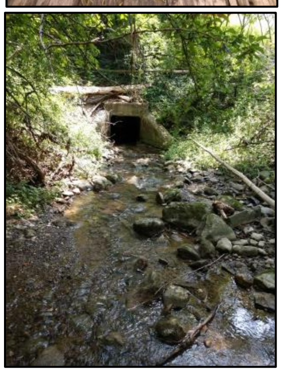
Water quality and flow of ten tributaries to Skaneateles Lake, 2019

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Cover images (l-r: top): View from Randall Gulf of Skaneateles Lake, Glen Cove, View of eastern side of Skaneateles Lake; (l-r: bottom) Upper Bear Swamp, Harold Brook

1. Introduction

1.1. Skaneateles Lake: Characteristics, use, and management

Skaneateles Lake is located in central New York within Onondaga, Cortland, and Cayuga counties (Figure 1a); this area is known as the "Finger Lakes" region due to the presence of eleven long, narrow lakes formed by a receding glacier. The lake is the second easternmost Finger Lake (Figure 1b) and approximately 19 km south-southwest of Syracuse, NY and 8 km east of Auburn, NY. The Village of Skaneateles lies at the northern end of the lake, at the outflow; the lake is oriented along a north/northwest and south/southeast axis. Of the eleven Finger Lakes, Skaneateles Lake is the third deepest (maximum = 90.5 m, mean = 43.5 m), has the fourth largest volume ($1{,}563 \times 10^6$ m^3), and has the fifth smallest surface area (35.9 km^2; Schaffner and Oglesby 1978).

Skaneateles Lake is classified by New York State as an AA waterbody; under the highest rating, water from the lake can be used for potable purposes and must meet certain water quality criteria established by the New York State Department of Health (NYSDOH). The City of Syracuse uses the lake as its primary source of water, and maintains an active watershed management program (i.e. Skaneateles Lake Watershed Agricultural Program) in order to protect water quality. Two intakes located in the northern end of the lake, approximately 1.3 and 2 km south of the Village of Skaneateles, withdraw the drinking water. Skaneateles Lake is also used recreationally for swimming, boating, and fishing.

Skaneateles Lake has a relatively small watershed (154 km^2) and is made up of primarily agricultural (36%) and forested (34%) lands with very little residential and commercial development. According to the 2017 Harmful Algal Bloom Action Plan for Skaneateles Lake (NYSDEC 2017), an estimated 80% of nonpoint source phosphorus loading, a potential trigger for harmful algal blooms (HABs), was attributed to agricultural land within the watershed. One way to manage water quality within the lake is to manage the watershed; best management practices are intended to improve the quality and/or lessen the quantity of water entering the lake via the tributaries.

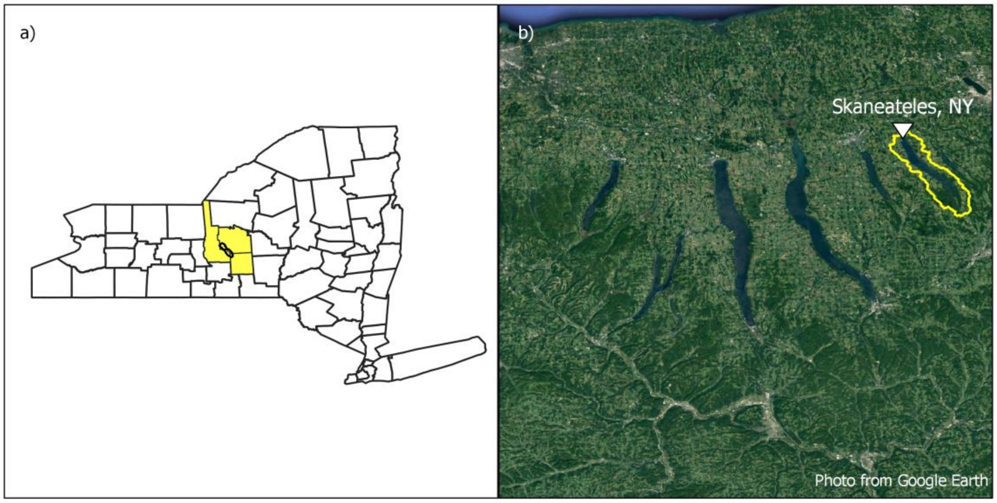

Figure 1. Location of Skaneateles Lake and its watershed in (a) New York and (b) the Finger Lakes region.

