.5 cm (±0.016 ft). The Diver rests on the bottom of the stilling well, which exchanges water with Herring Brook through perforations drilled into the PVC pipe. The Diver collects hourly measurements of pressure and temperature, and barometric correction is performed with the data described in Section 4.1.
- The pressure transducer is seasonally decommissioned during winter months to avoid ice damage. During this interval, stream-stage data are collected 3x daily by photographing the stage gage using a “Wingscapes TimelapseCam”[12].

The following describes FoEM data-collection and management methodology:

1) During the first several months of operation (May thru mid-July 2018), flow measurements were taken once to twice weekly to compile enough data to generate a rating curve. Measurement frequency was then reduced to every 6 to 14 days and during higher-flow events (where the rating curve still needs more definition) until seasonal decommissioning on 11/30/18.
2) At each measurement, the trained FoEM volunteer:
    a. Allows the FlowTracker to run through its autocalibration.
    b. Initiates data collection by inputting the manual stage gage reading into the FlowTracker.

[10] Sophie Wilderotter, Physical Science Technician, USDA-ARS Cranberry Research Station, East Wareham, MA.
[11] https://www.xylem-analytics.com.au/productsdetail.php?SonTek-FlowTracker-Handheld-ADV-15
[12] https://www.wingscapes.com/wingscapes-timelapsecam-camera

c. Uses the graduated scale across the face of the structure to take 14-15 measurements across the 0.76-meter control-structure opening.

d. For each measurement, if the FlowTracker notes measurements that exceed the error criteria (e.g. boundary effects, flow angle > 20º), one or more repeat measurements may be taken. If repeat measurements do not reduce error below the default criteria, the measurement is kept (errors are reported in FlowTracker output files). Some errors are unavoidable due to the hydraulics of the flow structure. Under some flows, eddies form along the control structure walls (typically river right[13]), and boundary effects are common within 7 cm of the wall on river left.

e. After each measurement, the datafiles are downloaded to a laptop, reviewed, and essential data (date, time, stage, flow, accuracy and error messages) are transferred to a project database. An example FlowTracker output file is presented in **Appendix B**.

3) Discharge measurements taken with the FlowTracker are related to water-level measurements from the stage gage to develop a rating curve for the gaging station.

4) Data from the pressure transducer are downloaded every few months and maintained in a spreadsheet in which they are barometrically compensated, compared to manual stage-gage measurements, and related to the rating curve to provide a time-series flow hydrograph.

5) Care is taken not to disturb the channel upstream of the control structure, as this may affect the rating curve. Nevertheless, the stage/flow data are scrutinized for potential shifts in the rating curve.

FoEM plans to continue gathering flow and stage data for at least several years. During either 2019 or 2020 we hope to coordinate flow measurement and water-quality sampling of the outlet stream with other nutrient-related analyses performed on the pond.

5.0 DATA REVIEW & INTERPRETATION

The sections below present results of FoEM's monitoring activities and provide interpretation that ties together precipitation, water-level elevations, water-level trends, and pond outflow toward a better understand the hydrology of Savery Pond.

5.1 PRECIPITATION TRENDS

Precipitation is the driving force for the water-level and streamflow trends observed during FoEM's hydrologic monitoring, In order to provide context for our observations, FoEM reviewed both long-term and recent precipitation data. **Figure 5-1** presents annual precipitation at the Plymouth Municipal Airport over the past 20 years. Over the 2.3-year period of pond- and groundwater level monitoring (summer 2016 thru present), annual precipitation showed a rising trend relative to the 47.1 in/yr long-term average, increasing from 71 percent (2016) to 98 percent (2017) to 129 percent (2018). 2018 is the wettest of the 20-year record and is therefore expected to exhibit relatively high groundwater levels and streamflow.

Figure 5-2 shows monthly precipitation from 2016 thru 2018 based on data from the Plymouth Municipal Airport and the Janson manual rain gage. Data from the Janson gage are expected to be more representative of local conditions due to its proximity to the pond; however, the Janson gage does not accurately measure

[13] In this report, "river right" refers to the right bank of the stream when facing downstream.

precipitation as snowfall. In addition, accumulated rainfall is not necessarily recorded daily at the Janson Gage (2-to-3-day collection intervals sometimes occur)[14]. The Janson and Plymouth data show relatively good agreement, accept for several months in 2016 where the Janson values likely reflect totals where recording dates did not fall exactly on monthly transitions. Over the 3-year record, particularly dry conditions were noted in the summer of 2016 and relatively wet conditions were noted in January-April and August-November of 2018.

5.2 POND-LEVEL & GROUNDWATER TRENDS

Figure 5-2 compares WLE trends in Savery Pond and the Janson Well to monthly precipitation data from 2016 thru 2018. The following observations apply:

- Pond levels generally ranged from 25.5 to 25.8 feet NAVD88. Isolated high WLE's are likely associated with high rainfall events, and the wet Autumn of 2018 caused a notable increasing WLE trend. An isolated low WLE (25.0 feet in late September 2016) is associated with a cranberry harvest in which water from the pond was pumped into the East Bog.
- Groundwater levels in the Janson Well ranged from 17 to 20.5 feet NAVD88 and exhibited between 2.2 and 2.9 feet of seasonal variation. Seasonally low WLE's occurred in early winter (November-January) and seasonal highs occurred in spring (April-June). The overall increase in WLE's from 2016 thru 2018 is consistent with increasing annual precipitation over the same period. The following concepts provide a basis for understanding seasonal groundwater level variations in the regional water-table aquifer.
    - Seasonal variation in groundwater recharge results from changes in the soil-moisture budget within the root zone. As noted in Section 4, temporal recharge patterns are caused by seasonal differences between root-zone inflow (precipitation) and losses to evapotranspiration. Average monthly recharge is expected to diminish from around 4 inches during winter months to <0.5 inches during the summer months (**Figure 3-3**). During particularly dry summers, evapotranspiration can potentially dry out the root zone such that months of subsequent precipitation are needed to re-wet the soils and restore recharge released from the bottom of the root zone.
    - Recharge released from the bottom of the root zone migrates downwards towards the underlying water table. Unsaturated soils above the water table are called the "vadose zone", and time is required for a seasonal recharge pulse to travel thru the vadose zone and reach the water table. This is expressed as a time-lag between the post-summer recharge pulse generated in the root zone and the onset of rising groundwater levels (November-January).
- Seasonal variations in groundwater levels can also be affected by groundwater pumping. Domestic pumping effects groundwater levels during the growing season, when irrigation of lawns and gardens results in consumptive groundwater use. During the rest of the year, domestic pumping returns to the water table as septic-system return flow. Domestic groundwater pumping is expected to be small relative to municipal withdrawals at the Town's "Ellisville Well", located 1,800 feet northeast of Savery Pond (**Figure 1-1**). Communications with Town staff indicate the Ellisville Well was pumped heavily throughout the 2018 high-demand season (Sgarzi, 2019), presumably at its design rate of approximately 850 gallons per minute. 2018 pumping in the Ellisville Well was higher than previous years because the Town's nearby "Savery Pond Well" (located 3,700 feet southwest of the pond) was temporarily out of commission (ibid). Estimating the effects of

[14] Future monitoring at the Savery Pond PWS will automatically provide a high-resolution time series as well as daily precipitation totals.

municipal pumping on groundwater levels would need to consider the portion (and location) of pumpage that returns locally to the regional water-table aquifer.

The water-level behavior described above is consistent with local hydrogeologic conditions and occurrence of pond outflow to Herring Brook. Inflows to Savery Pond occur from direct precipitation and as groundwater discharge from the regional aquifer (expressed as underwater springs within the pond). Outflows occur to Herring Brook and back into the regional aquifer. The relative stability of pond levels reflects that fact that levels are held nearly constant by the control structure at the headwaters of Herring Brook (**Figure 4-1**). The structure has a bottom elevation of approximately 24.6 feet NAVD88, and pond elevations that exceed this value cause commensurate discharge to Herring Brook. Relative to the range of pond elevations, the (larger) range of groundwater level variation in the Janson Well likely reflects both seasonal and annual variations in groundwater recharge and pumping. The fact that WLE's in the well are considerably lower than the pond reflects the fact that the well is hydrogeologically "downgradient" from the pond and that the hydraulic connection between the pond and the aquifer may be affected by the permeability of the sediments accumulated on the pond bottom. The geographic pattern of flow between the regional aquifer and pond, along with the role of pond-bottom sediments, is discussed in Section 5.3.

5.3 GROUNDWATER ELEVATION MAPPING

FoEM used the WLE data collected during the August-2018 synoptic water-level survey to map groundwater and surface-water elevations and to infer groundwater flow patterns. **Table 4-1** summarizes surveyed WLE's and **Figure 5-3** maps the WLE's along with interpreted water-table elevation contours and groundwater flow directions. Map symbology differentiates between private wells, the Town's municipal "Ellisville Well", a monitoring well in the shallow perched aquifer that underlies the East Bog, and surface-water stage gages in ponds and at the headwaters of Herring Brook. Based on the accuracy of the elevation survey and the electric well sounder, WLE accuracy *between* wells is generally expected to be within several tenths of a foot and significantly better among *groups* of measurements that reference a single surveyed elevation benchmark (**Appendix A**).

Interpretation of groundwater flow patterns on **Figure 5-3** is consistent with the USGS interpretation by Hansen & Lapham (1992). Groundwater in the Savery Pond vicinity flows towards the coast, from west to east. The shape of the regional WLE contours drawn by the USGS (**Figure 4-2**) suggests that groundwater from upgradient (west) gently converges on Savery Pond, and that seepage losses from the pond causes downgradient (east) groundwater to diverge with the pond as a local source. As the USGS had few measured WLE's near Savery Pond, their interpretation simply reflects consistency with standard hydrogeologic interpretation of groundwater/surface-water interaction for a pond that penetrates a water-table aquifer. FoEM's map provides *detailed* WLE measurements immediately west, north and northeast of Savery Pond. Water-table contours derived from these WLE's confirms the USGS interpretation of convergent flow as groundwater approaches the pond from the west and divergent flow on the east side of the pond. Measured WLE's are unavailable on the south side of the pond, so interpreted contours and flow directions were drawn to maintain consistency with flow patterns to the north.

Locally-mapped groundwater flow patterns are more complex than the regional interpretation presented by the USGS in the following ways:

- The Bog Pond is interpreted to affect water-table elevations east of Savery Pond. WLE's in the Bog Pond are maintained by inflow from Herring Brook and are higher than neighboring groundwater levels. The WLE contours shown on **Figure 5-3** reflect FoEM's interpretation that the Bog Pond is locally recharging the water-table aquifer. The fact that the Bog Pond WLE appears to be higher than the underlying water table suggests that sediments immediately underlying the pond or accumulated on the pond bottom may have lower permeability than the (sandy) aquifer materials, thus holding the pond level "perched" above the regional water table.

