Monitoring of Streamflow and Water Quality in the Four Largest Tributaries to Skaneateles Lake, 2018



prepared for:
Skaneateles Lake Association
PO Box 862
Skaneateles, NY 13152

prepared by:
UPSTATE FRESHWATER INSTITUTE
224 Midler Park Drive
Syracuse, NY 13206

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Glossary

Term	Definition
Baseflow	the portion of streamflow that is generated from groundwater inputs, not from precipitation or snowmelt
Cross-sectional area	the area of a two-dimensional plane that intersects a three-dimensional object
Evapotranspiration	the combined loss of water from a watershed from evaporation and transpiration (process by which water is carried through plants from roots to small pores on the underside of leaves and is released to the atmosphere)
Ground-truthing	information provided by direct observations to validate another set of measurements
Head	the height or depth of a body of water
In-situ	in an objects original place
Interception storage	precipitation that does not reach the soil but is instead intercepted by the leaves and branches of forest and agricultural plants
Load (or loading)	the mass quantity of a substance delivered to a water body over a given period of time (for example, pounds per second or kilograms per day)
NTU	nephelometric turbidity units (relative units of the turbidity measurement)
Oligotrophic	the condition of a lake having low levels of nutrients and primary production (algae)
p-value	the probability of obtaining a result equal to or greater than what was actually observed, when the null hypothesis is true (a p-value less than 0.05 is usually the level to determine statistical significance).
R^2	also known as the coefficient of determination; proportion of the variability in the dependent variable that is predictable from the independent variable
Reach	a specific section of a stream with defined upstream and downstream boundaries used for environmental studies
Runoff	the portion of streamflow that results from precipitation or snowmelt that is not infiltrated into the ground and flows over the land surface directly into a stream channel
Specific conductance	the measure of how well a water can conduct an electrical current (used as a surrogate of total dissolved solids, salt content, or salinity)
Stream stage	height or depth of water above stream bottom
Transparent Velocity Head Rod (or TVHR)	a flat Plexiglas® sheet of specific width with meter sticks used to estimate stream velocity
Turbidity	cloudiness or haziness of a fluid caused by individual particles that are generally invisible to the naked eye
Watershed	the area of land surrounding a water body that contributes water to that body

1. Background

1.1. Skaneateles Lake and its Major Tributaries

Skaneateles Lake is located in central New York, approximately 19 kilometers (km) south-southwest of Syracuse and 8 km east of Auburn. It is the second easternmost of the Finger Lakes. The main axis of the lake is oriented approximately along a north/northwest-south/southeast line with the Village of Skaneateles at its northern end. Skaneateles Lake has a surface area of 35.9 km^2, a volume of 1,563 x 10^6 cubic meters (m^3), and mean and maximum depths of 43.5 and 90.5 meters (m). Skaneateles Lake is the third deepest of the 11 Finger Lakes; it has the fourth largest volume, but the fifth smallest surface area (Schaffner and Oglesby 1978).

The lake has a small watershed (154 km^2) relative to its size; i.e., the smallest watershed to surface area ratio of the Finger Lakes. The lake's exceptional water quality, including its oligotrophic (low primary production) state, has been attributed in part to this feature (Oglesby and Schaffner 1978, Perkins et al. 2009). Land cover in the Skaneateles Lake watershed is dominated by forest and grasslands (44%), pasture and hay (25%), and row crops (25%). Residential and commercial development in the watershed is relatively low (4% by area). Hydrologic inputs are rather diffuse, with many small tributaries rather than a single dominant input. The lake has a single natural outflow at its northern end, Skaneateles Creek, which flows north to the Seneca River and eventually to Lake Ontario. The lake has a long hydraulic retention time. That is, it flushes relatively slowly, about once every 18 years on a completely-mixed basis, the second slowest of the Finger Lakes (Schaffner and Oglesby 1978).

Skaneateles Lake is an extremely valuable aquatic resource that is tremendously important to the economies of the surrounding towns and villages and the eastern Finger Lakes region. The pristine aesthetic quality of the lake attracts tourism and is important for maintaining property values along its shores. The shoreline of the lake is largely developed with cottages and year-round homes. More than 1,000 residences are located along the lake’s 34 miles of shoreline. Boating, swimming, and fishing are popular activities on Skaneateles Lake. The lake is also the principal source of water for the City of Syracuse and Village of Skaneateles. The City of Syracuse maintains an active watershed management program for Skaneateles Lake to protect its water quality. Because of the exceptional water quality of Skaneateles Lake, the water supply is unfiltered. Municipal drinking water is withdrawn from two different intakes that extend approximately 1.3 and 2.0 km south from the Village of Skaneateles. The New York State Department of Environmental Conservation (NYSDEC) has classified Skaneateles Lake as AA waterbody, which is its highest rating.

The exceptional water quality of Skaneateles Lake is presently threatened by harmful algal blooms (HABs), which occurred during late summer and early fall of 2017 and 2018. Not only do these blooms of cyanobacteria create aesthetic problems, but they are also capable of producing toxins that threaten use of the lake as a water supply. Although toxins (i.e., microcystin) have been detected in the waters of Skaneateles Lake and in public water supply intakes, they have not been detected in the distribution system. Reducing nutrient inputs from tributaries is a primary management approach for controlling HABs, which highlights the need to quantify phosphorus and nitrogen loadings from the lake's tributary streams. The four largest tributaries to Skaneateles Lake, Bear Swamp Creek, Grout Brook, Shotwell Brook, and Harold Brook, drain approximately 60% of the lake's watershed. This report summarizes the results of a robust monitoring program conducted on these four streams in 2018 on behalf of the Skaneateles Lake Association (SLA). The importance of monitoring both the water quantity and water quality these tributaries is reinforced by the paucity of environmental data currently available. The United States Geological Survey (USGS) is not currently operating flow gauges on any of these streams and very little comprehensive water quality monitoring has been conducted previously.

1.2. Objectives

The overarching goal of the 2018 stream monitoring program conducted by UFI on behalf of the Skaneateles Lake Association (SLA) was to quantify both hydraulic and material loadings to Skaneateles Lake from its four largest tributary streams. This information will be used in the future to support a lake management plan (Nine Element Plan) as well as both watershed and in-lake models of the Skaneateles Lake ecosystem. While monitoring of Shotwell Brook has been supported by the Town of Skaneateles since 2016, no comparable effort was in place for Bear Swamp Creek, Grout Brook, or Harold Brook. In 2018, SLA contracted with UFI to conduct a comprehensive monitoring program on these three additional tributaries and to enhance its efforts on Shotwell Brook. This monitoring program includes a suite of field and laboratory measurements that will provide a robust representation of nutrient and sediment loading from these streams that will be critical for the future development of watershed and water quality models for Skaneateles Lake. Additionally, this monitoring program will establish baseline loading conditions and provide a basis for the location of nutrient reduction projects.

Specifically, the objectives of the study were to: (1) develop estimates of streamflow using stream stage, velocity, and cross-sectional area measurements for a range of conditions; (2) characterize the water quality of each of the four tributaries with high frequency (15-minute measurement interval) *in-situ* probes to provide near-continuous measurements of temperature (T; in degrees Celsius or °C), specific conductance (SC; in micro-Siemens per centimeter or µS/cm), and turbidity (Tn; in nephelometric turbidity units or NTU); and (3) measure concentrations of various water quality constituents during both baseflow and runoff event conditions. The following parameters were measured during 15 bi-weekly surveys and three storm events intended to capture high flow conditions:

- total phosphorus, total dissolved phosphorus, soluble reactive phosphorus
- total nitrogen, nitrate+nitrite, total ammonia
- particulate organic carbon, dissolved organic carbon
- total suspended solids, turbidity, silica

2. Methods

2.1. Study Location

The four largest tributary streams to Skaneateles Lake were selected for this study in an effort to efficiently characterize important sources of nutrients and other key water quality constituents. Brief descriptions of each of the streams are provided below, including land use information (Table 1).

Table 1. Drainage area and land cover characteristics of selected Skaneateles Lake tributaries. Land cover values based on 2011 National Land Cover Database and sub-watershed models available at Wikiwatershed.

		Land cover percentages				
Tributary	**Drainage area (km^2)**	**Developed**	**Forest & grassland**	**Pasture & hay**	**Row crops**	**Wetland**
Bear Swamp Creek	40	2	64	9	15	10
Grout Brook	36	4	65	13	17	2
Shotwell Brook	9	7	21	35	32	5
Harold Brook	5	4	17	33	41	6

Bear Swamp Creek, the largest of the tributaries, is a second order stream in the southeast portion of the Skaneateles Lake watershed. Bear Swamp Creek has a drainage area of approximately 40 km^2, representing 26% of the Skaneateles Lake watershed. Land cover in the Bear Swamp Creek watershed is dominated by forest and grassland (64%) and agricultural (24%). Ten percent of the watershed is classified as wetlands and just 2% of the land is developed.

Grout Brook, the second largest tributary to Skaneateles Lake, is a second order stream located in the southeast portion of the Skaneateles Lake watershed. The drainage area of Grout Brook is 36 km^2, which accounts for 24% of the Skaneateles Lake watershed. Forest and grasslands account for 65% of the watershed and 30% of the drainage area is devoted to agricultural land uses. The remainder of the watershed is either developed land (4%) or classified as wetland (2%).

Shotwell Brook enters Skaneateles Lake near the northeast corner of the lake, approximately 3 km south-southeast of the Village of Skaneateles and approximately 1.5 km southeast of the drinking water intakes. Shotwell Brook's watershed (9 km^2) accounts for approximately 6% of the lake's drainage area. Agricultural land uses account for 67% of land usage in the Shotwell Brook watershed. Approximately 21% of the watershed is forest and grasslands. Developed lands and wetlands account for 7% and 5% of the drainage area, respectively. Because of its land use make-up, and despite its small size, Shotwell Brook is known to be an important source of turbidity to Skaneateles Lake, especially during periods of high flow. Shotwell Brook has been monitored by the Upstate Freshwater Institute (UFI) since 2016 with funding from the Town of Skaneateles.

Harold Brook is a second order stream located in the northwestern portion of the Skaneateles Lake watershed about 5 km south of the Village of Skaneateles and 3 km south of the water supply intakes. Harold Brook, which is the smallest of the four tributaries included in this study, has a drainage area of approximately 5 km^2. Agricultural land uses dominate the watershed with 74% of the drainage area devoted to pasture, hay, and row crops. The remainder of the Harold Brook drainage area is classified as forest and grassland (17%), wetlands (6%), or developed (4%).

Monitoring locations for these streams were selected to be near their mouths and readily accessible via bridges and culverts. Monitoring equipment was installed at each of these locations to avoid the influence of lake water and for convenience in sample collection and equipment maintenance. The sampling locations were each located at the mouths of each tributary in the study in order to most accurately quantify nutrient and sediment loading into the lake. The monitoring location for Bear Swamp Creek was located in a small seasonal village between Firelane 176 and Appletree Point, about 500 feet from the mouth of the creek (42°49'21.06N, 76°19'46.91W). The Grout Brook monitoring location was located off Route 66B (Glen Haven Rd.) about 1700 feet south of the stream's mouth (42°45'35.39N, 76°16'12.70W). Shotwell Brook was monitored at the Route 41 (East Lake Rd.) bridge between Pork St. and Coon Hill Rd. (Figure 1). This location is approximately 690 feet upstream of the brook's mouth (42.924°N, -76.408°W). The Harold Brook monitoring location was located off Route 41A (West Lake Rd.), south of the junction where Rt. 117 (Benson Rd.) meets Route 41A. The sampling location is approximately 1000 feet upstream from the mouth (42°53'51.31N, 76°25'10.91W).