1.2. Major tributaries

The four largest tributaries to Skaneateles Lake are considered “major” tributaries due to the size of their subwatersheds (≥ 5 km^2) and potential influence on water quality of the lake (Figure 2). The major tributaries include Bear Swamp Creek, Grout Brook, Shotwell Brook, and Harold Brook. These tributaries have had little previous monitoring, except water quality and streamflow were monitored in 2018 by Upstate Freshwater Institute (UFI) with funding from the Skaneateles Lake Association. As of May 15, 2019, the United States Geological Survey (USGS) installed a gage on Grout Brook, about 1 mile upstream of the UFI monitoring location. Drainage areas for the majority of these tributaries are not available from the United States Geological Survey (USGS) and have been estimated. The drainage areas in this report were delineated in the online tool StreamStats (USGS 2016) and resemble values reported by Pradhanang (2009) more so than previous reports (UFI 2019, OBG 2019).

Grout Brook has the largest watershed (27 km^2) of the four major tributaries. It is a second order stream that enters at the most southern end of the lake. A majority of the watershed is forested (60%); however, there is substantial amount of agricultural land in the eastern portion of the subwatershed (Table 1; Figure 2).

Bear Swamp Creek is a second order stream with the second largest drainage area (24 km^2). The watershed of Bear Swamp Creek has the largest portion of forested land (62%; Table 1). Upstream portions of the tributary run through wetlands and a state-owned forest preserve (See Section 1.3 for additional description of upstream conditions).

Shotwell Brook enters Skaneateles Lake in the northeast corner of the lake, approximately 3 km south-southeast of the Village of Skaneateles and 1.5 km southeast of the drinking water intakes. It has the third largest watershed of the major tributaries (8.6 km^2). The watershed of Shotwell Brook has the largest percentage of developed land of the major tributaries (7%); however, a majority of the land is used for agriculture (64%; Table 1; Figure 2). Streamflow and select water quality parameters (i.e. turbidity and forms of phosphorus) of Shotwell Brook have been monitored annually since 2016 by UFI with funding from the Town of Skaneateles.

Harold Brook is a second order stream located in the northwest region of the lake, approximately 4 km southwest of the drinking water intakes. Of the four major tributaries, Harold Brook has the smallest drainage area (5 km^2), but it has the largest percentage of agricultural land (73%; Table 1; Figure 2).

Table 1. Drainage area (km^2) and land cover (%) of major tributaries to Skaneateles Lake. Area delineated from StreamStats (USGS 2016). Land cover from 2016 National Land Cover Dataset (Yang et al. 2018).

Tributary	Area (km^2)	Pasture and hay (%)	Cultivated crops (%)	Forest and grasslands (%)	Developed (%)	Wetlands (%)	Other (%)
Grout Brook	27	18	13	60	5	2	2
Bear Swamp Creek	24	7	15	62	4	10	2
Shotwell Brook	9	21	43	20	7	7	2
Harold Creek	5	8	65	17	4	5	1