- It is not surprising that the Bog Pond was previously developed as a potential cranberry bog, since perched conditions are commonly seen as favorable for bog construction. Perched conditions maintain saturation close to the land surface, yet depth-to-saturation can be controlled by constructed ditches and control structures and by adding (locally available) sand to the land surface. This is the case for the East Bog, where hydrogeologic reconnaissance revealed shallow saturation in peaty soils perched upon and underlying clay layer (FoEM, 2019b). On **Figure 5-3**, this perched condition is demonstrated by a WLE in East-Bog monitoring well "MW-2" that is about 5.5 feet above the interpreted regional water table and 4.4 feet above the surface of Savery Pond.
- The influence of low-permeability perching layers beneath the Bog Pond and the East Bog is apparent from the WLE mapping. A kettle feature such as Savery Pond can also accumulate lower-permeability sediments on the pond bottom that provide hydraulic resistance to groundwater/surface-water exchange. The bottom substrate of Savery Pond varies spatially from clean sand to silty sand to silt to organic "muck". None of these sedimentary textures limit permeability as much as the dense clay layer that underlies the East Bog; however, groundwater/surface-water exchange may be partially restricted in portions of the pond with lower-permeability bottom sediments. The extent to which pond-bottom sediments may create areas of low-permeability "skin" is unknown and is not reflected on **Figure 5-3**.

It should be noted that 2 of the 18 mapped WLE's shown on **Figure 5-3** are approximate, but do not significantly affect the interpretation of groundwater flow patterns. Specifically:

- Private well "PW-9" (the most southeast well used in the study) was too far from established benchmarks to include in the elevation survey; however, the land owner had a professionally-contracted survey available with 2-foot elevation contours. Based on this survey, we expect that the WLE for PW-9 is accurate to within about ±2 feet.
- The Town's Ellisville Well could not be accessed for a static water-level measurement, nor could the wellhead elevation be directly surveyed. The WLE for the Ellisville Well during the synoptic survey was interpreted to be less-than 18.8 feet NAVD88 based on the following rationale:
    - Town surveyors measured the elevation of the concrete pad just outside the wellhouse at 25.66 feet NAVD88. The well-construction report by Metcalf & Eddy (1980) states that "*an additional length of 18-inch diameter casing was welded to the top of the in-place well casing to bring the height to a level 4 feet above ground surface*". FoEM therefore interprets the wellhead elevation as approximately 29.7 feet NAVD88.
    - Historic water-level measurement and pump-testing data provided by Town staff include 6 static depth-to-water measurements, mostly taken during the months of September thru February between 2010 and 2014. Static DTW's ranged from 9.8 to 10.9 feet.
    - Because the Ellisville Well was pumped heavily during the summer of 2018, its effective static water level during the synoptic survey is expected to be deeper than the range of values noted above. FoEM therefore interprets a static WLE for the Ellisville Well during the synoptic survey as <18.8 feet NAVD88. The degree to which the static WLE was lower than historic winter values is unknown.

While domestic wells completed close to the water table dominate this groundwater elevation survey, the Ellisville Well is completed over 100 feet below the regional water table. A geologic log was not readily available for the Ellisville Well, but it should be noted that the texture of sediments between the water table and the well intake can cause vertical hydraulic gradients that may cause the WLE at the well intake to differ slightly from the water-table elevation.

The groundwater flow directions interpreted on **Figure 5-3** have important implications regarding the potential for nutrient loading from local septic systems. Current patterns of residential development show low residential densities on the upgradient side of the pond and more moderate densities on the downgradient side. Septic recharge to the water table downgradient of the pond is not expected to effect pond water quality, since groundwater carries this septic recharge away from the pond towards the coast. Only five residences are mapped as strictly upgradient of the pond. However, out of three septic-related facilities at the Indianhead Resort (two group bathrooms and a trailer-refuse dumping station), one bathroom occurs in an area where groundwater *may* be flowing towards the pond. This information should be incorporated into the nutrient balance for the pond, along with the fact that background phosphorus concentrations in the regional aquifer appear to be very low. FoEM's characterization of background concentrations is based on an August-2017 composite groundwater sample taken from 7 wells located west of Savery Pond. The sample was analyzed by Envirotech Laboratories (Sandwich MA) and showed "no detect" on orthophosphate (less than the detection limit of 0.005 mg/l) and a nitrate concentration of 0.26 mg/l.

5.4 SAVERY POND OUTFLOW

The following subsections describe how Savery Pond outflow to Herring Brook was measured and how trends observed over a 7-month measuring period relate to hydrologic conditions and processes. It should be noted that this documentation covers just the *first* season of Herring Brook monitoring, that monitoring is ongoing, and that monitoring methods will be adjusted over time to best match conditions at the gaging site.

Rating Curve

FoEM developed a rating curve for the Herring Brook gaging station based on 25 concurrent measurements of streamflow and stream stage collected between 5/14/18 and 12/1/18 (**Figure 5-4**). Streamflow is measured in cubic feet per second (cfs), which is equivalent to 449 gallons per minute (gpm). The rating curve was constructed as two linear, intersecting "legs" that relate flow to stage. The data show a very good linear correlation between stage and flow ($R^2 = 0.96$) at stage heights ranging from 0.4 to 0.66 feet, and adequate linear correlation ($R^2 = 0.86$) from 0.66 to 0.8 feet. **Figure 5-4** also includes an exponential rating curve fit to the entire data set ($R^2 = 0.93$); however, visual inspection of the curve suggests that the observed data are better explained by the two linear legs than the single continuous exponential curve.

It is worth noting that higher flows (>0.7 cfs) are represented by only 4 data points, all of which occurred after a large rainstorm on 10/27/18. It is unclear whether the steeper "leg" of the rating curve fit to the post-10/27/18 data represents the inherent hydraulics of the stream channel or whether the rainstorm may have affected the channel and shifted the rating curve. Additional data collection will reveal whether the rating curve has shifted or whether the steeper leg reflects a near-exponential relationship between stage and flow.

Accuracy of Estimated Streamflow Hydrograph

The two-leg, linear rating curve was applied to the continuous record of stream stage collected with the datalogger to generate a continuous hydrograph of estimated streamflow (**Figure 5-5**). The graph also shows flows manually measured with the FlowTracker (24 measurements) and daily precipitation derived from local PWS's. The graph shows generally good agreement between the measured flows and the flows estimated by applying the rating curve to measured stage except for 2 measurements taken on 9/18/18 and

10/20/18. The graph also shows multiple small-scale variations occurring over the course of a day which are generally less than ±0.05 cfs. Several explanations can be offered for these observations:

- The small-scale variations may be real or may be associated with barometric correction of the transducer data collected from the stilling well. FoEM staff noted that high winds can cause surges of flow through the control structure; however, this does not account for the nearly-constant occurrence of small-scale variations. Much of the barometric data were collected about a half mile southeast of Savery Pond, and accuracy of barometric measurements ranged from around ±0.03 feet prior to 7/13/18 transitioning to ±0.09 for subsequent measurements from an *Ambient Weather* Model WS-2902A PWS (Section 4.1). The "Diver" transducer that measures stream stage is accurate to ±0.016 feet; however, total error can be as large is the sum of both stage and barometric error. Overall, the small-scale variations do not significantly impair characterizing streamflow trends, but they may explain small differences between measured flow and flow estimated by applying the rating curve to the stage hydrograph. Based on the lower leg of the rating curve, summed stage errors of 0.05 to 0.1 feet correspond to flow errors 0.08 to 0.16 cfs.
- Barometrically corrected water-level measurements from the "Diver" transducer (taken every hour) are compared to the closest-in-time manual water-level measurement from the stage gage (taken at random times during FlowTracker measurements) on **Figure 5-6**[15]. Departures from the "best fit" line between transducer and manual measurements are typically within 0.05 feet, which is consistent with the equipment accuracies discussed above. Apparent departures may also occur because manual stage-gage measurements are taken at random times, a "gap" of up to 30 minutes may occur between correlated transducer measurements.
- About 20 minutes is required to perform the multiple measurements taken over a FlowTracker measurement "event" – whereas the associated single stage measurement occurs at the beginning of the FlowTracker event. Any change in flow or datalogger error that occurs over the course of the Flowtracker event will not be reflected by the single stage measurement.
- While the streamflow measurement location was deemed the best available, flow at the downstream end of the control structure is not hydraulically laminar across the entire channel width. The control structure is only about 0.76 meters (2.5 feet) wide, and localized flow eddies have been observed at different streamflows along the stream-right control-structure wall (and sometimes the stream-left wall). The eddies are accompanied by local instability, which effects flow-measurement accuracy. Flows in the control structure are often concentrated along the stream-left wall, and the geometry of the FlowTracker often results in "boundary effects" within 7 cm of this wall. Error associated with these local boundary effects could be imposed upon 10 percent to 20 percent of the spatially-distributed streamflow.

Some degree of error is inherent in measuring streamflow. The USGS ranks "excellent" quality measurements as those where about 95 percent of the *daily* discharges are within 5 percent of the true value. "Good" and "fair" rankings indicate that about 95 percent of the daily discharges are within 10 and 15 percent of true values (respectively)[16]. Since *daily average* discharges are based on *multiple instantaneous* measurements, some fraction of the individual instantaneous measurements will exceed the daily-average error criteria cited for a given data-quality rating. Given actual flow conditions encountered within the control structure, measurement departures on the order of ±15 percent are not surprising. Inspection of **Figure 5-5**

[15] Transducer measurements include a programmed instrument "offset" which results in about 0.5-foot difference between the datalogger and manual measurements.

[16] https://pubs.usgs.gov/sir/2006/5036/section7.html

suggests that 20 of the 24 manual flow measurements appear to be within 15 percent of corresponding flow values on the continuous hydrograph developed by applying the rating curve to the transducer stage data.

Observed Streamflow Trends

The flow hydrograph on **Figure 5-5** shows that 2018 pond outflows progressed from about 0.5 cfs in the late spring, to low flows on the order of 0.2 cfs during summer months, climbing to values of 0.6-2.0 cfs after October 27th. The data show that pond outflow responds to individual precipitation events. Most of this event-based response is likely associated with direct rainfall upon the pond surface, since groundwater levels due not appear to significantly respond to isolated rainfall events (**Figure 5-2**). However, *seasonal* streamflow variations are likely influenced by seasonal groundwater level trends, which peak during the spring months.

In order better understand event-based streamflow responses, FoEM evaluated a 2.1-inch event on June 4-5, 2018 that added 4.9 acre-feet of rainfall directly to the pond surface. The rainfall was measured nearby at "Fred's WS" which is likely accurate to around ±10 percent[17]. Prior to the rainfall event, Herring Brook was exhibiting declining flows; however, the event caused a relative increase in flow that lasted around 10 days (**Figure 5-5**). Based on the departure from the antecedent streamflow trend, FoEM estimated resulting additional flow of 6.9 acre-feet over the 10-day rise and subsequent recession. Within the accuracy of these precipitation and streamflow estimates, direct precipitation accounts for about 70 percent of the temporary increase in streamflow. The remaining 30 percent may be attributed to runoff from adjacent wetlands and bogs and subsurface pathways immediately adjacent to the pond (where groundwater is particularly shallow)

Summer low flows in Herring Brook can be interpreted as baseflow sustained by groundwater entering the pond. Observed 2018 baseflow exhibits a declining trend from late spring (0.5 cfs) to summer (0.2 cfs) building up to late fall (0.6 cfs). These baseflows are likely higher than average because 2018 was a relatively wet year (Section 4.1). Baseflow data are not yet available for 2018-2019 winter conditions. Estimates of "flushing time" ("residence time") can be generated using these baseflows and the pond volume of 179 acre-feet (Section 4.1). Baseflows ranging from 0.2 to 0.6 cfs provide associated flushing times of 450 to 150 days (respectively). Flushing times would likely be longer during more average-rainfall years. In reality, the pond is not fully "flushed" over these timeframes because perfect mixing of new rainfall entering the water column does not occur.