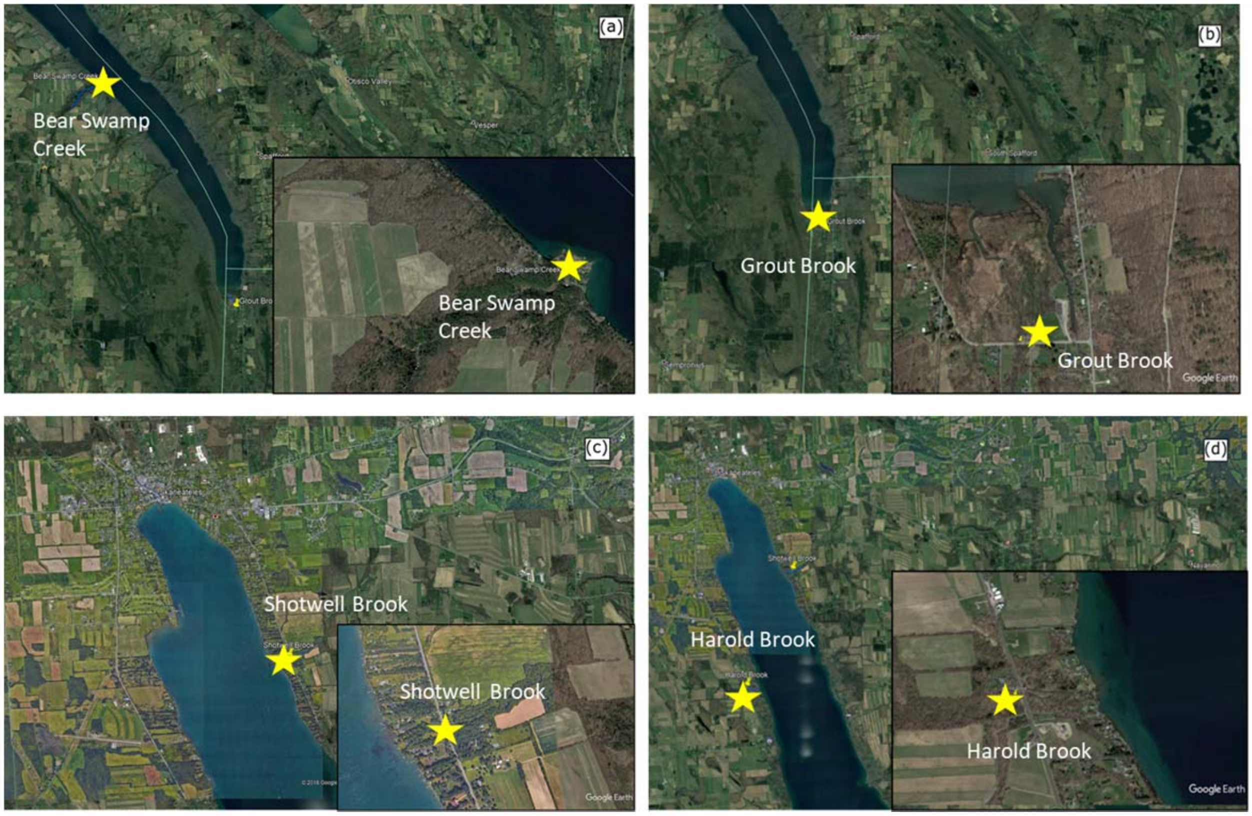

Figure 1. Aerial photos depicting sampling locations for the four streams included in this study: (a) Bear Swamp Creek, (b) Grout Brook, (c) Shotwell Brook, and (d) Harold Brook. All images were obtained from Google Earth.

2.2. Cross-sectional Area, Velocity, and Estimates of Streamflow

Streamflow is a critical variable, necessary for the environmental analysis of streams. Streamflow (Q; in cubic feet per second or cfs) is calculated as the product of a stream's cross-sectional area (A; in square feet or ft^2) and velocity (V; feet per second or ft/s). A graphical representation of a stream channel, including the components of streamflow, is provided in Figure 2. Multiple measurements of area and velocity over a wide range of conditions are needed to accurately characterize the flow conditions of a stream. For this study, a statistical relationship, called a rating curve, between stream depth (or stage, S) and streamflow was developed so that near-continuous flow can be estimated from easily measured, near-continuous stage measurements.

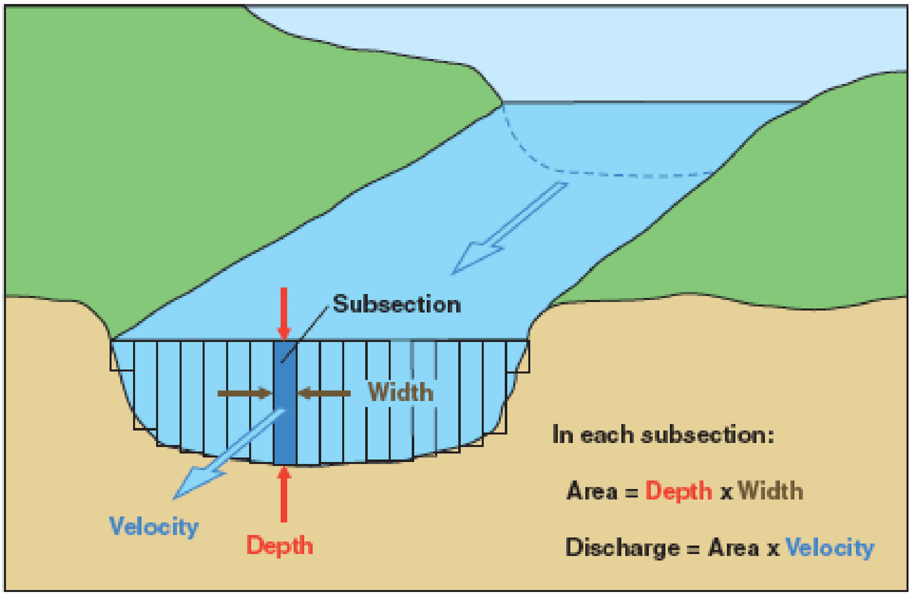

Figure 2. A graphical representation of the components of streamflow (also called discharge; courtesy of the USGS).

Stream cross-sectional area measurements were made by making depth measurements at intervals across the width of the stream and using geometric calculations (similar to Figure 2). Velocity measurements were made with three tools or techniques so that results could be compared and verified: (1) the float method, (2) a velocity meter, and (3) a transparent velocity head rod (TVHR; Fonstad et al. 2005). Velocity measurements were made at multiple sites across the width of the stream if possible with the velocity meter and TVHR. For consistency, area and velocity measurements were made at the same locations at each site. Paired area and velocity measurements and resulting streamflow estimates were then paired with *in-situ* stage measurements to create a representative rating curve for each of the four streams.

2.2.1. The Float Method

The float method is a common method for estimating stream velocity (Michaud and Wierenga 2005). It involves measuring the travel time (in seconds) of a buoyant float over a reach of known distance (in feet). The process is repeated several times per trip over the same reach and the average travel time is divided into the reach length. The result is the average surface velocity. The surface velocity is adjusted to an average flow velocity (the velocity at a mid-point in the flow depth) by multiplying the surface velocity by 0.8 or 0.9 (Michaud and Wierenga 2005). For this study, all surface velocities estimated from the float method were adjusted by a factor of 0.85.

For Bear Swamp Creek, the reach was about 40 feet, using relatively permanent rocks and trees in the landscape at Threemile Point to designate the upstream and downstream markers. The reach for Grout Brook was 38 feet from the Route 66B (Glen Haven Rd) bridge to a designated location downstream marked by a relatively permanent feature of the landscape (in this case, a particular tree protruding into the stream). For Shotwell Brook, the reach was defined as the length of the stream underneath the Route 41 Bridge from an upstream gage marker to the overspill of the concrete culvert base (44 ft; see Figure 3). The float method was not used for Harold Brook because the stream was too shallow and the floating object would get caught on protruding rocks and bed materials, leading to inaccurate measurements.

Figure 3. Reach of Shotwell Brook used for velocity and area measurements. The photograph was taken at the overspill, looking upstream.

2.2.2. The Velocity Meter

Stream velocity measurements were also made with a Global Water velocity meter (Global Water Instrumentation Inc. 2009). The Global Water velocity meter was positioned at multiple cross-sectional locations and depths in the brook to provide a depth-width integrated velocity measurement on each trip when there was adequate flow volume. Because it is depth-width integrated, this average velocity was used directly in streamflow estimation. The velocity meter was replaced with a new unit following a number of inaccurate measurements made early in the 2018 monitoring program.

2.2.3. The Transparent Velocity Head Rod (TVHR)

For this study, UFI fabricated a TVHR (a flat Plexiglas® sheet of specific width with meter sticks) based on the description provided by Fonstad et al. 2005. Briefly, the method involves placing the TVHR into the streamflow and measuring the difference between the height of the water (called head) on the upstream side of the Plexiglas® and the height of the water on the downstream side (Figure 4a and b). The difference in the upstream and downstream head is proportional to the water velocity, given the TVHR dimensions (Fonstad et al. 2005). This tool was used at multiple locations across the stream width, when possible, to estimate average velocity on each trip. No velocity adjustments are needed for this technique.

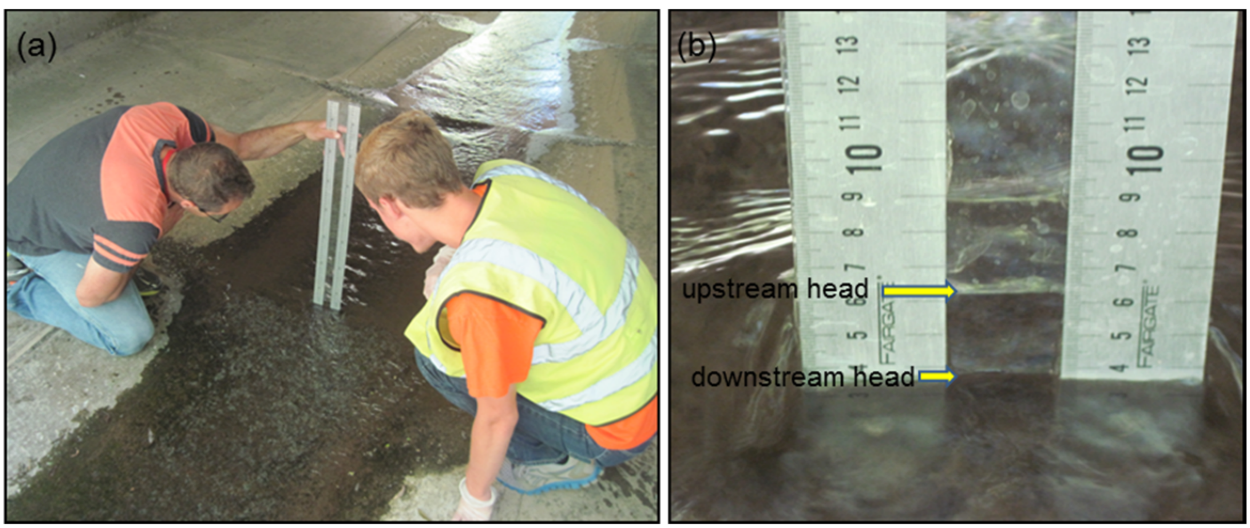

Figure 4. The use of the TVHR in Shotwell Brook at low flow: (a) TVHR in stream, and (b) difference in upstream and downstream head.

2.3. *In-situ* Equipment

The *in-situ* measurements consisted of stream stage and water quality parameters (T, SC, and Tn). Stage was measured by a Campbell Scientific model CS450 pressure sensor (Campbell Scientific 2012) and water quality measurements were made with a YSI Series 6600 multi-probe datasonde (YSI 2011). At Shotwell Brook, the pressure sensor and datasonde were installed in pools approximately 10 feet downstream of the culvert (Figure 5). The pressure sensor and datasonde both moved several times during the study because of high flows. These two sensors were connected to a battery and data logger and the 15-minute data was sent via cellular modem to UFI in Syracuse for storage and analysis. *In-situ* readings were validated with an independent YSI multi-probe datasonde on sampling trips (this process is referred to as ground-truthing). This installation was replicated at Bear Swamp Creek, Grout Brook, and Harold Brook.

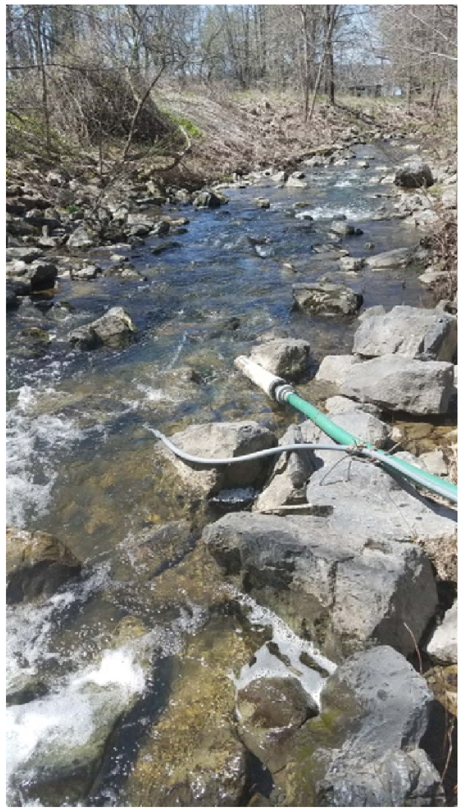

Figure 5. Location of *in-situ* monitoring equipment in Shotwell Brook.