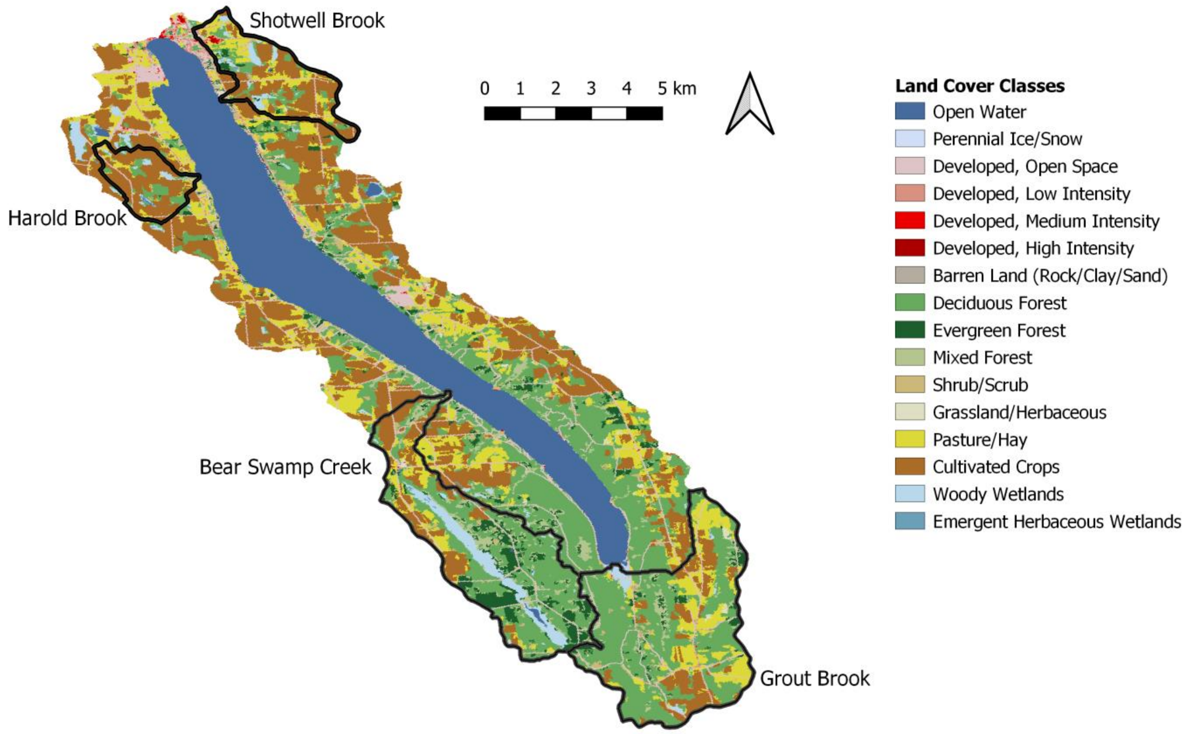

Figure 2. Boundaries of the subwatersheds of major tributaries to Skaneateles Lake and associated land uses. Areas delineated from StreamStats (USGS 2016). Land cover from 2016 National Land Cover Dataset (Yang et al. 2018).

1.3. Minor tributaries

Major tributaries are not the only hydrologic inputs to Skaneateles Lake; however, very little quantitative data about the "minor" tributaries exists. A gap analysis indicated that water quality and flow information from six minor tributaries would be of significant value to future water quality modeling efforts (OBG 2019). The minor tributaries selected for monitoring in 2019 include: Randall Gulf, Snow Brook, One Mile Creek, Five Mile Brook, and Glen Cove. Additionally, an upstream location of Bear Swamp Creek (a major tributary) was selected based on the potential for water quality differences compared to downstream. The watersheds of the minor tributaries are smaller than the major tributaries (≤ 5 km^2); the drainage areas listed here are approximated as there are no USGS gages present on any of the minor tributaries. Qualitative observations by local residents suggest that some of the selected minor tributaries are ephemeral in nature, meaning that the streambed is sometimes dry or contains only pools of water.

The upstream location of Bear Swamp Creek (known hereafter as Upper Bear Swamp) is located at the southernmost end of the Bear Swamp Creek watershed (Figure 3). The approximately 5 km^2 watershed is mostly within a state-owned forest preserve and has the highest percentage of forested land relative to the other minor tributaries (76%; Table 2). This upstream monitoring location was selected because wetlands and upstream damming by beavers may affect the stream stage (depth) and water quality at the mouth (Pradhanang 2009, OBG 2019).

Five Mile Creek has the second largest watershed of the minor tributaries (4 km^2). It is located approximately 9 km south southeast of the Village of Skaneateles. Over 50% of the watershed is used for agricultural purposes (Table 2). Members of Syracuse University monitored stream stage, temperature, and water quality (i.e. phosphorus) of Five Mile Creek in 2019 as well.

Glen Cove is located in the southern portion of the lake (Figure 3). Of the 3 km^2 watershed, a majority (63%) is agricultural land (Table 2). Water quality in this tributary was also monitored by Syracuse University during the summer of 2019.