Flushing-time calculations are of interest in evaluating nutrient cycling, particularly when relatively clean pond inflows displace nutrient-laden water stored in the pond[18]. Along with the baseflow observed in Herring Brook, a rigorous flushing-time assessment would include the groundwater flowing *through* the pond. Only a portion of the groundwater flowing into the pond discharges to Herring Brook, while the remainder exits the pond on its downgradient (east) side and re-enters the regional aquifer. It is not realistically possible to measure the pond's total groundwater inflow or its net subsurface outflow. Calibrated groundwater flow models are good tools to estimate groundwater exchanges with surface-water features. Existing USGS models (Masterson et al, 2005; Hansen & Lapham, 1992) are regional in scale and likely not well calibrated to local conditions. Review of the Masterson model indicates that it does reflect groundwater flow both into and out of Savery Pond. Accounting for the portion of groundwater that passes through the pond (rather than discharging to Herring Brook) would shorten the flushing time estimates above.

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[17] The model of this PWS is not published, but the Ambient Weather Model WS-2902A PWS has a reported rainfall accuracy of ±10 percent.

[18] As discussed in Section 5-3, background phosphorus concentrations upgradient of Savery Pond in the regional aquifer are expected to be negligible.

It should be noted that Pond flushing is expected to increase with higher groundwater levels and diminish with lower groundwater levels. Pond flushing during 2018 may have been more substantial than during prior years due to above-average precipitation.

6.0 RECOMMENDATIONS

The following recommendations pertain solely to hydrologic data collection on Savery Pond. Data collection efforts to support nutrient budget analysis and evaluation of algal dynamics are addressed separately under ongoing efforts by FoEM, the Town and their consultants.

1. Collection of precipitation, groundwater-level, pond-level and streamflow data should continue over the next several years, and this report should be updated to reflect a larger range of climatic conditions.
2. Climate data from the Savery Pond PWS are generally sufficient for future needs; however, barometric pressure trends should be monitored with a dedicated transducer with higher accuracy than the PWS.
3. The hydrology of Savery Pond should be interpreted based on the observed range of water-levels and streamflows along with consideration of trends in precipitation (recharge) and groundwater pumping. The recent USGS groundwater flow model (in its current form or updated with higher resolution near Savery Pond) could be used to assess how these factors affect groundwater flushing through Savery Pond, with model results incorporated into the pond water budget and nutrient budget.
4. Although groundwater flow patterns are poorly defined on the south side of Savery Pond, it may be worthwhile to confirm the locations of the septic drainfields that service the Indianhead Resort, estimate septic loading from campground use and consider whether associated nutrients are likely to be transported towards the pond.

7.0 ACKNOWLEDGMENTS AND PROJECT CONTACT

FoEM wishes to express gratitude to the Town of Plymouth and Kim Tower (Environmental technician in the Town's Department of Marine and Environmental Affairs) for their continued support of scientific investigations on Savery Pond designed to better understand hydrology, nutrient cycling and recurring algal blooms. We also express gratitude to FoEM volunteers Roger Janson (who has tirelessly contributed to data collection), Pret Woodburn (who has managed the pond stage gage), and Tom Schwartzman (for GIS mapping).

FoEM also wishes to express appreciation to the following manufacturers who generously donated equipment used in this study:

- Van Essen Instruments (https://www.vanessen.com/) donated two datalogging pressure transducers and a direct-read cable.
- Waterline Envirotech LTD (https://www.waterlineusa.com/) donated a calibrated water level meter (well sounder); and,
- SonTek (a xylem brand, https://www.sontek.com/) donated a FlowTracker stream discharge measurement instrument.

Readers interested in more information about this investigation or about Savery Pond in general can consult the Savery Pond website www.saverypond.org.

8.0 REFERENCES

Firth, Russell. 2019. Personal communication between Russel Firth (Town of Plymouth Surveyor/GIS Analyst) and Peter Schwartzman (Friends of Ellisville Marsh) in January 2019.

FoEM (Friends of Ellisville Marsh). 2019a. *SA Bathymetric Survey of Savery Pond, Ellisville MA, August 2017 (Revised 2019).* Dated January 7, 2019. https://www.saverypond.org/publications.

FoEM (Friends of Ellisville Marsh). 2019b. *Savery Pond East Bog Hydrogeologic Reconnaissance Investigation.* In press, and will be posted on: https://www.saverypond.org/publications.

Hansen, B & W. Lapham. 1992. *Geohydrology and Simulated Ground-Water Flow, Plymouth-Carver Aquifer, Southeastern Massachusetts.* U.S. Geological Survey Water Resources Investigations Report 90-4204.

Masterson, J.; C. Carlson and D. Walter. 2009. *Hydrogeology and Simulation of Groundwater Flow in the Plymouth-Carver-Kingston-Duxbury Aquifer System, Southeastern Massachusetts*. U.S. Geological Survey Scientific Investigations Report 2009-5063.

Metcalf & Eddy, Inc. 2018. *Letter Report to the Town of Plymouth MA on Construction, Development and Testing of the Ellisville Gravel-Packed Well* dated September 10, 1980 (partial reproduction provided by Town of Plymouth.

Sgarzi, Sheila. 2018. Personal communication between Sheila Sgarzi (Water & Wastewater Engineer, Town of Plymouth) and Peter Schwartzman (Friends of Ellisville Marsh) in September 2018.

SMAST, 2015. *Town of Plymouth Pond and Lake Atlas, Final Report*. Prepared by Coastal Systems Program School for Marine Science and Technology (SMAST) University of Massachusetts Dartmouth, Dated June 2015.

Wilderotter, S. and C. Kennedy, 2019. Personal communications between Sophie Wilderotter (Physical Science Technician) & Casey Kennedy (Research Hydrologist) of the U.S. Department of Agriculture with Peter Schwartzman (Friends of Ellisville Marsh) in January 2019.

Table 4-1 Summary of Synoptic Water-Level Survey

Site ID	Description	Well Depth (feet)	Measuring Point	MP Elevation (ft NAVD88)*	Water Depth or Gage Height (ft)	Water Level Elevation (ft NAVD88)	Measurement Date/Time
PW-1	Domestic Well	52	Top of well casing	47.69	29.13	18.56	8/24/2018 12:57
PW-2	Domestic Well	Unknown	Top of well casing	48.82	30.91	17.91	8/24/2018 15:30
PW-3	Domestic Well	20	Top of well casing	33.64	15.40	18.24	8/24/2018 4:37
PW-4	Domestic Well	36	Top of well casing	41.93	25.00	16.93	8/24/2018 15:05
PW-5	Domestic Well	42	Top of well casing	50.12	27.41	22.71	8/24/2018 18:00
PW-6	Domestic Well	Unknown	Top of well casing	37.58	19.20	18.38	8/24/2018 14:20
PW-7	Domestic Well	Unknown	Well cap access port	42.36	26.53	15.83	8/26/2018 19:15
PW-8	Domestic Well	Unknown	Top of well casing	110.22	84.43	25.79	8/24/2018 10:48
PW-9	Domestic Well	82	Well cap access port	53.00	44.20	8.80	8/25/2018 11:12
PW-10	Domestic Well	80	Top of well casing	45.47	17.64	27.83	8/24/2018 10:00
PW-11	Domestic Well	60	Well cap access port	44.85	20.25	24.60	8/25/2018 11:57
PW-12	Domestic Well	55	Top of well casing	44.80	18.30	26.50	8/24/2018 18:15
PW-13	Domestic Well	70	Top of well casing	65.04	36.98	28.06	8/24/2018 18:30
MW-2	Monitoring Well at East Bog	6.7	Top of piezometer	33.96	3.94	30.02	8/26/2018 11:30
Ellisville Well	Town of Plymouth Production Well	135	Pressure Transducer	29.65	10.90	18.75	uppermost value from 2010-14 statics
SW-1	Savery Pond Gage	n/a	"0.00" on gage	24.35	1.24	25.59	8/24/2018 13:30
SW-2	Herring Brook Gage	n/a	"0.00" on gage	24.55	0.49	25.04	8/24/2015 19:15
SW-3	Bog Pond Gage	n/a	"0.00" on gage	21.91	1.68	23.59	8/23/2018 18:00

* All elevations surveyed to within 0.05 feet with the exception of PW-9 (elevation from site survey map) and Ellisville Well (see report text).