2.4. Chemistry Samples

Water chemistry samples were collected as grab samples from each of the four streams during 15 bi-weekly surveys and three high flow events. Samples were analyzed for dissolved organic carbon (DOC), particulate organic carbon (POC), total ammonia (tNH_3), nitrate+nitrite (NOx), total nitrogen (TN), total phosphorus (TP), total dissolved phosphorus (TDP), soluble reactive phosphorus (SRP), silica (SiO_2), total suspended solids (TSS), and turbidity (Tn) according to Standard Methods (Rice et al. 2012). Particulate phosphorus (PP) was calculated as the difference between TP and TDP and dissolved organic phosphorus (DOP) is calculated as the difference between TDP and SRP. All chemical analyses were performed at UFI's ELAP-certified laboratory in Syracuse. The Environmental Laboratory Approval Program (ELAP) is responsible for the certification of laboratories performing environmental analyses on samples originating from New York State, thus ensuring the accuracy and reliability of these analyses.

3. 2018 Environmental Conditions

Representative snowfall, temperature, and precipitation data for the Skaneateles Lake watershed was obtained from the National Weather Service (NWS) station in Auburn, NY. The NWS Auburn station is located approximately 10 km west of the Village of Skaneateles and 11.9 km west of the mouth of Shotwell Brook.

3.1. 2018 Temperature and Precipitation

Air temperatures during 2018 were lower than the long-term (1980-2017) average in January, March, April, and November (Figure 6a). During the months of February, May, August, and September of 2018 air temperatures were above the long-term average. Temperatures were close to the long-term average in June, July, and October.

Total precipitation was well above average during January–March of 2018, followed by much drier conditions during April–June (Figure 6b). Above average precipitation returned for most of the August–November period, with the highest monthly totals occurring during November (6.1 inches). Cumulative precipitation for the January–November period of 2018 was 9.0 inches higher than the long-term average (Figure 6c). However, precipitation during summer (June–September) was just 0.3 inches higher than average.

3.2. Snowfall Winter 2018 - Spring 2018

Snowfall in Auburn was elevated during the winter of 2017–2018 compared with long-term average conditions. Total snowfall during the 2017–2018 winter season was 132.2 inches, substantially higher than the average annual snowfall of 99.7±34.6 inches (± represents ± one standard deviation). The 2017–2018 winter season ranked as the 5th highest annual total over the 1999–2017 period. The highest total was observed in 2003-2004 (153.4 inches) and the lowest was observed in 2011–2012 (43.4 inches).

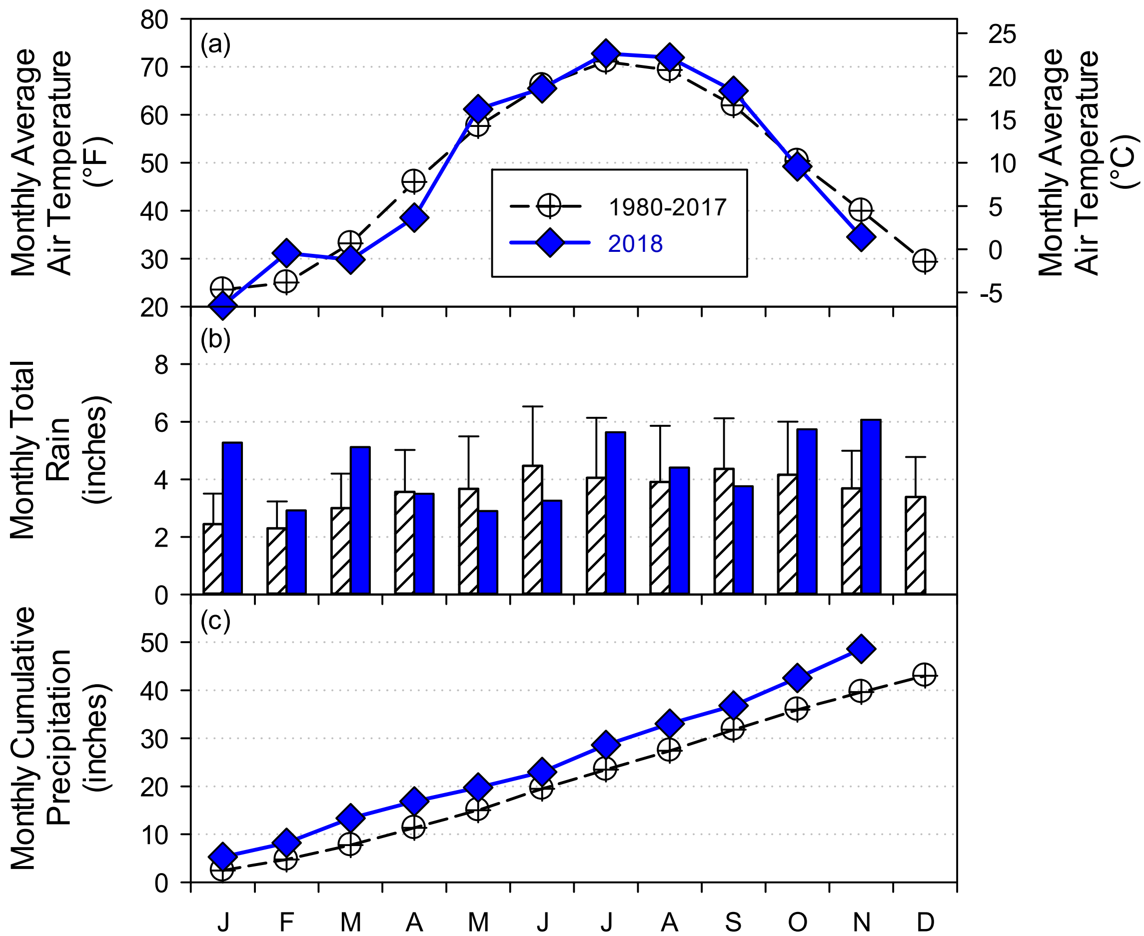

Figure 6. Auburn NWS meteorological conditions in 2018 compared with the 1980–2017 average as represented by the: (a) monthly average air temperature in degrees Fahrenheit (b) monthly total rain in inches (error bars are standard deviations on monthly averages), and (c) monthly cumulative rain in inches.

4. Results

4.1. Cross-sectional Area, Velocity, and Estimates of Streamflow

The three methods used to estimate water velocity compared well for most of the study interval (Figure 7, 8, 9, 10). The largest differences were observed with the TVHR, which generally under-predicted compared to the other methods. Having three methods available for velocity estimation was critical because each method had its own specific advantages and short-comings. For example, the TVHR and float methods were the only methods that could be used during low flow conditions in dry part of the summer. We found that the velocity meter usually required a minimum of 2.5 inches of water depth; less than 2 inches of depth caused invalid results. When possible, an average of the three methods was used in flow calculations.

Over the course of the 2018 study, velocity measurements for Bear Swamp Creek ranged from 0.6 ft/s to 3.1 ft/s and cross-sectional areas ranged from 3.3 ft^2 to 26.0 ft^2 (Figure 7a). Grout Brook velocity measurements ranged from 0.5 ft/s to 1.9 ft/s and cross-sectional areas ranged from 11.3 ft^2 to 29.9 ft^2 (Figure 8a). Velocity measurements for Shotwell Brook ranged from 0.5 ft/s to 12.6 ft/s and cross-sectional areas varied from 0.2 ft^2 to 4.0 ft^2 (Figure 9a). Harold Brook velocity measurements ranged from 0.6 ft/s to 3.9 ft/s and cross-sectional areas ranged from 0.04 ft^2 to 1.2 ft^2 (Figure 10a). For each sampling trip streamflow was calculated as the product of velocity and cross-sectional area measurements. In total, 17 direct streamflow measurements were made at each stream from March 21 through November 9. A number of faulty velocity meter results from the early portion of the 2018 monitoring season were omitted from the analyses presented in this report.

The statistical relationship between stage (S; independent variable) and streamflow (Q; dependent variable), called a rating-curve, is provided for each stream (Figure 7b, 8b, 9b, 10b). The rating curve for Shotwell Brook is based on three years of measurements (2016–2018), while only measurements from 2018 are available for Bear Swamp Creek, Grout Brook, and Harold Brook. Bear Swamp Creek had more sporadic data than the other tributaries, resulting in a lower level of statistical significance as indicated by the relatively high p-value (0.018) and low R^2 (0.36). This is indicative of the need for further monitoring to collect more data to establish a more robust rating curve. The resulting equations for Grout Brook, Shotwell Brook, and Harold Brook were highly statistically significant as indicated by the low *p*-value for each tributary (<0.0001) and high R^2 (0.95, 0.91, 0.97, respectively). This relationship was applied to the 15-minute measurements of stage from the *in-situ* pressure sensor (adjusted from the pool to an equivalent stage in the culvert) to obtain a (nearly) continuous 15-minute record of streamflow for Shotwell Brook for the study interval. Note that rating curves and flow estimates will be updated with additional data collected during future monitoring.

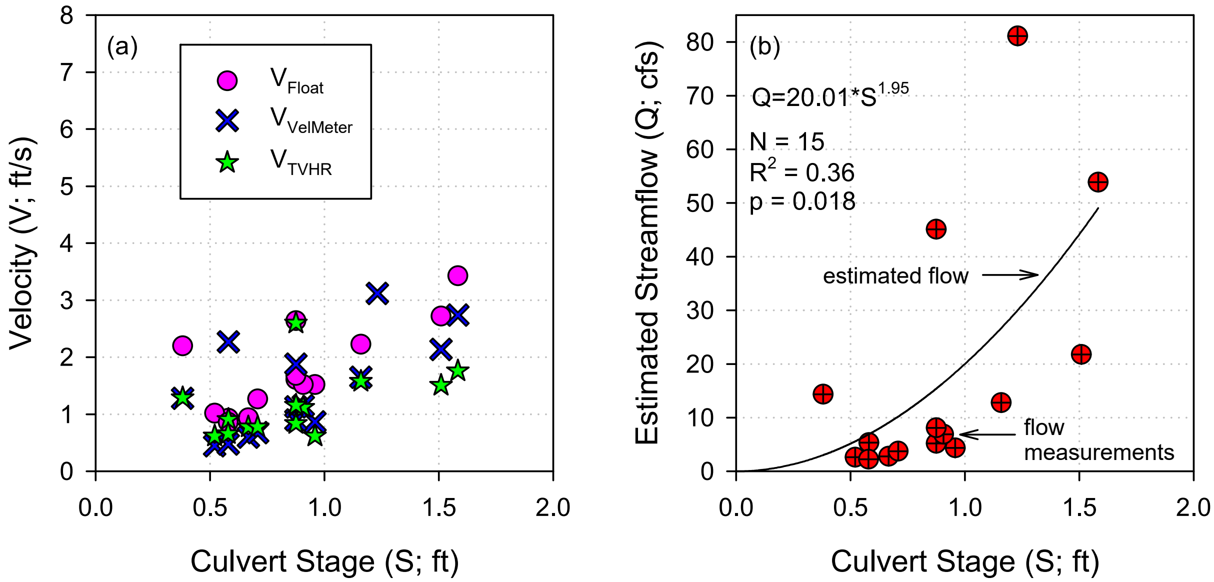

Figure 7. Estimating water velocity and streamflow in Bear Swamp Creek for 2018: (a) stage-velocity relationships for the three velocity estimation methods, and (b) stage-flow relationship (rating curve) with equation and statistics.