Randall Gulf is also located in the southern portion of the lake (Figure 3). The 3 km^2 watershed is mostly forested (53%), but also has substantial agricultural usage (42%; Table 2).

Undergraduate research was completed here by students from the State University of New York College of Environmental Science and Forestry (SUNY-ESF) in 2016-2017 (Carris 2018).

Snow Brook enters the lake near the Skaneateles Sailing Club, and the mouth is 4 km from the drinking water intakes. The tributary has a drainage area of 1.5 km^2 and is mostly comprised of cropland (Table 2). Undergraduate research has been completed here by students from SUNY-ESF in 2016-2017 (Carris 2018).

One Mile Creek is located in the northern portion of the lake at Mile Point, approximately 2 km south of the Village of Skaneateles and 1 km west of the drinking water intakes. Even though it has the smallest drainage area of the minor tributaries (1 km^2), the watershed is the most developed (41%; Table 2). The developed land is mostly characterized as developed open space (i.e. golf course and country club). Water quality in this tributary was also monitored by Syracuse University during the summer of 2019.

Table 2. Drainage area (km^2) and percent land cover of minor tributaries to Skaneateles Lake. Area delineated from StreamStats (USGS 2016). Land cover from 2016 National Land Cover Dataset (Yang et al. 2018).

Tributary	Area (km^2)	Pasture and hay (%)	Cultivated crops (%)	Forest and grassland (%)	Developed (%)	Wetlands (%)	Other (%)
Upper Bear Swamp	5.4	3	4	76	3	11	3
Five Mile Creek	3.6	8	49	28	4	3	8
Glen Cove	2.7	26	37	26	6	3	2
Randall Gulf	2.6	20	22	53	3	0	2
Snow Brook	1.5	3	70	21	3	0	3
One Mile Creek	1.1	32	26	0	41	0	1