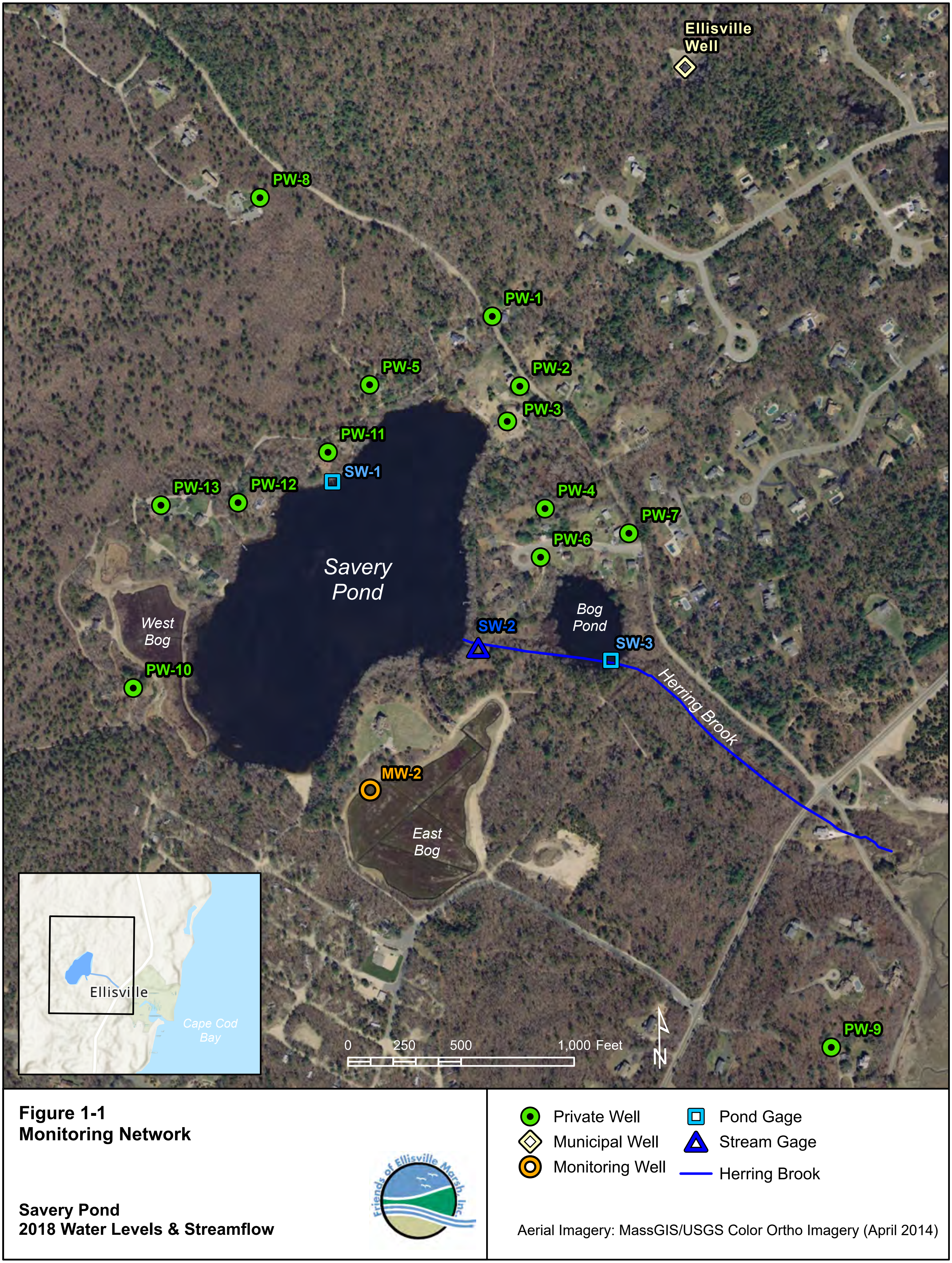
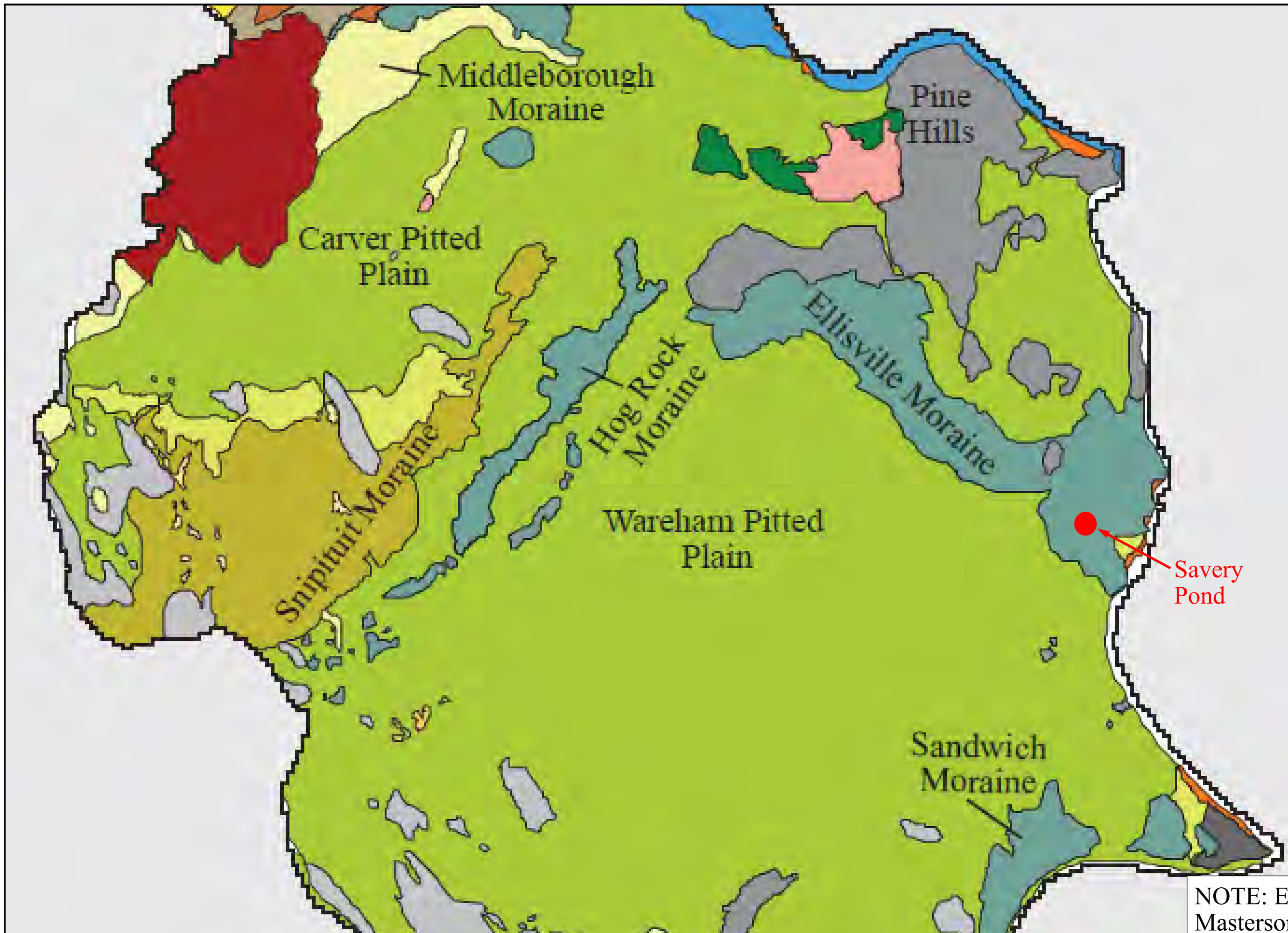


Figure 1-1
Monitoring Network

Savery Pond
2018 Water Levels & Streamflow

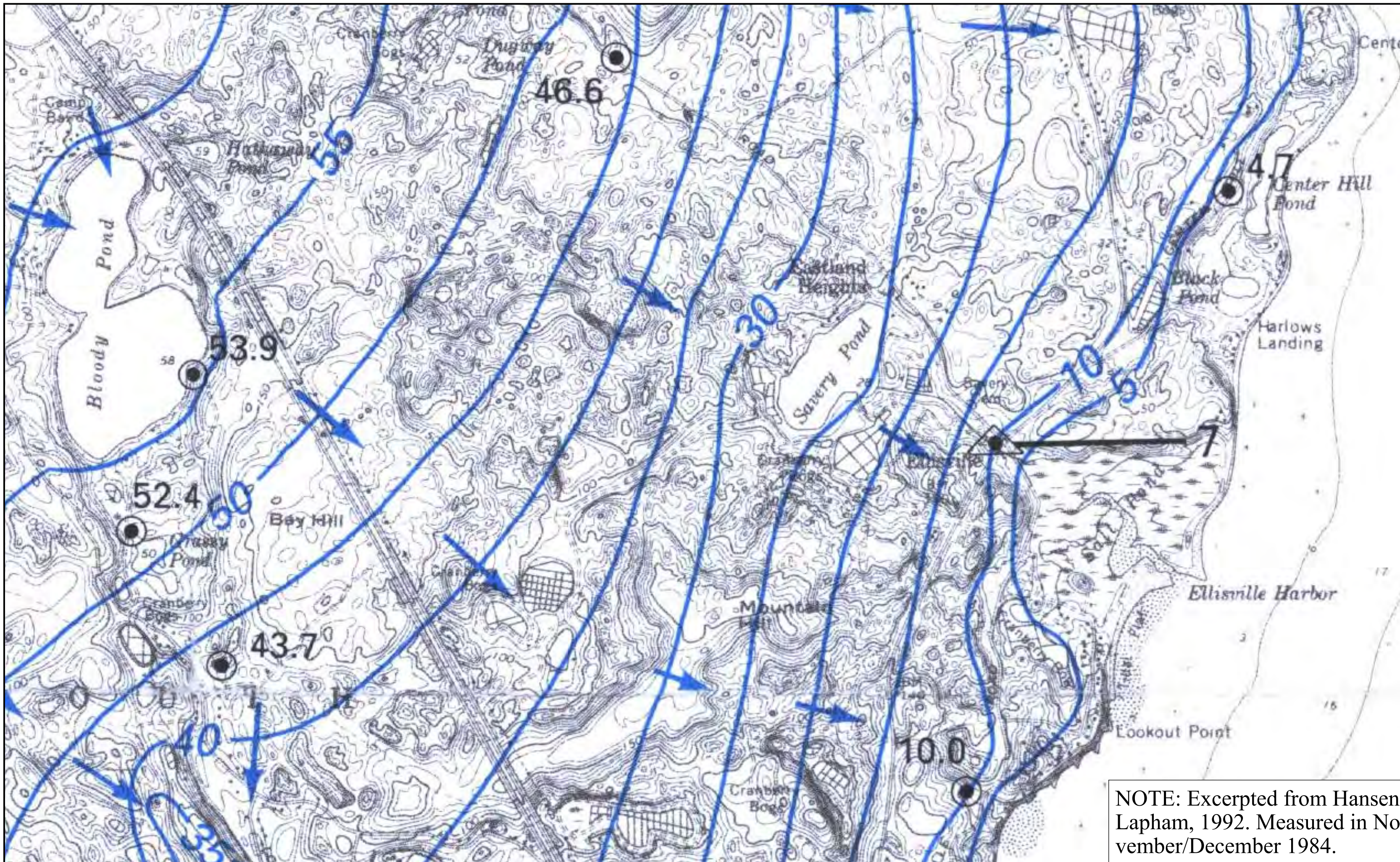
Aerial Imagery: MassGIS/USGS Color Ortho Imagery (April 2014)



NOTE: Excerpted from Masterson et al, 2009.

Figure 3-1
Surficial Geologic Units in the Ellisville Vicinity

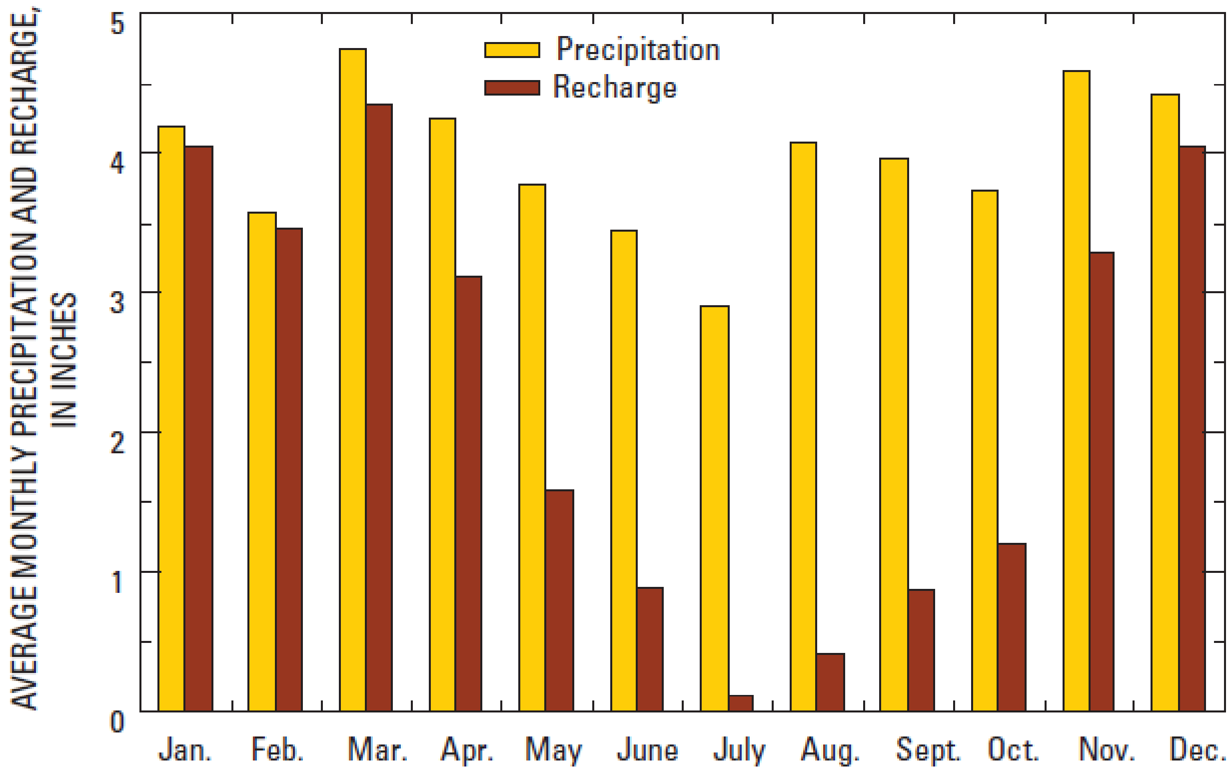
Savery Pond
2018 Water Levels & Streamflow



NOTE: Excerpted from Hansen & Lapham, 1992. Measured in November/December 1984.