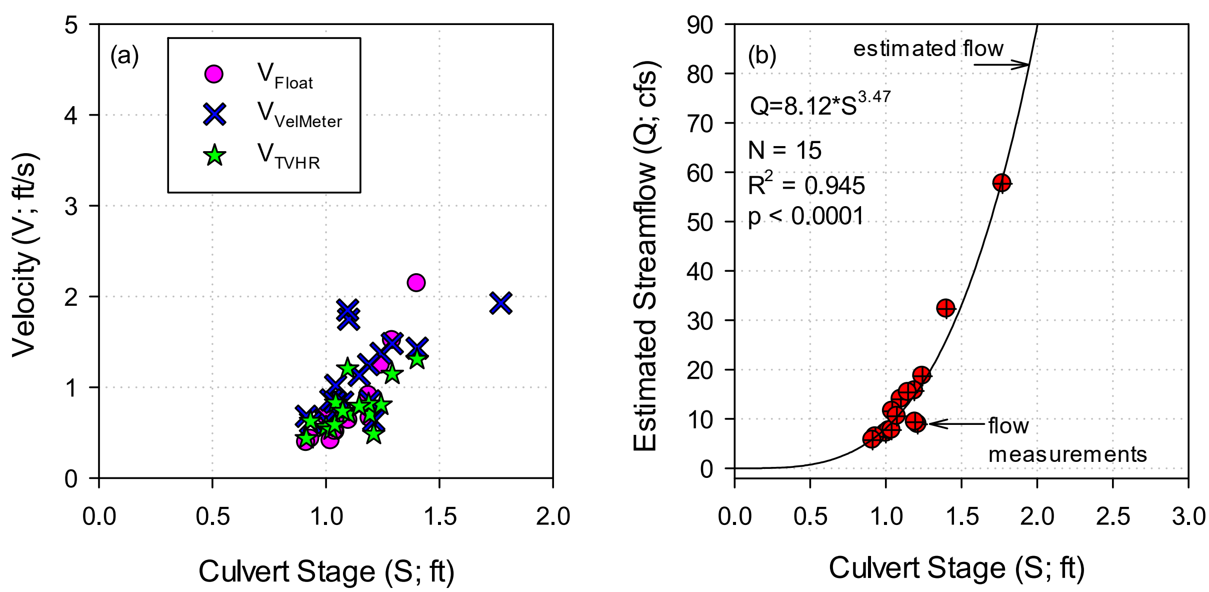

Figure 8. Estimating water velocity and streamflow in Grout Brook for 2018: (a) stage-velocity relationships for the three velocity estimation methods, and (b) stage-flow relationship (rating curve) with equation and statistics.

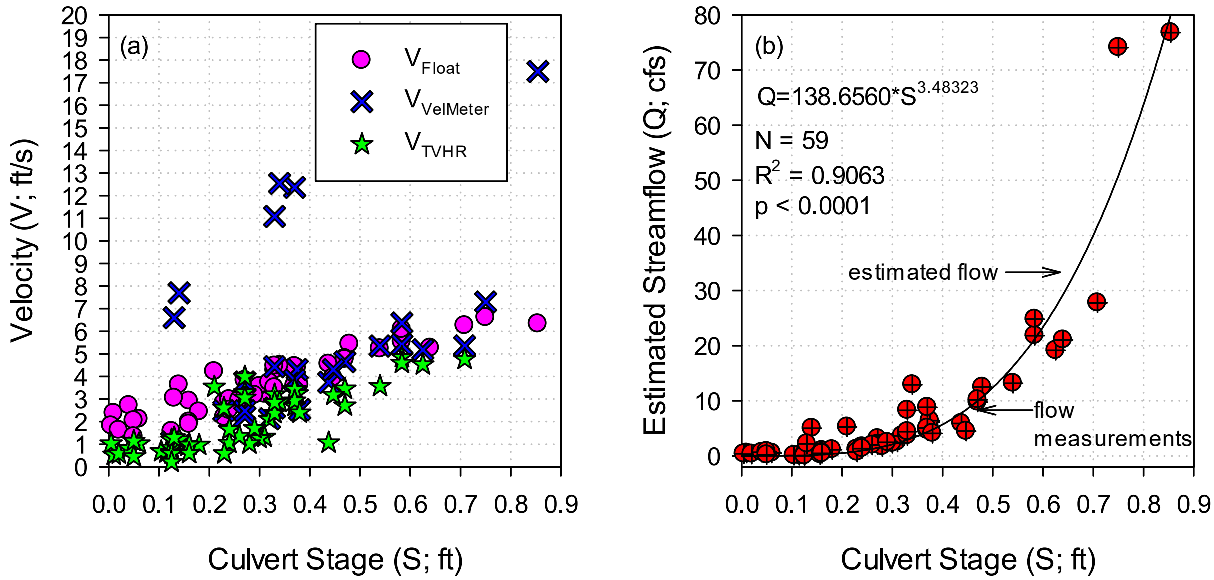

Figure 9. Estimating water velocity and streamflow in Shotwell Brook from 2016 to 2018: (a) stage-velocity relationships for the three velocity estimation methods, and (b) stage-flow relationship (rating curve) with equation and statistics.

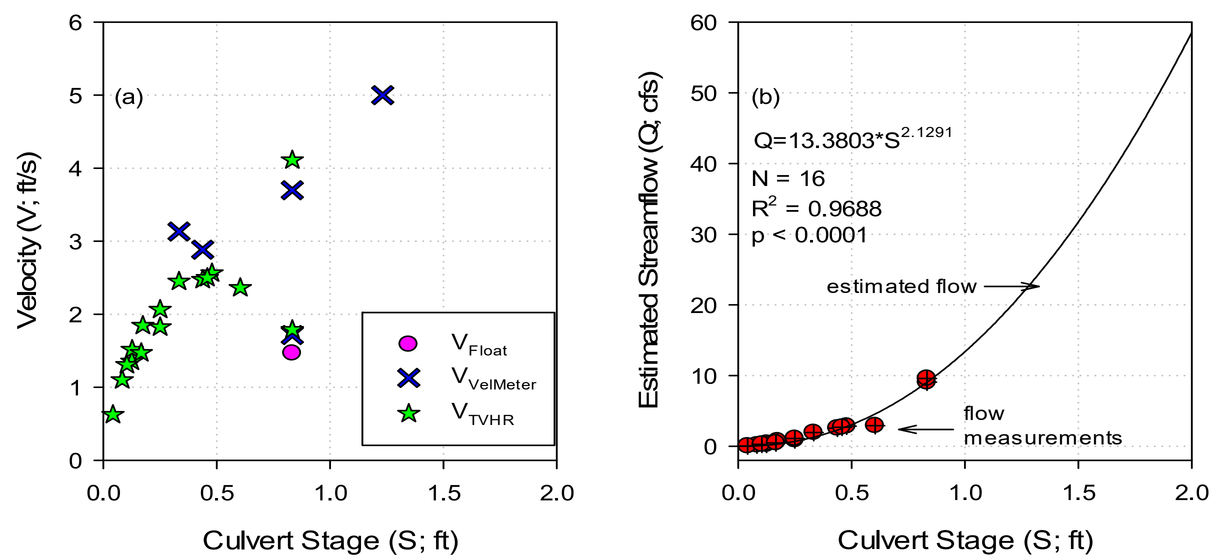

Figure 10. Estimating water velocity and streamflow in Harold Brook for: (a) stage-velocity relationships for the three velocity estimation methods, and (b) stage-flow relationship (rating curve) with equation and statistics.

4.2. High Frequency Measurements of Stream Stage and Water Quality

Over 15,000 measurements of stream stage, temperature, specific conductance, and turbidity were collected at each of the four Skaneateles Lake tributaries in 2018. In-stream sensors collected high frequency (15-minute) data for 166 days at Bear Swamp Creek, 172 days at Grout Brook, 250 days at Shotwell Brook, and 175 days at Harold Brook. There were brief periods when data could not be collected, sometimes after large runoff events dislodged the monitoring equipment from the stream and deposited it on the stream bank. UFI took steps to anchor the equipment in pools, but at times the flow was too strong to prevent displacement. Early removal of monitoring equipment from Bear Swamp Creek was necessitated by snow and ice conditions on the seasonally maintained access road.

Measurements of stream stage were generally responsive to both short-term precipitation patterns at Auburn and longer-term seasonal changes (e.g., leaf-off, soil saturation). Relatively dry conditions during May, June, and most of July were followed by a period of more frequent and more intense rainfall beginning in late July (Figure 11). Although stage in each of the streams increased in response to major rainfall events, the magnitude of the responses varied widely. For example, stage at Harold Brook increased by 10 inches during the late July rainfall event, while stage at Grout Brook increased by just 5 inches (Figure 11). These variable responses are influenced by multiple factors, including watershed size, slope, and spatial differences in rainfall.

Stream stage patterns were also affected by antecedent conditions and timing relative to the growing season. The streams responded more strongly to modest rainfall events in late November and early December than they did to the larger event in late July (Figure 11). The late July event occurred during the heart of the growing season and was preceded by a particularly dry period. In contrast, the conspicuous increases in stage during late November and early December occurred when evapotranspiration was low and soils were saturated from abundant antecedent precipitation. Stream stage generally increased from August to December, coinciding with plentiful rainfall and the transition from summer to winter.

Frequency distributions of stream stage revealed interesting differences in the hydrology of the four watersheds (Figure 12). Stream stage was shifted higher for the two larger streams, Bear Swamp Creek and Grout Brook, during base flow conditions. This was especially the case for Grout Brook, which had a stage of at least 8 inches even during the driest period of the summer. In contrast, stage in Shotwell Brook and Harold Brook was less than 2 inches for much of the monitoring period. Stream stage for Bear Swamp Creek followed a nearly normal distribution, which is in stark contrast to the right-skewed distributions observed in the other three streams (Figure 12). We hypothesize that this unusual hydrologic pattern is associated with the function of two upstream impoundments. Harold Brook is the flashiest of the four streams, with stages of nearly 1.5 feet measured during high flows.

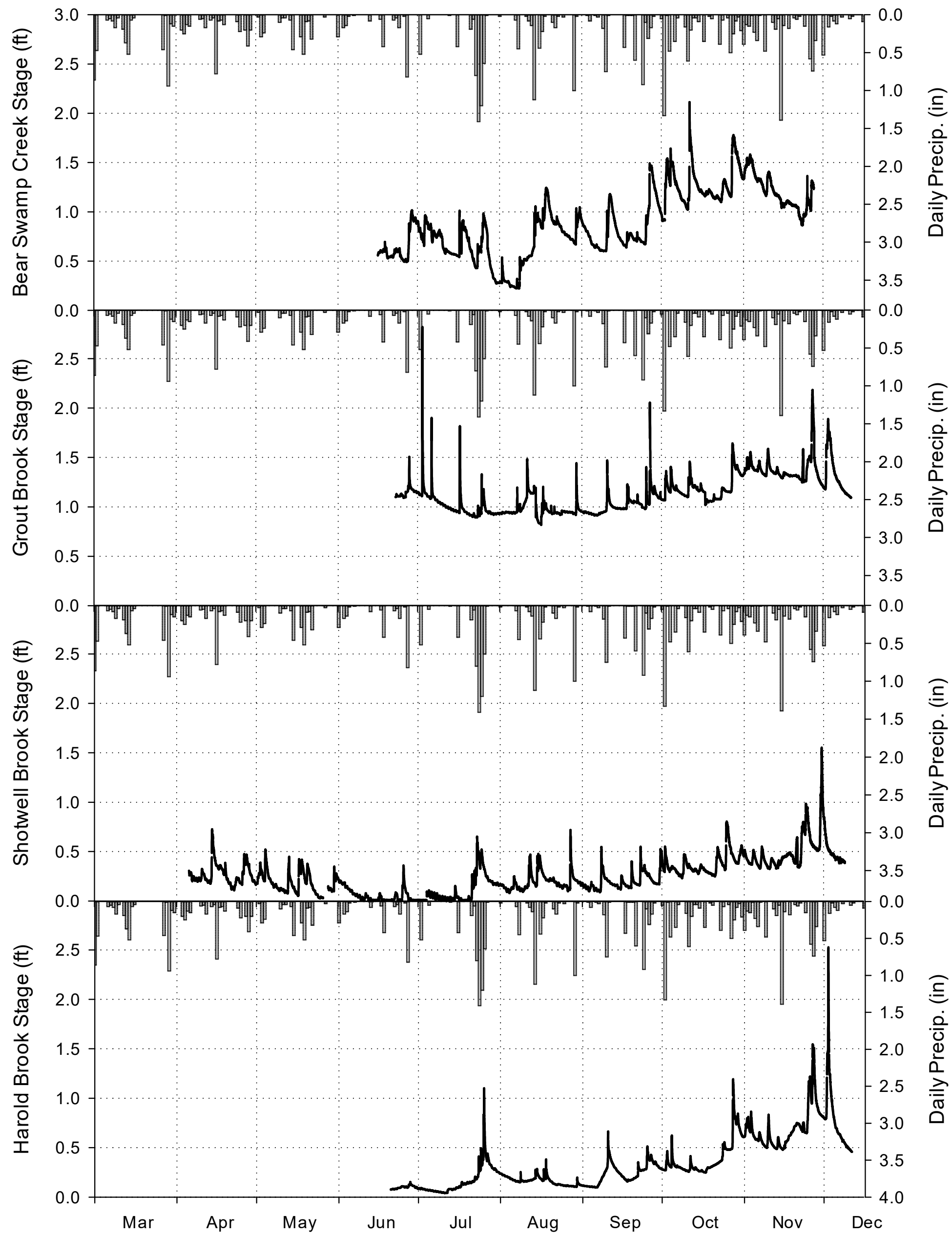

Figure 11. Time series of total daily precipitation and 15-minute stream stage for Bear Swamp Creek, Grout Brook, Shotwell Brook, and Harold Brook during 2018. Precipitation data acquired from the NOAA weather station in Auburn, NY.