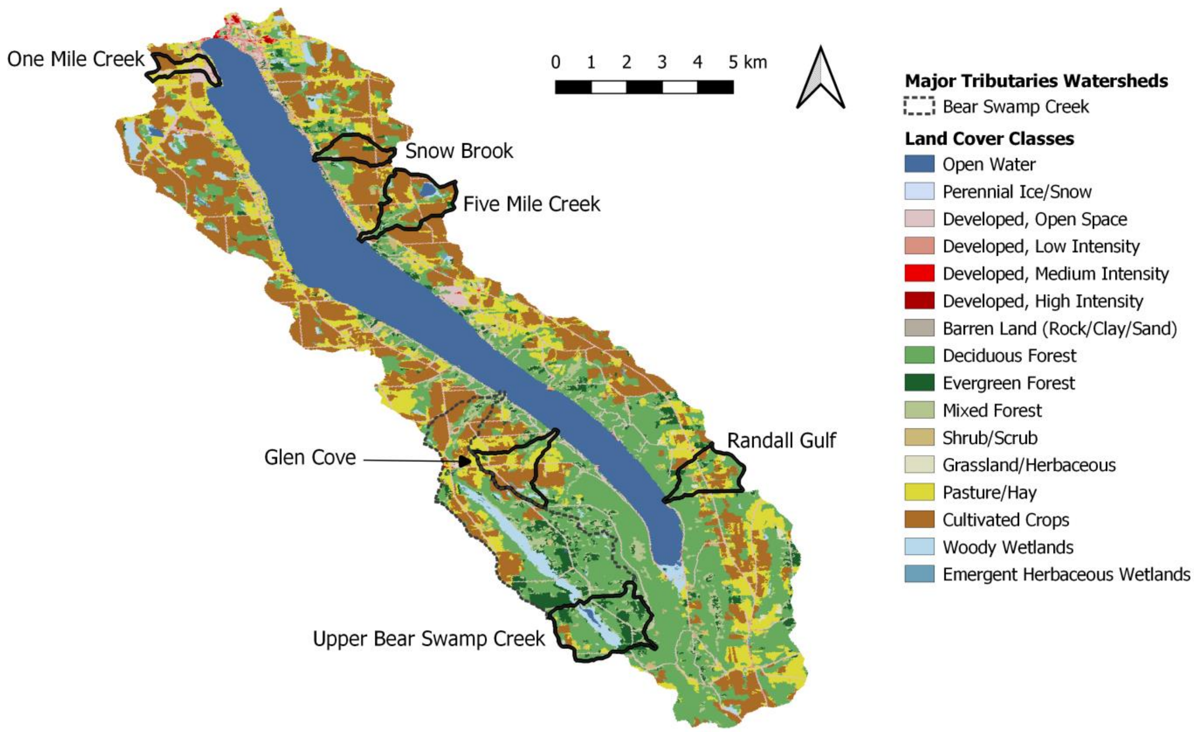

Figure 3. Boundaries of the subwatersheds of the minor tributaries to Skaneateles Lake and associated land uses. Areas delineated from StreamStats (USGS 2016). Land cover from 2016 National Land Cover Dataset (Yang et al. 2018).

1.4. Objectives

The overall goal of the 2019 major and minor tributary monitoring programs was to collect data in the tributaries of Skaneateles Lake that can be used in the development of a nine element (9E) watershed management plan and simulation models of Skaneateles Lake and its watershed.

Specific objectives of the major tributary monitoring program include:

1) Develop estimates of streamflow using stream velocity and cross-sectional area measurements over a range of conditions (i.e. high and low flow).
2) Provide near-continuous measurements of select water quality parameters using high frequency measurements from *in-situ* equipment.
3) Describe patterns of constituents affecting water quality during baseflow and high flow conditions.

Specific objectives of the minor tributary monitoring program include:

1) Provide initial flow and water quality measurements to close information gap.
2) Characterize nature of streams using both qualitative and quantitative methods.
3) Develop estimates of streamflow using stream velocity and cross-sectional area measurements over a range of conditions (i.e. high and low flow).
4) Describe patterns of water quality parameters during baseflow and high flow conditions.

2. Methods

2.1. Study areas and sampling period

Four major tributaries to Skaneateles Lake were monitored biweekly from May to November 2019. Bear Swamp Creek, Grout Brook, Shotwell Brook, and Harold Brook were selected based on the size of the drainage area (≥ 5 km^2) and potential influence on the lake (Figure 4). Additional monitoring was completed at all major tributaries during or shortly after 3 rain events during this time period. Three additional sampling events at Shotwell Brook took place before May with funding from the Town of Skaneateles. Each monitoring event consisted of field measurements and water quality sample collection when it was safe to do so.

In addition to the major tributaries, six minor tributaries to Skaneateles Lake were monitored approximately biweekly from May to November 2019. One Mile Creek, Snow Brook, Five Mile Creek, Glen Cove, Randall Gulf, and an upstream portion of major tributary Bear Swamp Creek were selected in order to better understand the character of these smaller tributaries and how they affect the lake or downstream (OBG 2019; Figure 5). Additional monitoring was completed during or shortly after three rain events. Water quality samples were collected on a monthly basis and during rain events; flow measurements were taken when water samples were collected. Monitoring events that did not include water quality and flow measurements were supplemented with visual assessments.

The major tributary sites selected for this monitoring period were utilized by UFI for previous monitoring efforts in 2018 (Table 3). The minor tributary sites were identified and confirmed by the late spring of 2019 (Table 4). Selection of all monitoring sites was determined on the basis of proximity to the mouth of the tributary without the influence of lake water on water quality, convenience in equipment deployment, maintenance, and data collection, and comparison to previous data (Figures 4, 5).

Table 3. Coordinates of sampling locations in major tributaries to Skaneateles Lake.