Figure 3-2
Regional Water-Table Elevations in the Ellisville Vinicity

Savery Pond
2018 Water Levels & Streamflow



Variability of precipitation and recharge at East Wareham, Massachusetts.
Average monthly precipitation and recharge for the period 1931–2006.
Modified from Masterson et al, 2009.

Figure 3-3
Precipitation and Estimated Recharge at East Wareham, MA

Savery Pond
2018 Water Levels & Streamflow

Figure 4-1
Stream Gage on Herring Brook

Savery Pond
2018 Water Levels & Streamflow

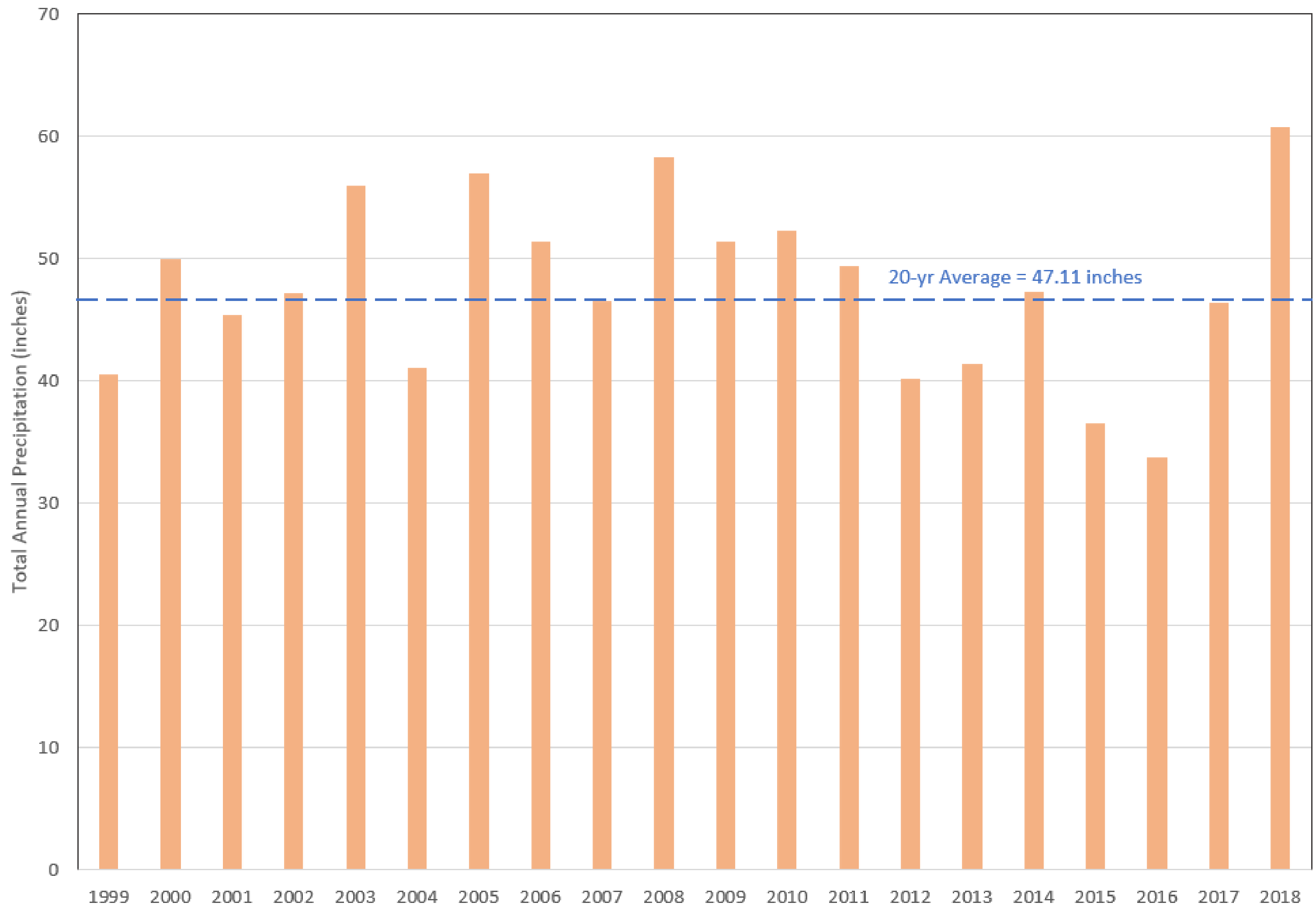


Figure 5-1
Annual Precipitation at Plymouth Municipal Airport

Savery Pond
2018 Water Levels & Streamflow

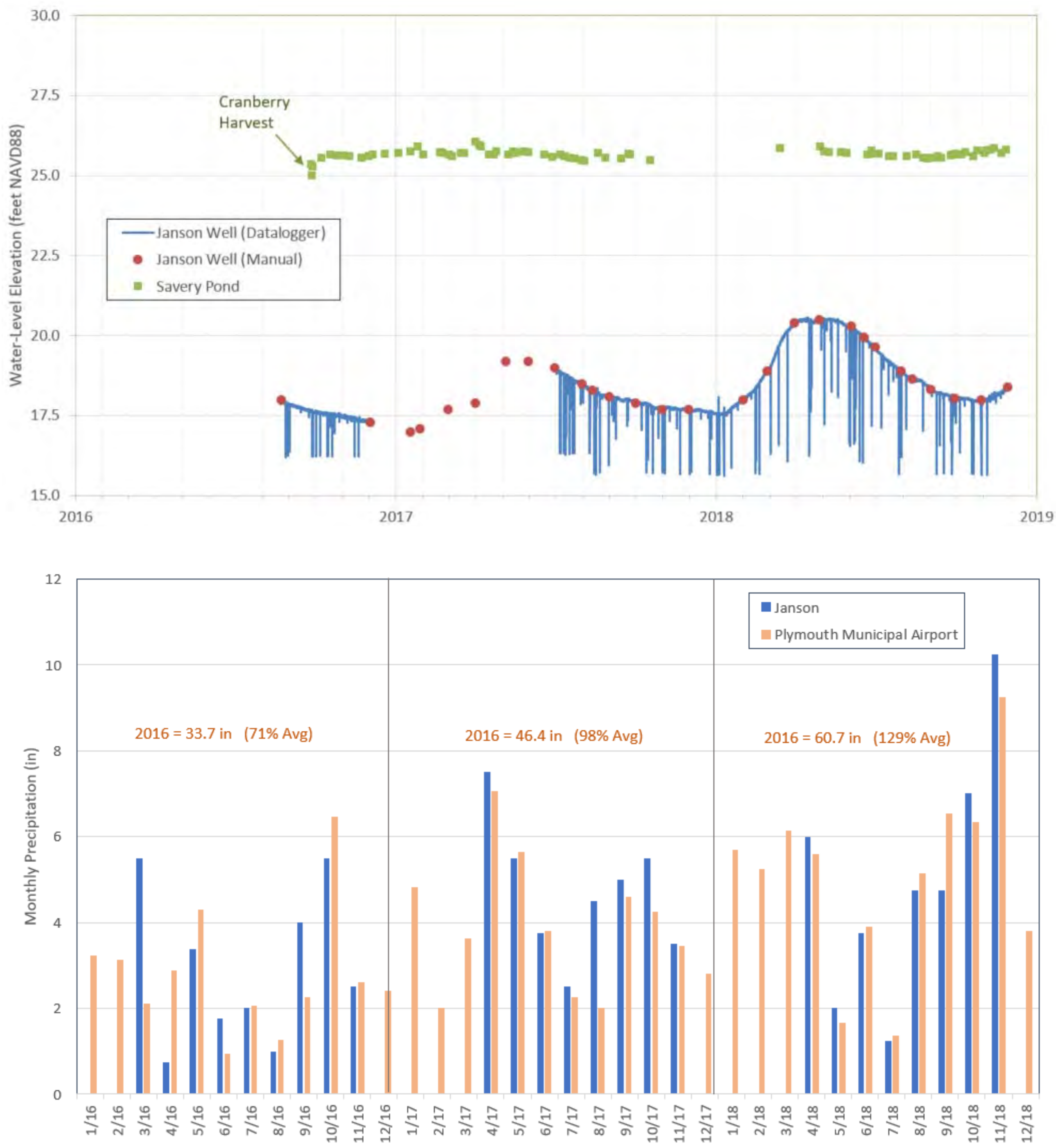


Figure 5-2