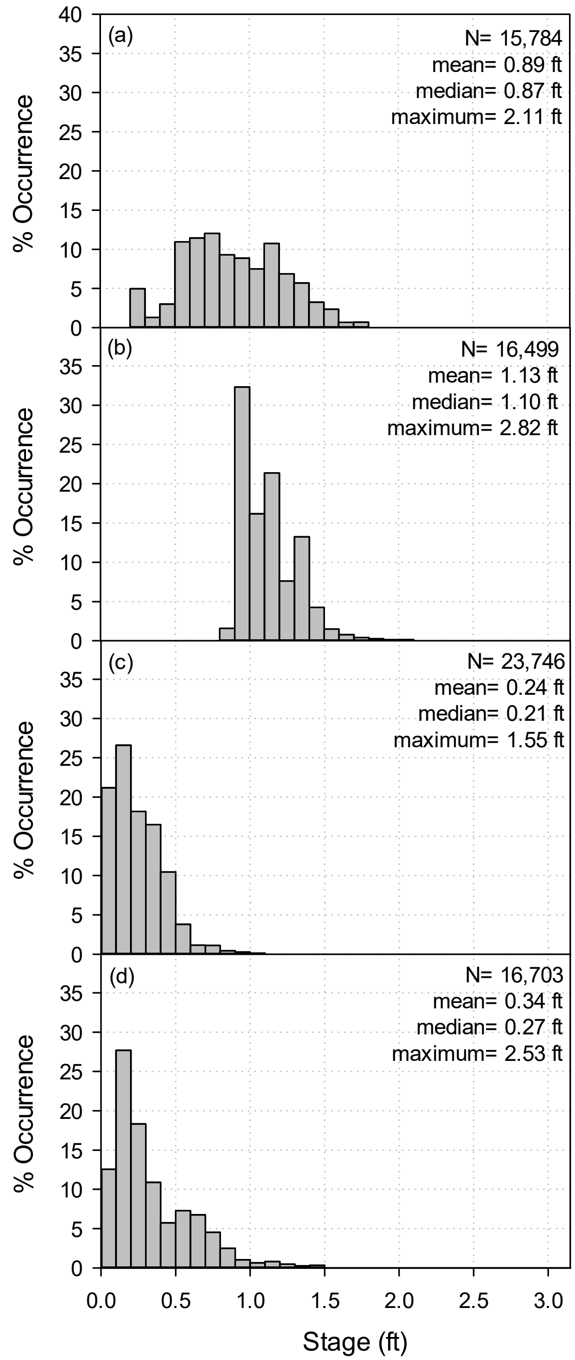

Figure 12. 15-minute stage observations in 2018 as frequency distributions with associated statistics in (a) Bear Swamp Creek, (b) Grout Brook, (c) Shotwell Brook, and (d) Harold Brook.

High frequency in-stream temperature measurements captured both diel and seasonal patterns (Figure 13a). Diel temperature variations are closely related to air temperature and appear as short-term peaks and valleys. Longer term variations, on the order of days, are associated with frontal systems and associated warm and cool air masses. A typical seasonal pattern of rising temperatures during spring, peak temperatures during mid-summer, and falling temperatures in fall was observed. Temperatures in Grout Brook were markedly lower than in the other streams, particularly during the warmer summer months (Figure 13, Table 2).

Specific conductance is a measure of the ionic content of water, quantified by the ability of water to conduct electrical current. Higher levels of specific conductance may be associated with human activities (e.g., application of road salt) or the natural hydrogeology of the watershed. Groundwater tends to be ionically enriched, and specific conductance tends to increase during dry periods when groundwater contributions to streamflow are high. Specific conductance typically decreases during runoff events due to dilution. This pattern is clearly displayed for the Skaneateles Lake tributaries as conspicuous decreases in specific conductance (Figure 13c) during significant runoff events characterized by marked increases in stage (Figure 13a). Shotwell Brook had the highest median specific conductance value and Bear Swamp Creek had the lowest (Table 2).

Median turbidity values were generally quite low in the Skaneateles Lake tributaries, ranging from 1.6 NTU in Bear Swamp Creek and Grout Brook to 2.4 NTU in Shotwell Brook (Table 2). However, abrupt spikes in turbidity were measured at each of the four streams during periods of high stage associated with major runoff events (Figure 13d). Turbidity values exceeding 1,000 NTU were measured in each of the four streams during increases in stream stage; however, these turbidity increases were usually short-lived. Large quantities of particulate material (e.g., silt, clay) are transported from the watershed to Skaneateles Lake during these events, resulting in turbid plumes observed entering the lake adjacent to stream mouths. Although these suspended particles generally contain phosphorus, this phosphorus is often tightly bound and unavailable to support algal growth in the lake. A relative turbidity scale is provided in Figure 14 for context.

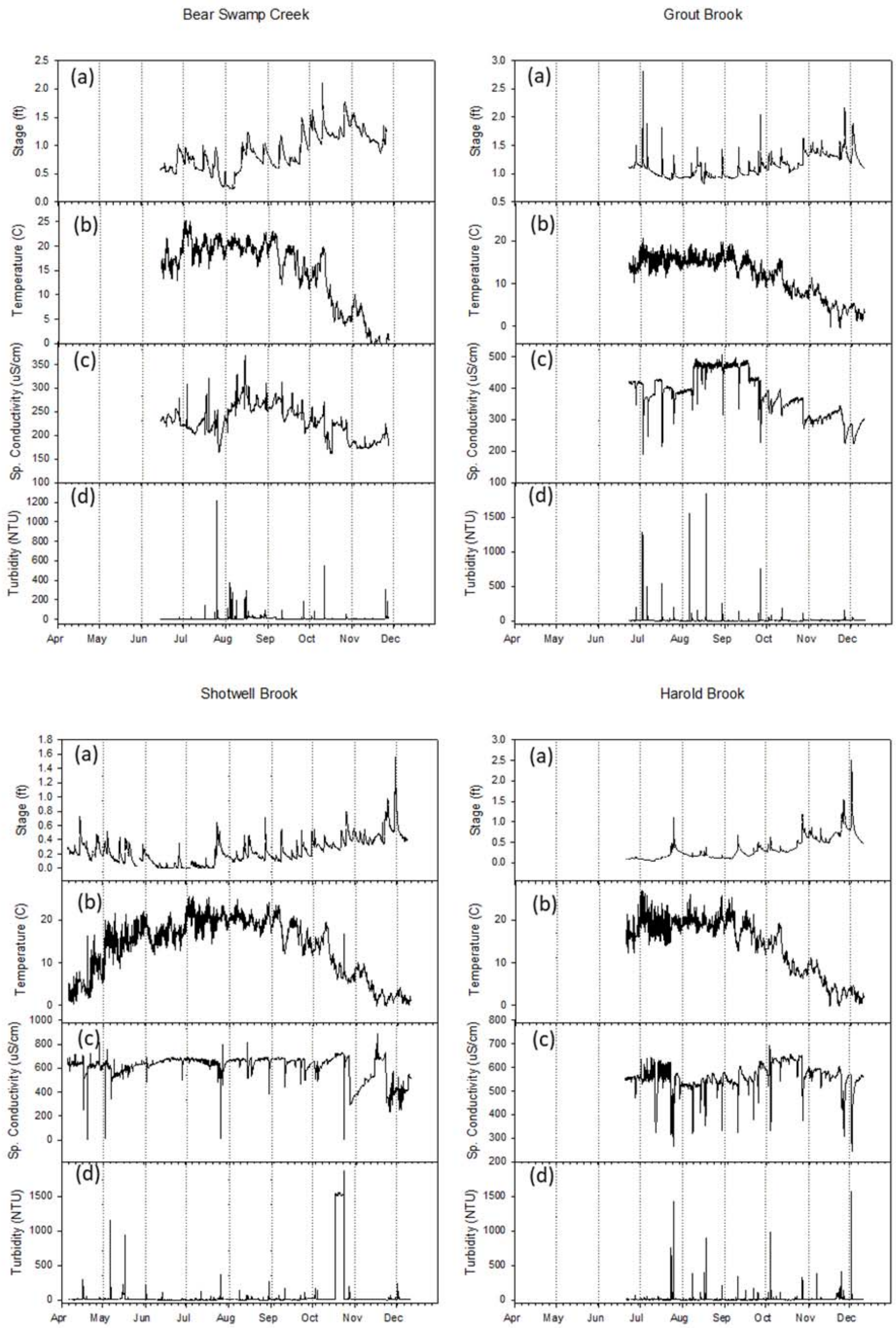

Figure 13. Time series of 15-minute measurements for Bear Swamp Creek, Grout Brook, Shotwell Brook, and Harold Brook: (a) stage, (b) temperature (c), specific conductance, and (d) turbidity.

Table 2. Summary of high frequency water quality measurements made with YSI multi-probe datasondes.

Parameter	Bear Swamp Creek			Grout Brook			Shotwell Brook			Harold Brook		
	n	median	mean	n	median	mean	n	median	mean	n	median	mean
Temp. (°C)	15,928	17.4	14.6	16,499	13.2	11.7	23,977	15.4	13.4	16,703	16.1	13.8
Sp. Cond. (µS/cm)	15,928	228	229	16,499	381	380	23,977	643	610	16,703	560	559
Turbidity (NTU)	15,928	1.6	4.5	16,499	1.6	5.3	23,977	2.4	44	16,703	1.9	8.8

Figure 14. A relative turbidity scale (image courtesy of www.learnnc.org).

4.3. Water Chemistry Results

4.3.1. Phosphorus

Samples were collected on 18 occasions during the late May to mid-December interval of 2018 for analysis of three forms of phosphorus: total phosphorus (TP), total dissolved phosphorus (TDP), and soluble reactive phosphorus (SRP). Although phosphorus concentrations were largely temporally uniform during the study period, noteworthy short-term increases were observed July 25, August 14, and September 10 (Figure 15). The higher phosphorus levels on July 25 and August 14 were associated with 1.34 and 0.81 inches of rainfall (measured at Auburn), respectively. The increase in phosphorus concentrations on September 10 occurred during a dry period with rainfall of just 0.1 inches on that day. Shotwell Brook had the highest median concentrations of TP, TDP, and SRP, while Grout Brook had the lowest values (Figure 16, Table 3). Phosphorus levels in Bear Swamp Creek were higher than expected based on the low intensity land uses that prevail in the watershed (64% forest and grassland, 10% wetland). We speculate that decomposition processes in the upstream wetland complex may contribute to higher TDP and SRP concentrations in Bear Swamp Creek. Phosphorus concentrations in Harold Brook were very responsive to rainfall events, consistent with the flashy nature of this stream.

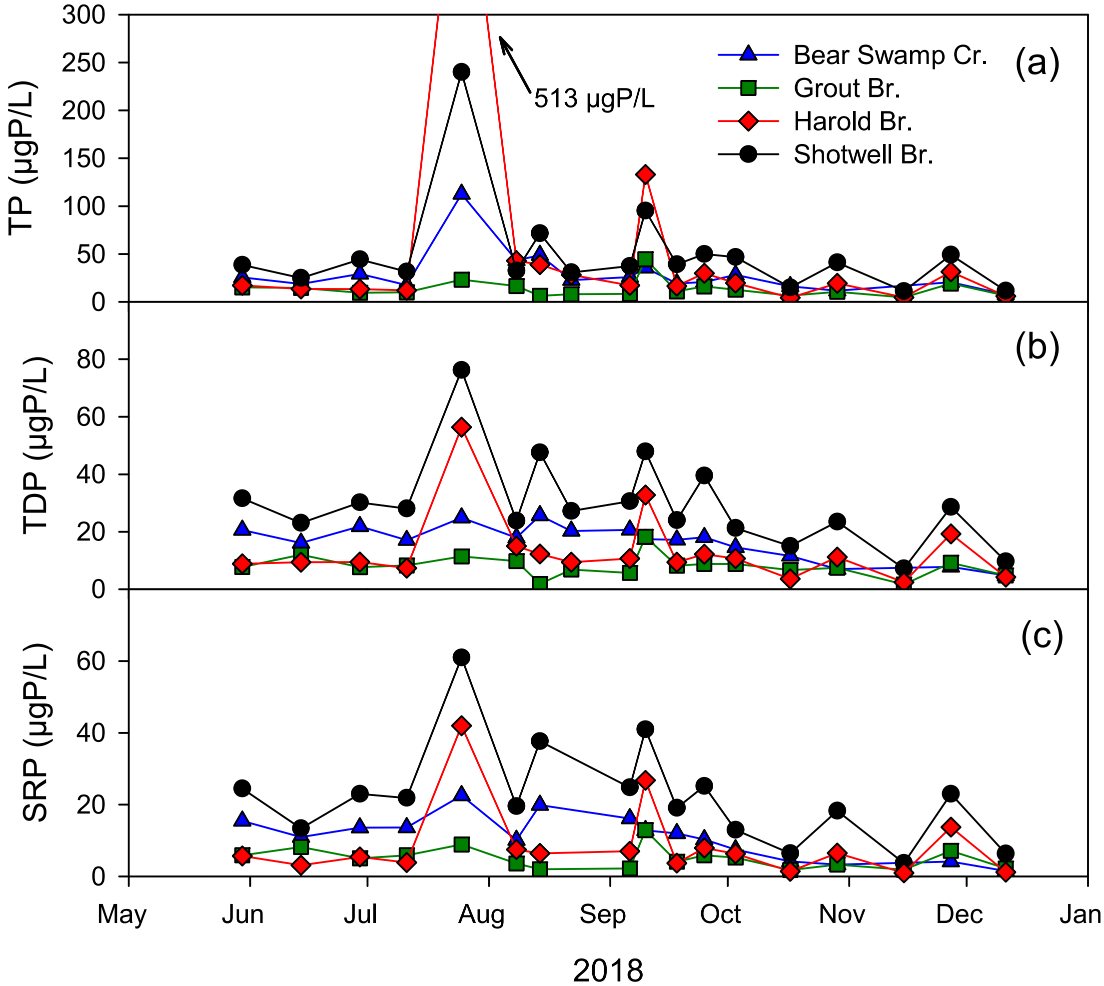

Figure 15. Time series of: (a) total phosphorus (TP), (b) total dissolved phosphorus (TDP), and (c) soluble reactive phosphorus (SRP) for Bear Swamp Creek, Grout Brook, Shotwell Brook, and Harold Brook.

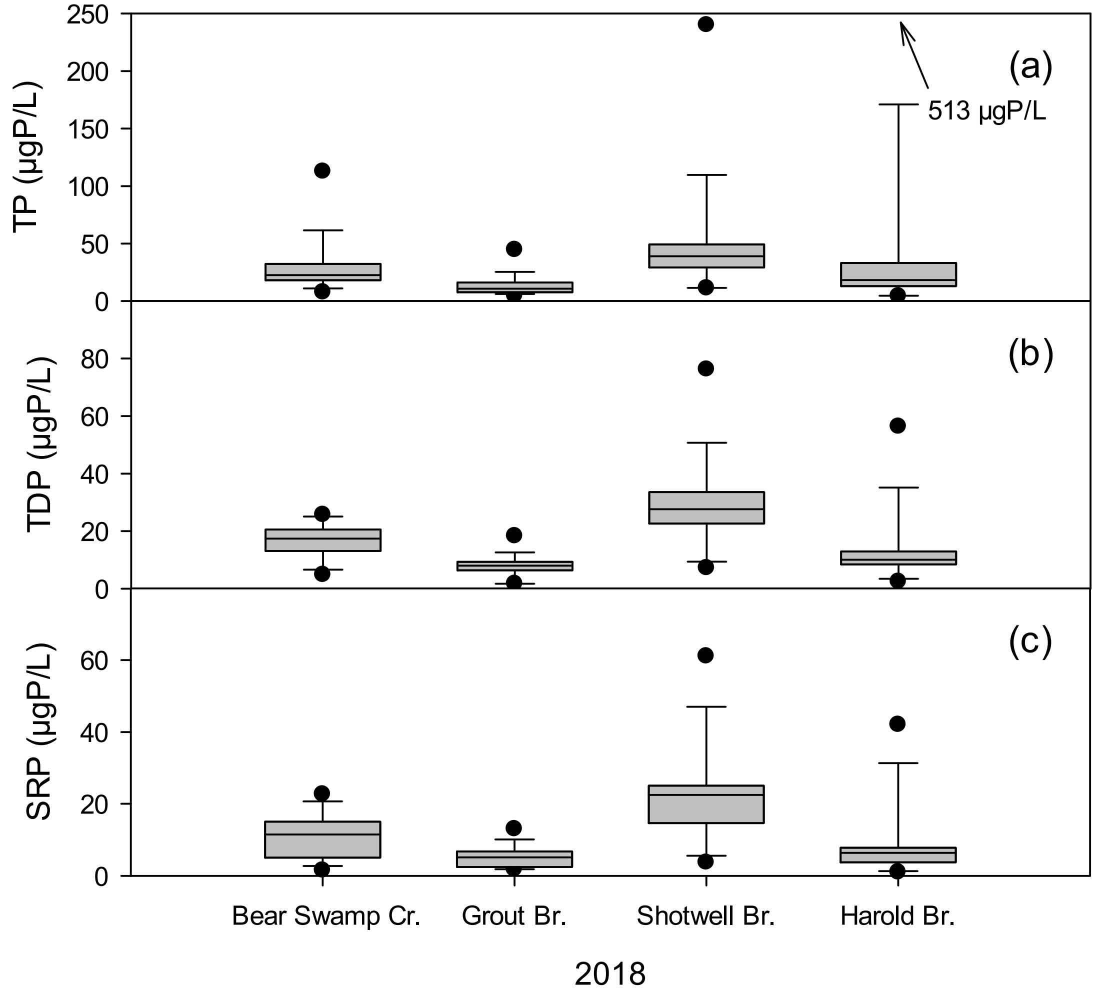

Figure 16. Box and Whisker plots for (a) total phosphorus (TP), (b) total dissolved phosphorus (TDP) and, (c) soluble reactive phosphorus (SRP) for Bear Swamp Creek, Grout Brook, Shotwell Brook, and Harold Brook. Box and Whisker graph representing statistical values for different phosphorus parameters. The bottom boundary of the box closest to zero represents the 25^{th} percentile, the line in the box marks the media, and the boundary of the box farthest from zero indicates the 75^{th} percentile. Whiskers above and below the box indicate the 90^{th} and 10^{th} percentiles and the black circles indicate statistical outliers.

4.3.2. Nitrogen

Samples were collected on 18 occasions during the late May to mid-December interval of 2018 for analysis of three forms of nitrogen: total nitrogen (TN), nitrate+nitrite (NOx), and total ammonia (T-NH_3). Total nitrogen concentrations in these streams were dominated by the NOx form (Figure 17, Table 3). Except for the short-term increases observed at Shotwell Brook on May 30 (T-NH_3), July 25 (TN, NOx, T-NH_3), and October 30 (T-NH_3), nitrogen concentrations remained fairly uniform during the study period (Figure 17). Harold Brook had the highest concentrations of both TN and NOx, followed by Shotwell Brook, Grout Brook, and Bear Swamp Creek (Figure 18, Table 3). The highest T-NH3 concentrations were measured in Shotwell Brook (Figure 17c, 18c). Watersheds with more extensive agricultural land cover (e.g., Harold, Shotwell) tended to export more nitrogen. Relatively low levels of nitrogen export from the Bear Swamp Creek watershed may be associated with denitrification of NOx in wetlands where anoxic conditions prevail.

Bear Swamp Creek

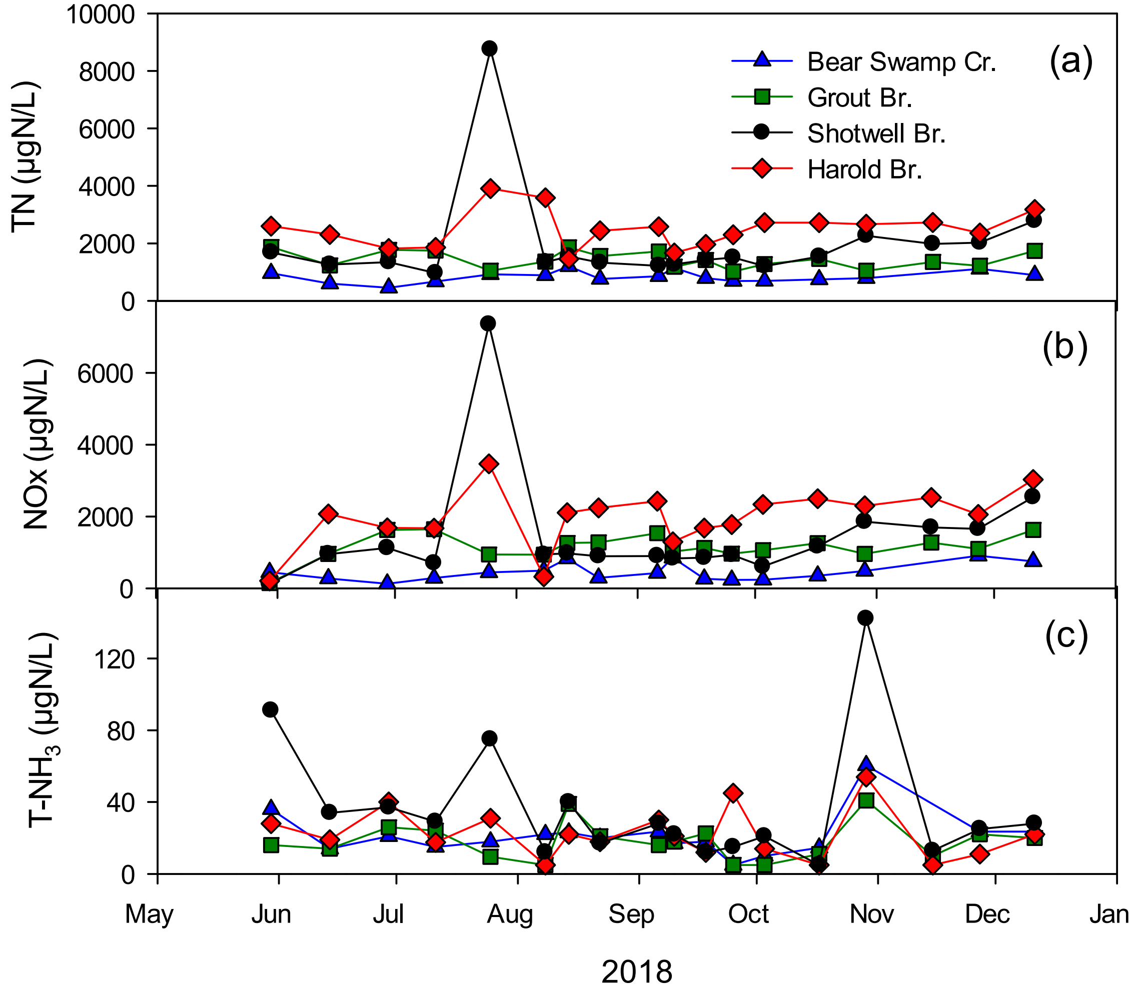

Figure 17. Time series of: (a) total nitrogen (TN), (b) nitrate + nitrite (NOx) and, (c) ammonia ($T\text{-}NH_3$) for Bear Swamp Creek, Grout Brook, Shotwell Brook, and Harold Brook.