Pond & Groundwater Level Trends vs. Precipitation

Savery Pond
2018 Water Levels & Streamflow

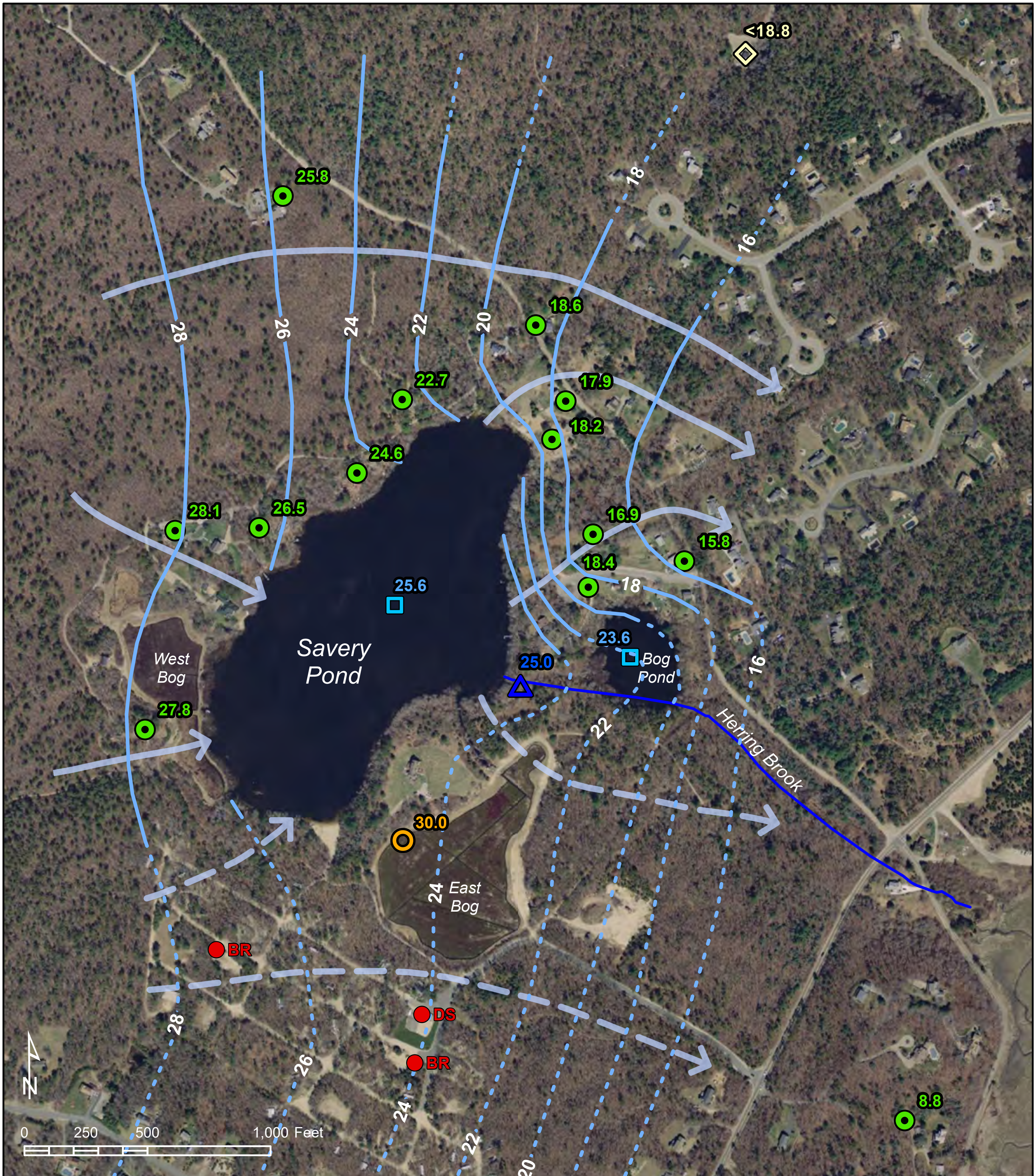


Figure 5-3
Groundwater Elevations & Interpreted Flow Directions

Savery Pond
2018 Water Levels & Streamflow

8.8 WLE (feet, NAVD88)
Private Well
Municipal Well
Monitoring Well
Pond Gage
Stream Gage
Indianhead Resort Facilities
BR=Bathroom, DS=Dump Station

Herring Brook
Groundwater Flow Direction
Water Table Contour (feet, NAVD88)
(dashed where inferred)

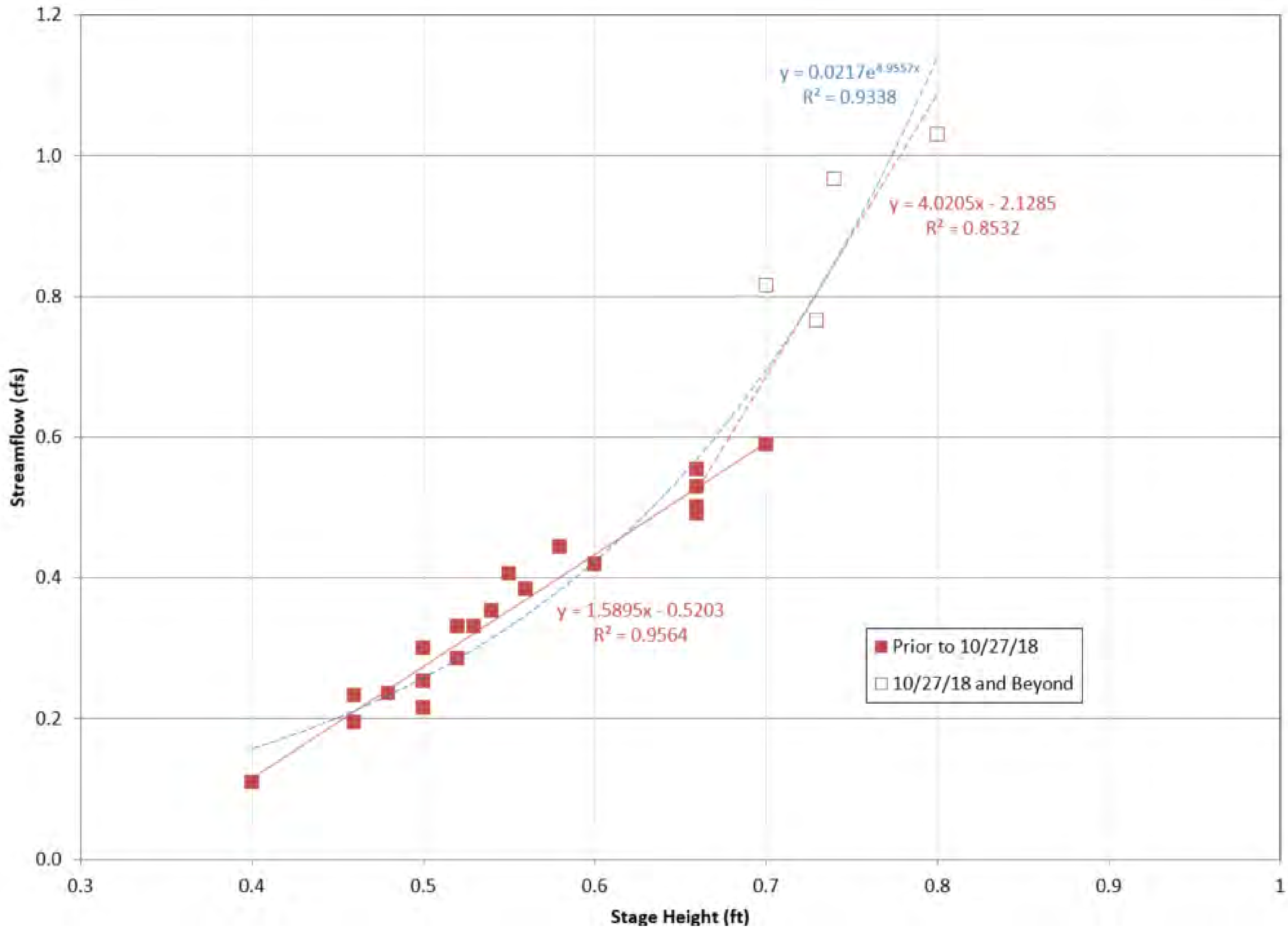


Figure 5-4
Herring Brook Rating Curve

Savery Pond
2018 Water Levels & Streamflow

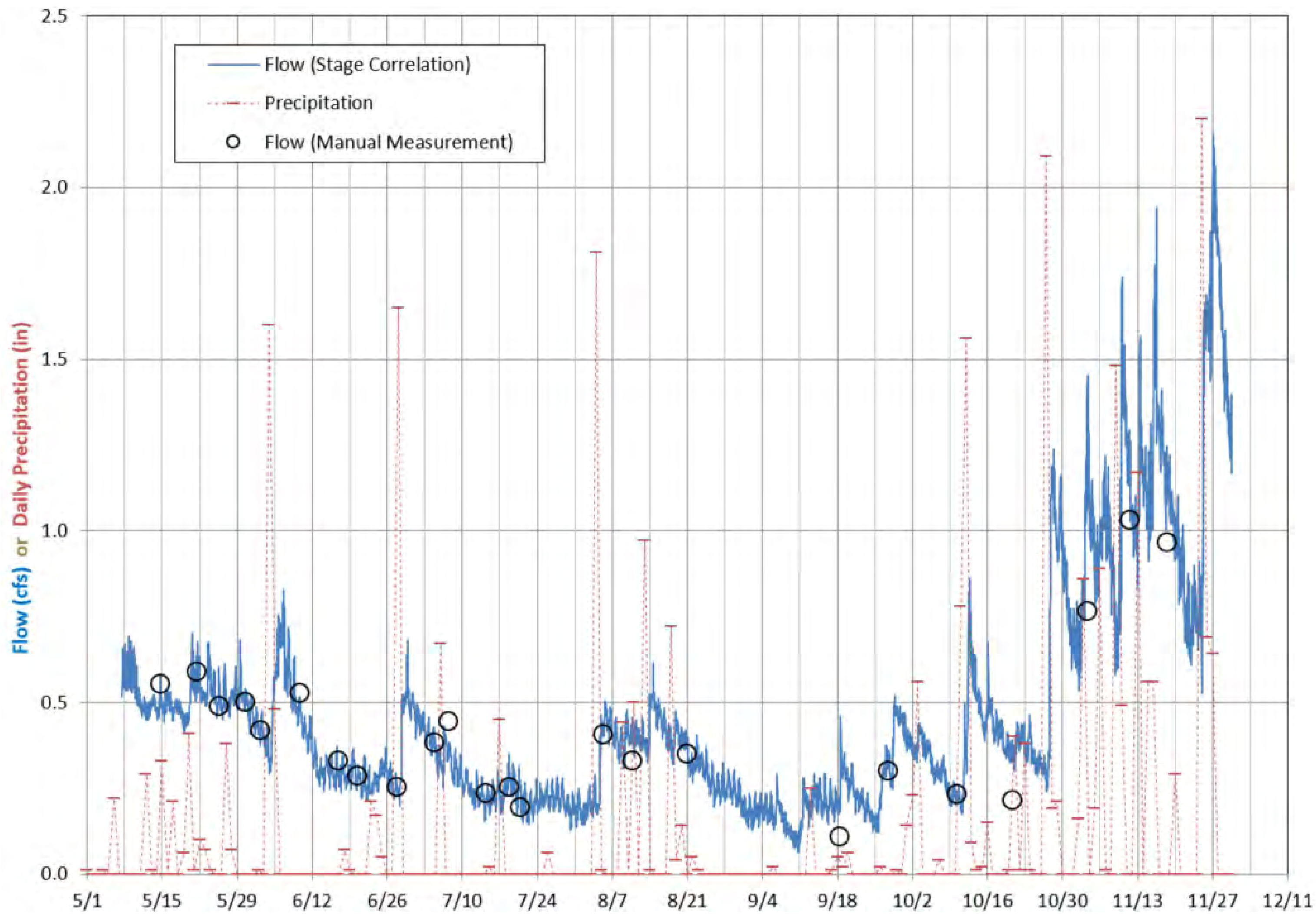


Figure 5-5
Herring Brook Estimated Flow Hydrograph (2018)