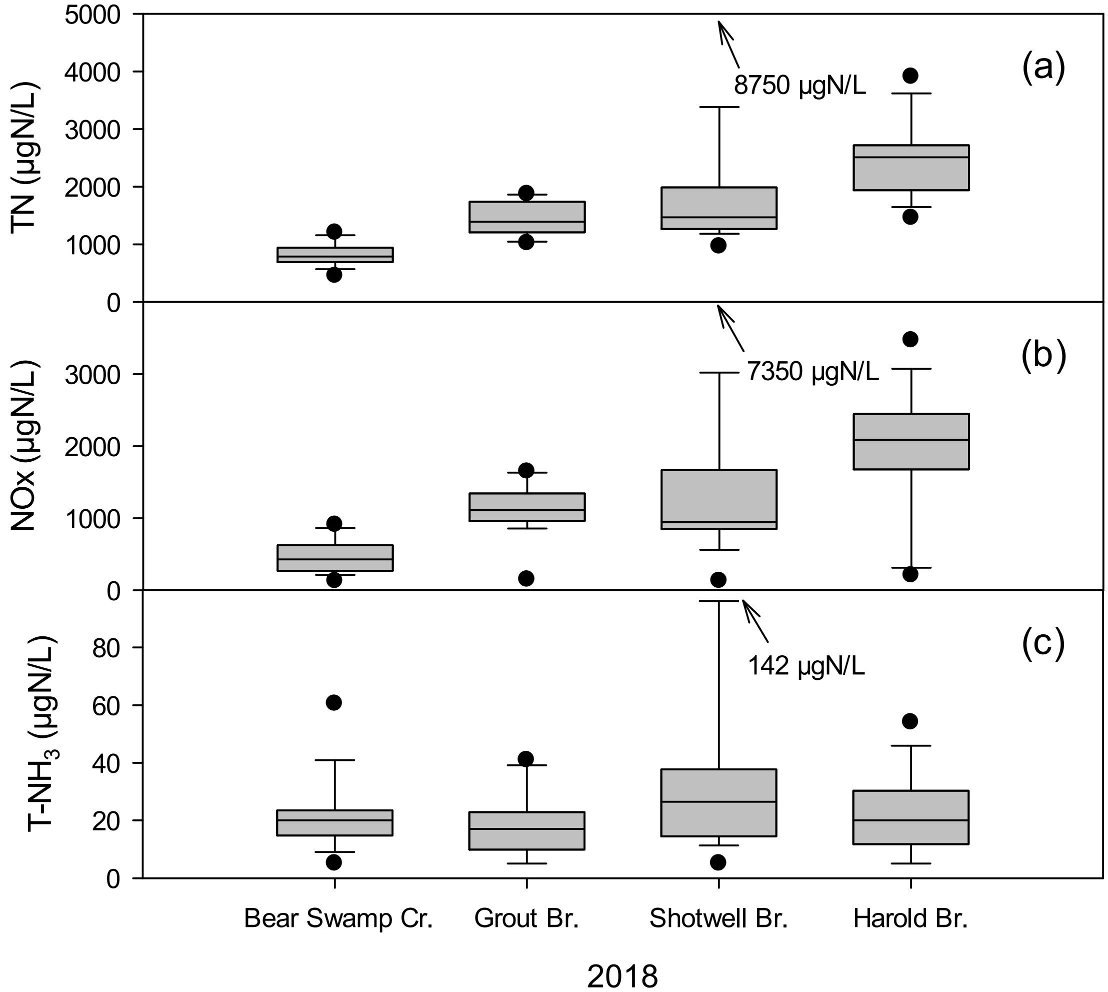

Figure 18. Box and Whisker plots for (a) total nitrogen (TN), (b) nitrate + nitrite (NOx) and, (c) ammonia (T-NH_3) for Bear Swamp Creek, Grout Brook, Shotwell Brook, and Harold Brook. Box and Whisker graph representing statistical values for different phosphorus parameters. The bottom boundary of the box closest to zero represents the 25th percentile, the line in the box marks the media, and the boundary of the box farthest from zero indicates the 75th percentile. Whiskers above and below the box indicate the 90th and 10th percentiles and the black circles indicate statistical outliers.

4.3.3. Carbon

Samples were collected on 18 occasions during the late May to mid-December interval of 2018 for analysis of two forms of carbon: dissolved organic carbon (DOC) and particulate organic carbon (POC). Concentrations of DOC were highest in Bear Swamp Creek (median=5.9 mg/L), followed by Shotwell Brook (5.3 mg/L), Harold Brook (3.1 mg/L), and Grout Brook (1.8 mg/L; Figure 19a, 20a, Table 3). The highest DOC concentrations of the study were measured on July 25 (Figure 19a), during a period of heavy rainfall. A total of 3.27 inches of rain was recorded at Auburn during July 24-26. Concentrations of POC varied from 0.02 to 1.49 mg/L and averaged 0.30 mg/L across all four streams (Figure 19b, 20b, Table 3). No organized spatial or temporal patterns were apparent from the POC data.

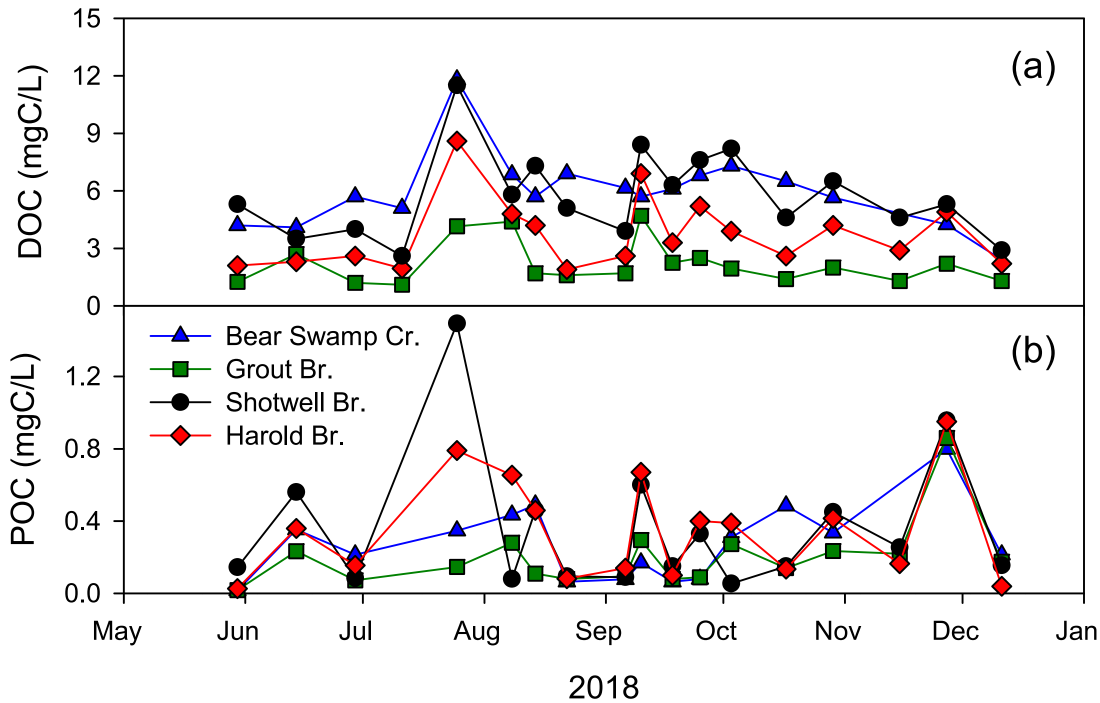

Figure 19. Time series of: (a) dissolved organic carbon (DOC) and (b) particulate organic carbon (POC) for Bear Swamp Creek, Grout Brook, Shotwell Brook, and Harold Brook.

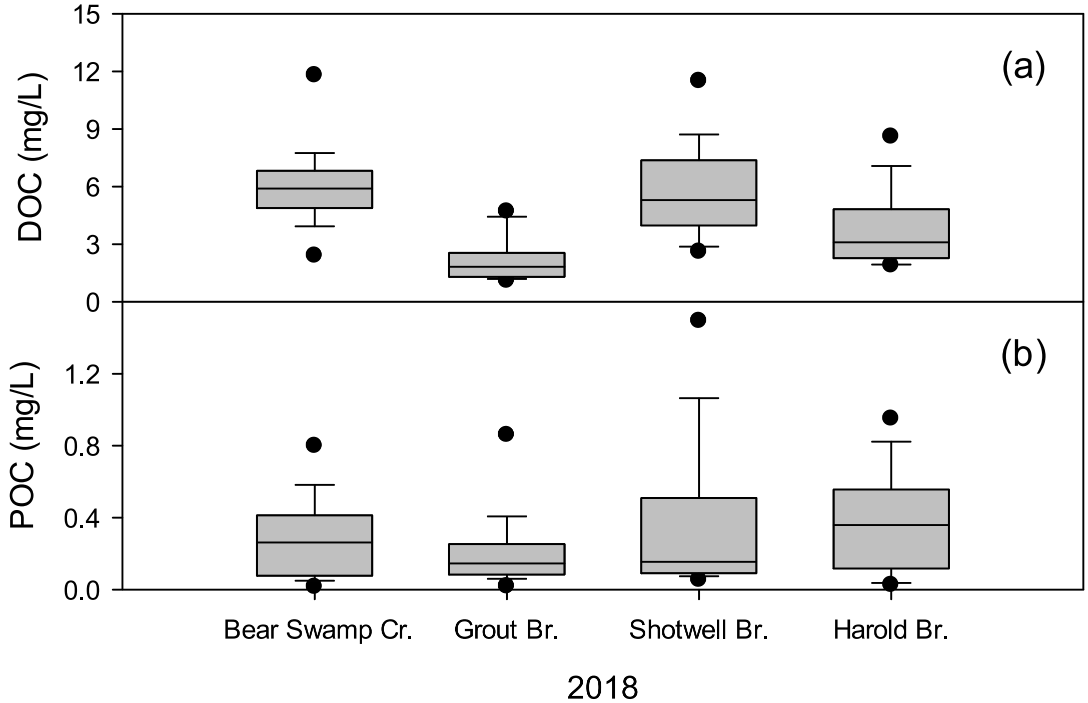

Figure 20. Box and Whisker plots for (a) dissolved organic carbon (DOC and (b) particulate organic carbon (POC) for Bear Swamp Creek, Grout Brook, Shotwell Brook, and Harold Brook. Box and Whisker graph representing statistical values for different phosphorus parameters. The bottom boundary of the box closest to zero represents the 25th percentile, the line in the box marks the media, and the boundary of the box farthest from zero indicates the 75th percentile. Whiskers above and below the box indicate the 90th and 10th percentiles and the black circles indicate statistical outliers.

4.3.4. Silica, Total Suspended Solids, Turbidity

Samples were collected on 18 occasions during the late May to mid-December interval of 2018 for analysis of silica (SiO_2), total suspended solids (TSS), and turbidity (Tn). Silica concentrations, which were relatively low in each of the four streams during June (< 5 mg/L), increased to 5-8 mg/L for the remainder of the study (Figure 21a). Grout Brook had the highest SiO_2 concentrations, followed by Shotwell Brook, Harold Brook, and Bear Swamp Creek (Figure 22a, Table 3). Concentrations of TSS were generally low, with 75% of the samples results less than 10 mg/L. However, much higher TSS concentrations were measured at Harold Brook, Shotwell Brook, and Bear Swamp Creek during periods of elevated precipitation in late July and early August (Figure 21b). It's interesting that TSS levels in Grout Brook remained low during these high flow periods. Based on the relatively modest increases in stage at Grout Brook during these events, we hypothesize that rainfall totals were greater in areas further to the north. Spatial and temporal patterns observed for Tn closely matched the patterns described for TSS (Figure 21c, 22c). This is not surprising given that both of these measurements are related to the quantity of particles suspended in the water.