Savery Pond
2018 Water Levels & Streamflow

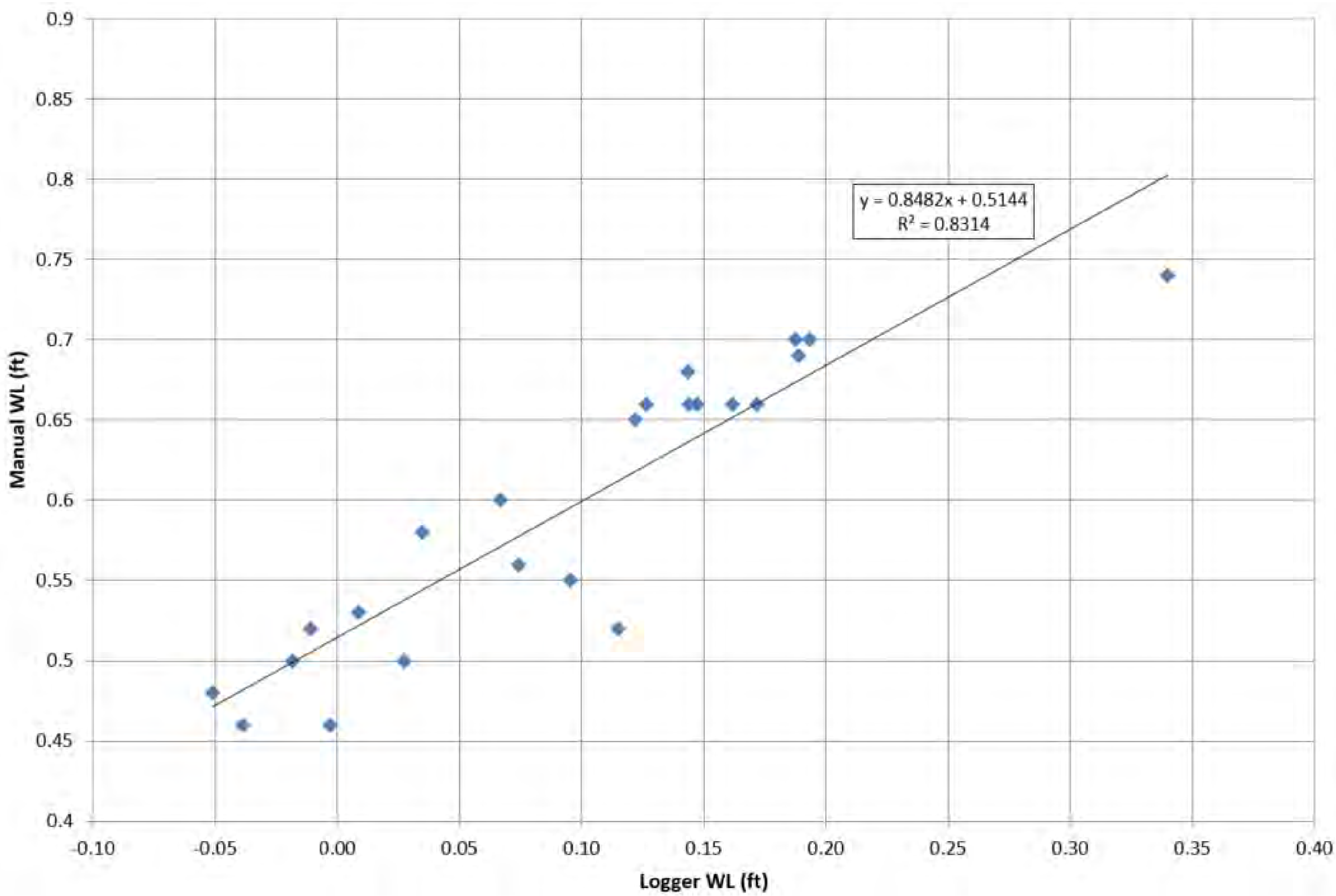


Figure 5-6
Comparison of Manual and Datalogger Water-Level Measurements

Savery Pond
2018 Water Levels & Streamflow

Appendix A

Elevation Survey

DISCUSSION OF ELEVATION SURVEY

As mentioned in Section 4.3 of the main report, Town of Plymouth land-survey engineers surveyed 11 elevations within the network of WLE measuring points on 8/21/18. Surveyed features included well caps (or top of well casings) and benchmarks comprised of spikes, driven rods, and cemented steps on residential structures. The survey was conducted with a Leica Model GS14 global positioning system (GPS) with an estimated vertical accuracy of ±0.1-0.5 feet – depending on obstructions to the sky. The following table was provided by the Town surveyor:

Point ID	Northing NAD 1983	Easting NAD 1983	Elev NAVD88	Description	Surveyor Note
1	2770027	915353.6	32.25	spk at MV2	Labeled Well Casing Elev=33.00
2	2771079	916249.2	37.49	gps rod @ 38 Savery Pond Road	
3	2771684	916042.4	53.96	top stone @ 1440 Old Sandwich Rd	
4	2771635	915797.6	33.76	well cap @ 1439 Old Sandwich Rd	
5	2771761	915867.9	48.97	well cap @ 1431 Old Sandwich Rd	
6	2772058	915771.7	47.83	well cap @ 1422 Old Sandwich Rd	
7	2771221	914694.8	42.03	roc top step 60 Lake Road	
8	2771242	914280.8	65.18	well cap @ 70 Lake Road	
9	2770401	914155.4	54.30	top stone @ well	
10	2772565	914601.4	122.34	roc conc 1375 Old Sandwich Road	
11	2773141	916574.7	25.67	loc propane pad @ Town Well	
12	2773141	916574.7	25.65	loc propane pad @ Town Well	

It should be noted that all measurements were taken on a relatively clear-sky day and most measurement locations were from cleared areas. Several measurement locations (#4, #7, #10) were within 10 feet of residential structures, which could have blocked a portion of the sky.

Figure A-1 shows the location of GPS benchmarks, GPS-surveyed wells, and wells with measuring-point elevations derived from level/transit surveying off GPS measurements. It should be noted that the level/transit surveys were closed to within ±0.05 feet. Therefore, measuring points within groups tied into a single GPS measured elevation should all be within 0.05 feet of one another.

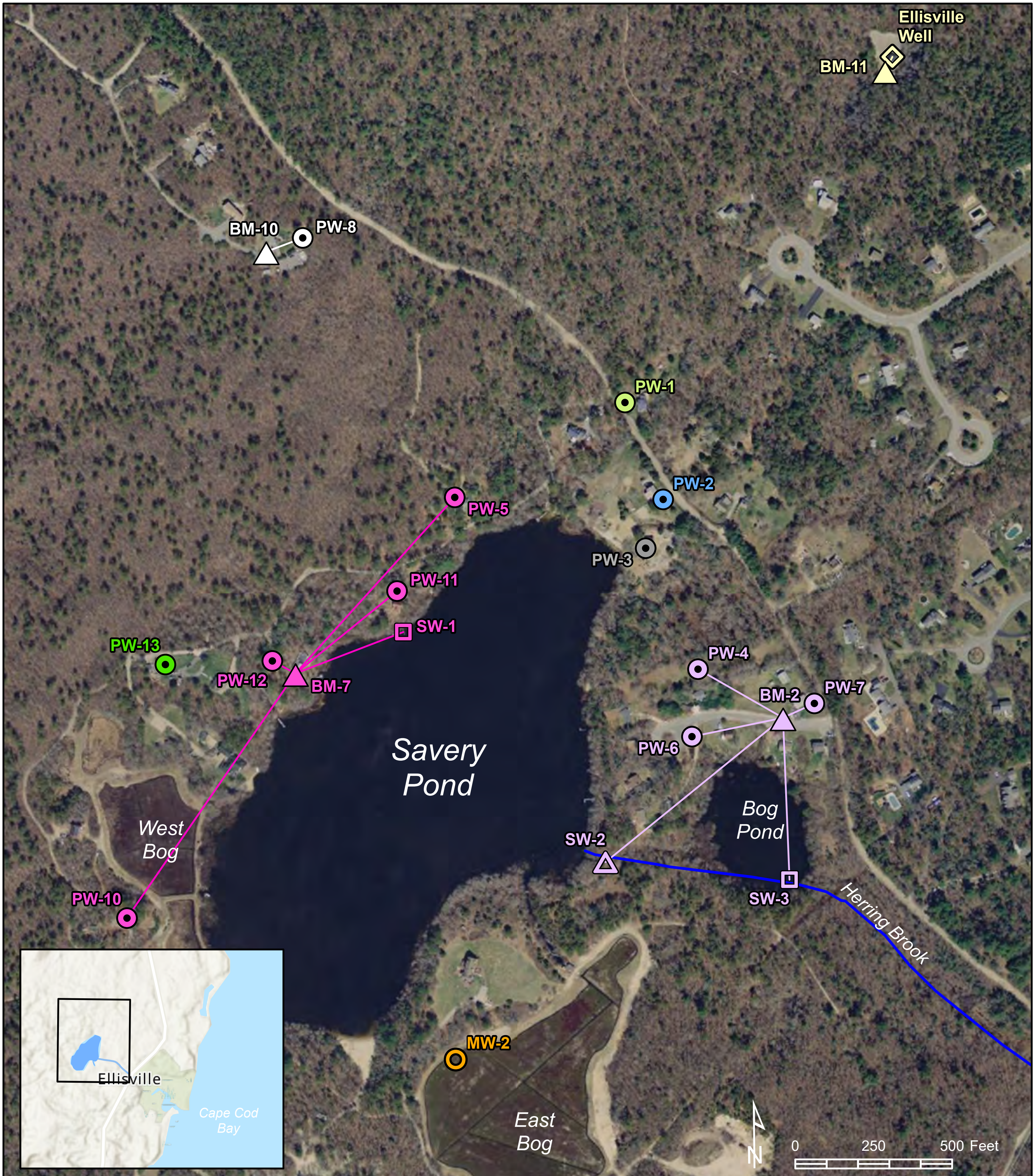


Figure A-1
Survey Points

Savery Pond
2018 Water Levels & Streamflow

Private Well (PW)
Municipal Well
Monitoring Well (MW)
Pond Gage (SW-1, SW-3)
Stream Gage (SW-2)
Benchmark (BM)
Measuring points tied into surveyed benchmarks (no line = directly surveyed)
Herring Brook

Appendix B

Example FlowTracker File

EXAMPLE FLOWTRACKER FILE

Discharge Measurement Summary

Date Generated: Thu Jan 10 2019

File Information

File Name	062918.01.WAD
Start Date and Time	2018/06/29 10:02:15

Site Details

Site Name	
Operator(s)	RC

System Information

Sensor Type	FlowTracker
Serial #	P1323
CPU Firmware Version	3.9
Software Ver	2.30
Mounting Correction	0.0%

Units (Metric Units)

Distance	m
Velocity	m/s
Area	m^2
Discharge	m^3/s

Discharge Uncertainty

Category	ISO	Stats
Accuracy	1.0%	1.0%
Depth	0.4%	0.2%
Velocity	1.4%	5.5%
Width	0.1%	0.1%
Method	1.9%	-
# Stations	3.0%	-
Overall	**3.9%**	**5.6%**

Summary

Averaging Int.	40	# Stations	17
Start Edge	REW	Total Width	0.760
Mean SNR	42.5 dB	Total Area	0.139
Mean Temp	23.05 °C	Mean Depth	0.183
Disch. Equation	Mid-Section	Mean Velocity	0.1658
		Total Discharge	**0.0230**

Supplemental Data

#	Time	Location	Gauge Height	Rated Flow	Comments
1	Fri Jun 29 09:59:46 PDT 2018	0.000	0.680		

Measurement Results

St	Clock	Loc	Method	Depth	%Dep	MeasD	Vel	CorrFact	MeanV	Area	Flow	%Q
0	10:02	0.00	None	0.180	0.0	0.0	0.0000	1.00	0.0501	0.009	0.0005	2.0
1	*10:03*	*0.10*	*0.6*	*0.180*	*0.6*	*0.072*	*0.0501*	*1.00*	*0.0501*	*0.014*	*0.0007*	*2.9*
2	10:04	0.15	0.6	0.180	0.6	0.072	0.0463	1.00	0.0463	0.009	0.0004	1.8
3	10:05	0.20	0.6	0.180	0.6	0.072	0.0549	1.00	0.0549	0.009	0.0005	2.1
4	10:06	0.25	0.6	0.180	0.6	0.072	0.0699	1.00	0.0699	0.009	0.0006	2.7
5	10:08	0.30	0.6	0.180	0.6	0.072	0.1480	1.00	0.1480	0.009	0.0013	5.8
6	10:11	0.35	0.6	0.180	0.6	0.072	0.0898	1.00	0.0898	0.009	0.0008	3.5
7	10:12	0.40	0.6	0.180	0.6	0.072	0.2173	1.00	0.2173	0.008	0.0018	7.6
8	10:13	0.44	0.6	0.180	0.6	0.072	0.2043	1.00	0.2043	0.007	0.0015	6.4
9	10:14	0.48	0.6	0.180	0.6	0.072	0.2086	1.00	0.2086	0.007	0.0015	6.5
10	10:15	0.52	0.6	0.180	0.6	0.072	0.1545	1.00	0.1545	0.007	0.0011	4.8
11	10:16	0.56	0.6	0.190	0.6	0.076	0.2675	1.00	0.2675	0.008	0.0020	8.8
12	10:17	0.60	0.6	0.190	0.6	0.076	0.2923	1.00	0.2923	0.007	0.0019	8.4
13	10:19	0.63	0.6	0.190	0.6	0.076	0.3116	1.00	0.3116	0.006	0.0018	7.7
14	10:20	0.66	0.6	0.190	0.6	0.076	0.3306	1.00	0.3306	0.006	0.0019	8.2
15	*10:21*	*0.69*	*0.6*	*0.190*	*0.6*	*0.076*	*0.2945*	*1.00*	*0.2945*	*0.010*	*0.0028*	*12.1*
16	10:21	0.76	None	0.190	0.0	0.0	0.0000	1.00	0.2945	0.007	0.0020	8.5

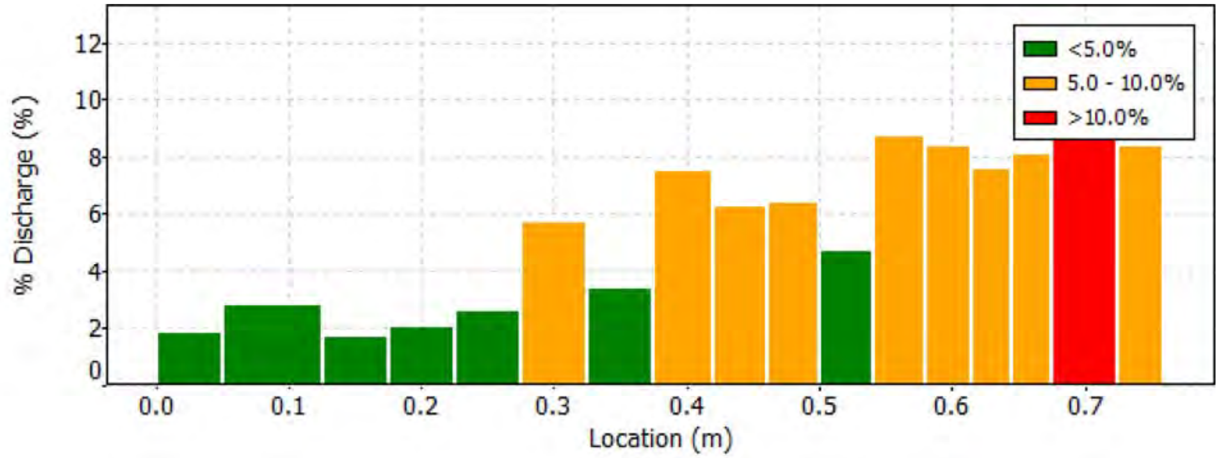
Rows in italics indicate a QC warning. See the Quality Control page of this report for more information.

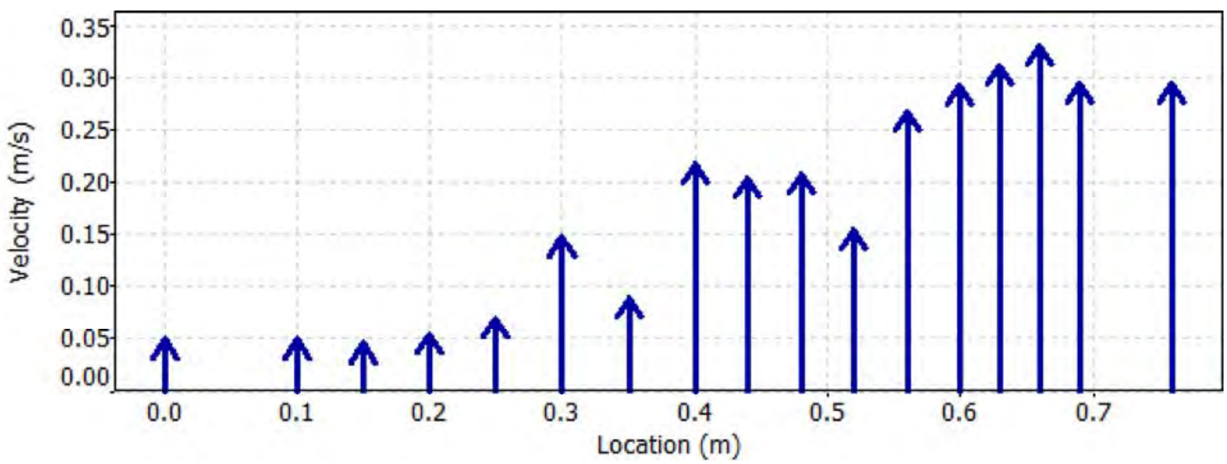
Discharge Measurement Summary

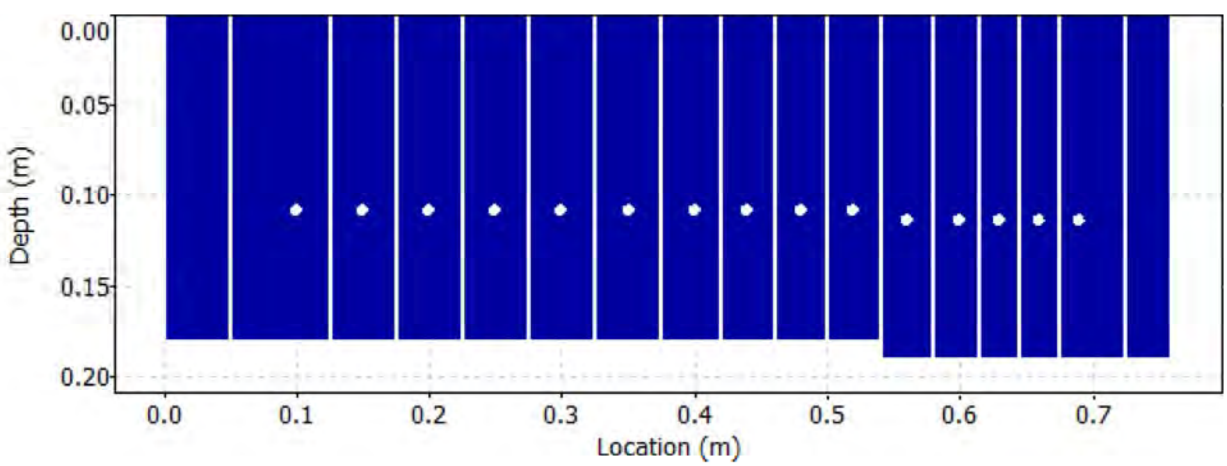
Date Generated: Thu Jan 10 2019

File Information	
File Name	062918.01.WAD
Start Date and Time	2018/06/29 10:02:15

Site Details	
Site Name	
Operator(s)	RC







Discharge Measurement Summary

Date Generated: Thu Jan 10 2019

File Information

File Name	062918.01.WAD
Start Date and Time	2018/06/29 10:02:15

Site Details

Site Name	
Operator(s)	RC

Quality Control

St	Loc	%Dep	Message
1	0.10	0.6	High angle: 22
15	0.69	0.6	Boundary QC is Fair; possible boundary interference

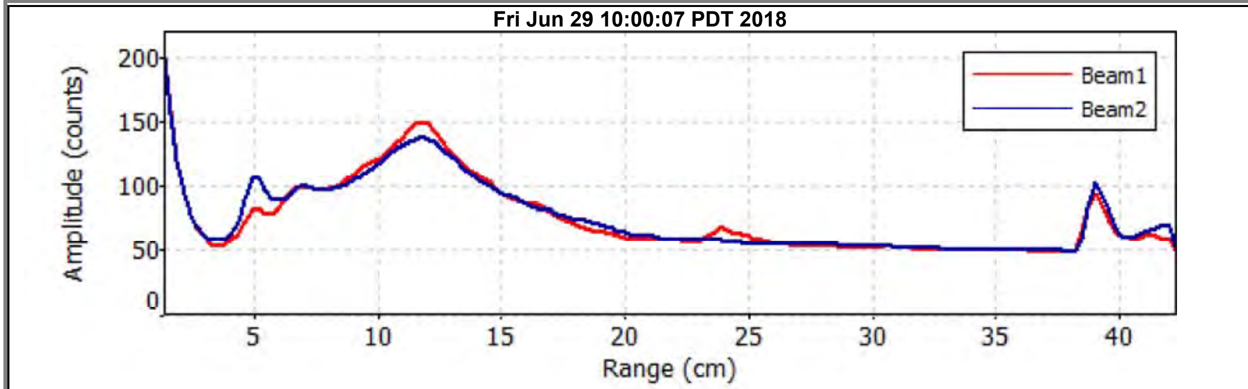
Discharge Measurement Summary

Date Generated: Thu Jan 10 2019

File Information	
File Name	062918.01.WAD
Start Date and Time	2018/06/29 10:02:15

Site Details	
Site Name	
Operator(s)	RC

Automatic Quality Control Test (BeamCheck)



- Noise level check - Pass
- SNR check - Pass
- Peak location check - Pass
- Peak shape check - Pass