Grout Brook

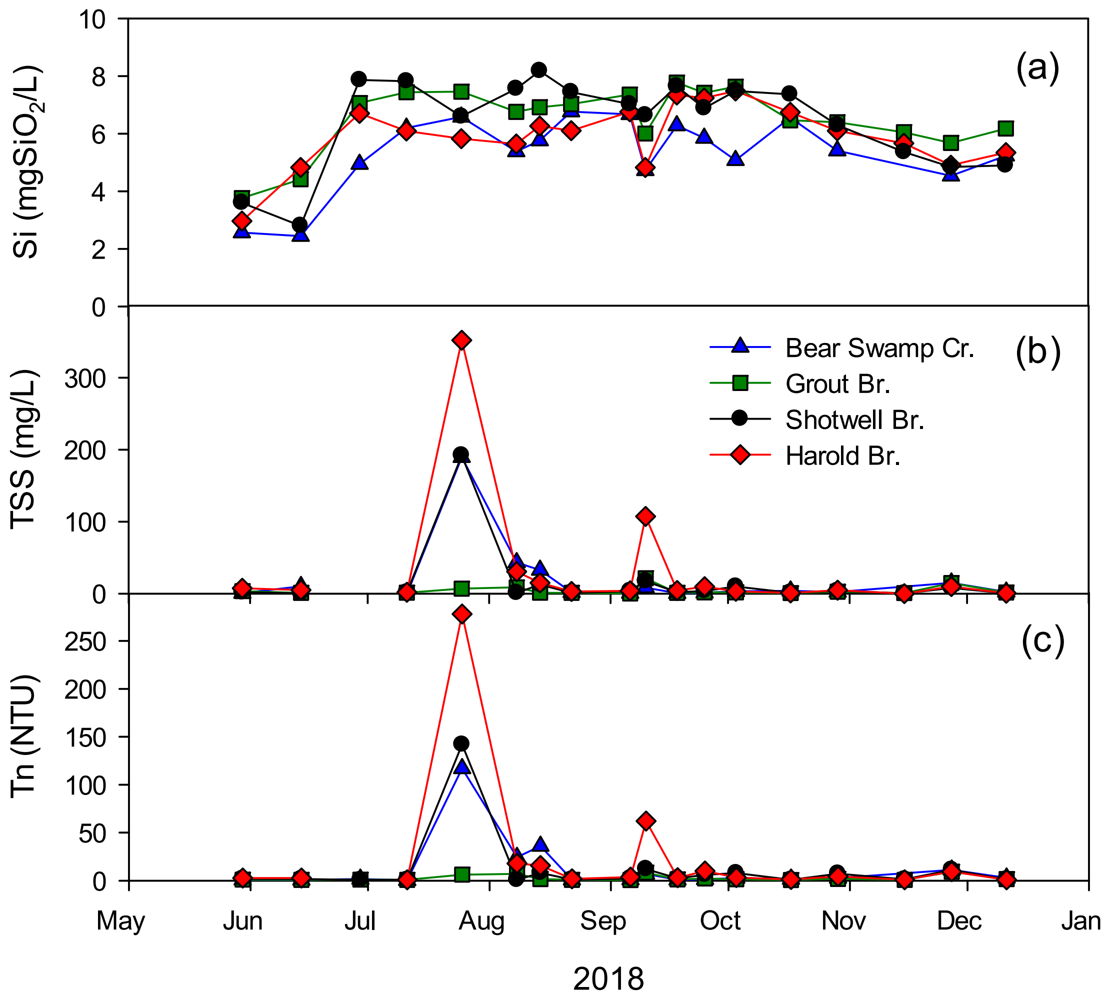

Figure 21. Time series of: (a) silica (SiO_2), (b) total suspended solids (TSS) and, (c) turbidity (Tn) for Bear Swamp Creek, Grout Brook, Shotwell Brook, and Harold Brook.

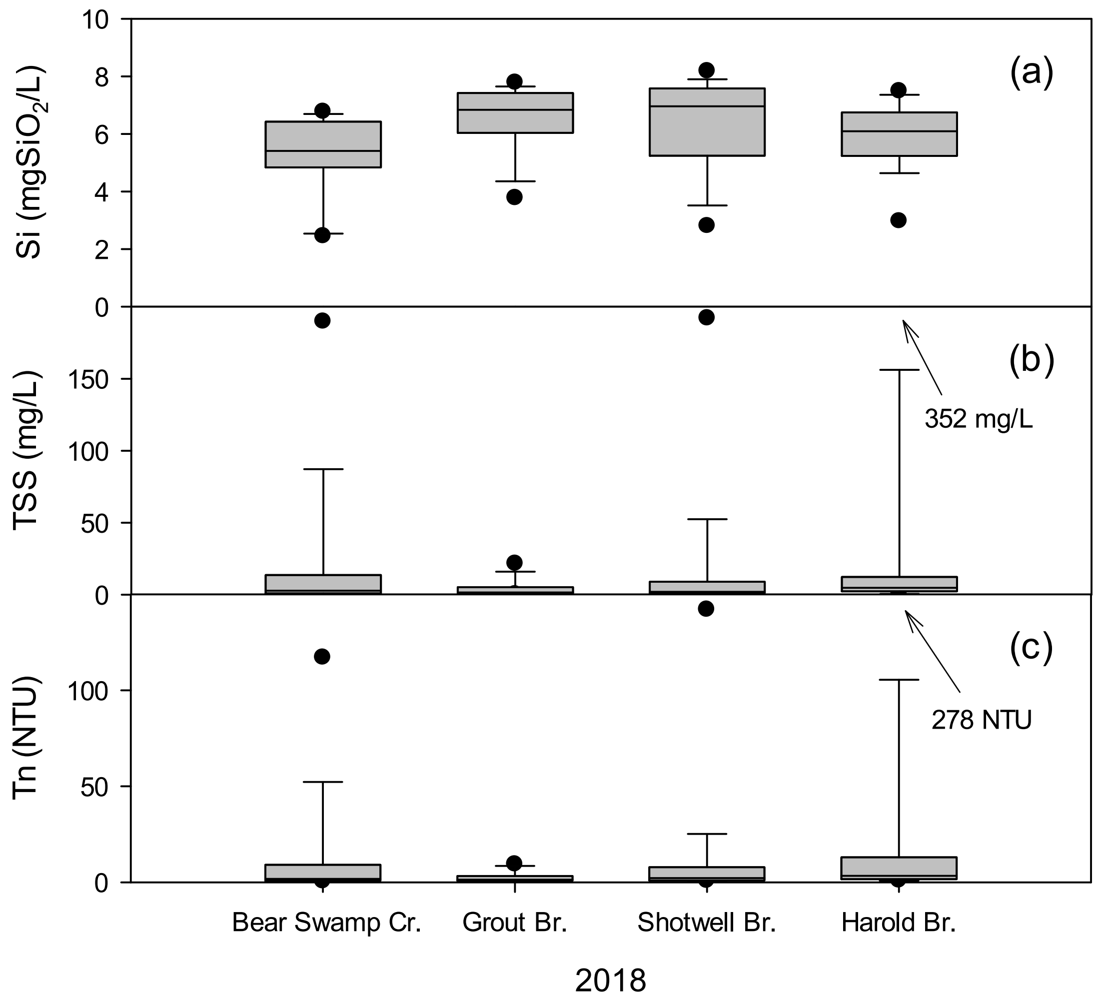

Figure 22. Box and Whisker plots for (a) silica (SiO_2), (b) total suspended solids (TSS) and, (c) turbidity (Tn) for Bear Swamp Creek, Grout Brook, Shotwell Brook, and Harold Brook. Box and Whisker graph representing statistical values for different phosphorus parameters. The bottom boundary of the box closest to zero represents the 25th percentile, the line in the box marks the media, and the boundary of the box farthest from zero indicates the 75th percentile. Whiskers above and below the box indicate the 90th and 10th percentiles and the black circles indicate statistical outliers.

Table 3. Statistical summary of water quality parameters measured in the laboratory.

Parameter	Bear Swamp Creek			Grout Brook			Shotwell Brook			Harold Brook		
	n	median	mean	n	median	mean	n	median	mean	n	median	mean
TP (µg/L)	18	24.3	30.5	18	10.9	13.6	18	39	50	18	18.4	53.5
TDP (µg/L)	18	17.4	16.8	18	8	8.1	18	27.7	29.7	18	10.1	13.6
SRP (µg/L)	18	11.0	11.1	18	5.2	5.3	17	22.5	23.5	18	6.4	9.3
TN (µg/L)	18	824	839	18	1395	1441	18	1470	1972	18	2510	2494
NOx (µg/L)	18	437	458	18	1115	1154	18	951	1454	18	2090	1986
tNH3 (µg/L)	18	19	21	18	17	18	18	27	36	18	20	22
DOC (mg/L)	18	5.9	6.0	18	1.8	2.2	18	5.3	5.7	18	3.1	3.7
POC (mg/L)	18	0.31	0.29	18	0.14	0.20	18	0.16	0.36	18	0.36	0.34
SiO2 (mg/L)	18	5.4	5.4	18	6.8	6.5	18	7.0	6.5	18	6.1	5.9
TSS (mg/L)	18	3.2	21.1	18	1.7	4.3	18	2.1	15.5	18	4.8	33
Tn (NTU)	18	2.1	13.2	18	1.4	2.7	18	2.1	11.6	18	3.3	24.6

5. Summary and Conclusions

With support from the Skaneateles Lake Association, UFI conducted a robust monitoring program of the four largest tributaries to Skaneateles Lake (Bear Swamp Creek, Grout Brook, Shotwell Brook, Harold Brook) during the late May to mid-December interval of 2018. Detailed measurements of stream stage, cross-sectional area, and velocity supported the development of rating curves, which were used to estimate streamflow. Measurements of stream stage, temperature, specific conductance, and turbidity were made at 15-minute intervals with sensors deployed in each of the four streams. Water samples were collected at each stream during 15 biweekly surveys and three high flow events. These samples were analyzed in UFI's laboratory for a suite of water quality parameters consisting of total phosphorus (TP), total dissolved phosphorus (TDP), soluble reactive phosphorus (SRP), total nitrogen (TN), nitrate+nitrite (NOx), total ammonia (T-NH_3), dissolved organic carbon (DOC), particulate organic carbon (POC), silica (SiO_2), total suspended solids (TSS), and turbidity (Tn).

The results of this monitoring program were evaluated in the context of local meteorological conditions and with an eye toward the development of material loading estimates to inform future modeling efforts and a Nine Element Plan for Skaneateles Lake. Noteworthy findings from the 2018 stream monitoring program are listed below.

- Rating curves developed for Grout Brook, Shotwell Brook, and Harold Brook are quite strong and should produce reasonable estimates of streamflow. However, additional measurements are needed during high flow to produce rating curves that are valid over a wider range of conditions.
- Streamflow estimates for Bear Swamp Creek were not strongly correlated with measurements of stream stage, resulting in an unsatisfactory rating curve. Future

monitoring should focus on appropriate placement of the pressure sensor and evaluation of protocols to improve velocity measurements. Operation of upstream impoundments and the potential for backflow from the lake should also be assessed.

- Stream stage was responsive to both short-term rainfall events and longer-term seasonal patterns. Streamflow generally increased during late summer and fall in response to larger rainfall events and the seasonal decrease in evapotranspiration. Harold Brook was found to be a relatively flashy stream, characterized by large increases in stage during rainfall events.
- Major runoff events caused decreases in specific conductance attributable to dilution of more saline groundwater. Conspicuous short-lived spikes in turbidity (>1,000 NTU) were observed during periods of high flow in each of the four streams, representing the transport of particulate material from the watershed to the lake.
- Base flow was higher and water temperature was lower in Grout Brook than in the other three streams. Specific conductance and turbidity values were shifted higher in Shotwell Brook and Harold Brook, the two watersheds with the lowest forest land cover and the highest percentage of agricultural land use.
- Phosphorus concentrations were highest in Shotwell Brook and lowest in Grout Brook. Levels of dissolved phosphorus (TDP, SRP) were also elevated in Bear Swamp Creek, despite a watershed with high percentages of forest (64%) and wetland (10%) land cover.
- Harold Brook had the highest nitrogen concentrations, followed by Shotwell Brook, Grout Brook, and Bear Swamp Creek. This ranking corresponds to the level of agricultural land use in these watersheds.
- Concentrations of DOC were highest in Bear Swamp Creek and lowest in Grout Brook. Median concentrations of POC in Harold Brook and Bear Swamp Creek were roughly double levels measured in Grout Brook and Shotwell Brook
- Silica concentrations were similar in Grout Brook, Shotwell Creek, and Harold Brook and shifted lower in Bear Swamp Creek.
- Although TSS and Tn were highest in Harold Brook, elevated values were also measured in Shotwell Brook and Bear Swamp Creek during periods of elevated streamflow. TSS and Tn were uniformly low in Grout Brook.

Another year of comprehensive monitoring of these four streams is recommended to capture a broader range of conditions and more fully characterize water quantity and water quality. Future monitoring should attempt to capture a wider range of streamflow, with particular emphasis on major runoff events. A more robust rating curve needs to be developed for Bear Swamp Creek in particular to support reasonably accurate estimates of streamflow. Additionally, a monitoring program for the numerous small streams that enter Skaneateles Lake should be considered. A noteworthy shortcoming of the 2018 Skaneateles Lake tributary monitoring program is the lack of measurements during spring. Rainfall and snowmelt during spring often trigger major runoff events that deliver a disproportionate fraction of the annual material load to lakes. Spring monitoring should be emphasized in future monitoring efforts to support a Nine Element Plan and development of both watershed and in-lake models.

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