Tributary	Latitude	Longitude
Bear Swamp Creek	42°49'21.06"N	76°19'46.91"W
Grout Brook	42°45'35.39"N	76°16'12.70"W
Shotwell Brook	42°55'27.70"N	76°24'18.30"W
Harold Brook	42°53'51.44"N	76°25'9.95"W

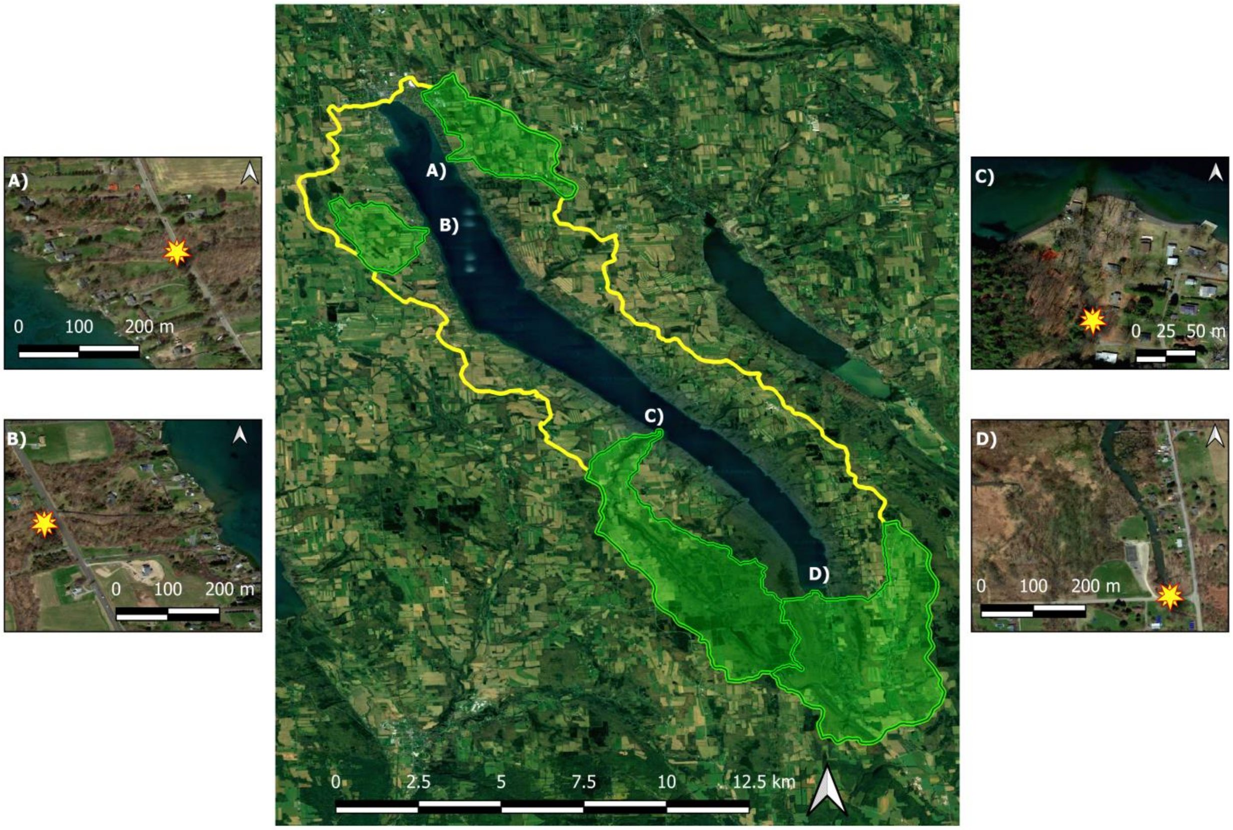

Figure 4. Subwatersheds (green) and mouths of major tributaries to Skaneateles Lake including Shotwell Brook (A), Harold Brook (B), Bear Swamp Creek (C), and Grout Brook (D). Sampling points for each tributary shown in inset maps. Watersheds delineated with StreamStats (USGS 2016). Satellite imagery from Google Earth (2018).

Table 4. Coordinates of sampling locations in minor tributaries to Skaneateles Lake.

Tributary	Latitude	Longitude
Upper Bear Swamp	42°45'5.08"N	76°18'13.78"W
Five Mile Brook	42°52'37.24"N	76°22'38.60"W
Glen Cove	42°48'37.13"N	76°18'41.99"W
Randall Gulf	42°47'11.35"N	76°16'26.23"W
Snow Brook	42°54'13.49"N	76°23'38.44"W
One Mile Creek	42°56'4.11"N	76°25'53.42"W

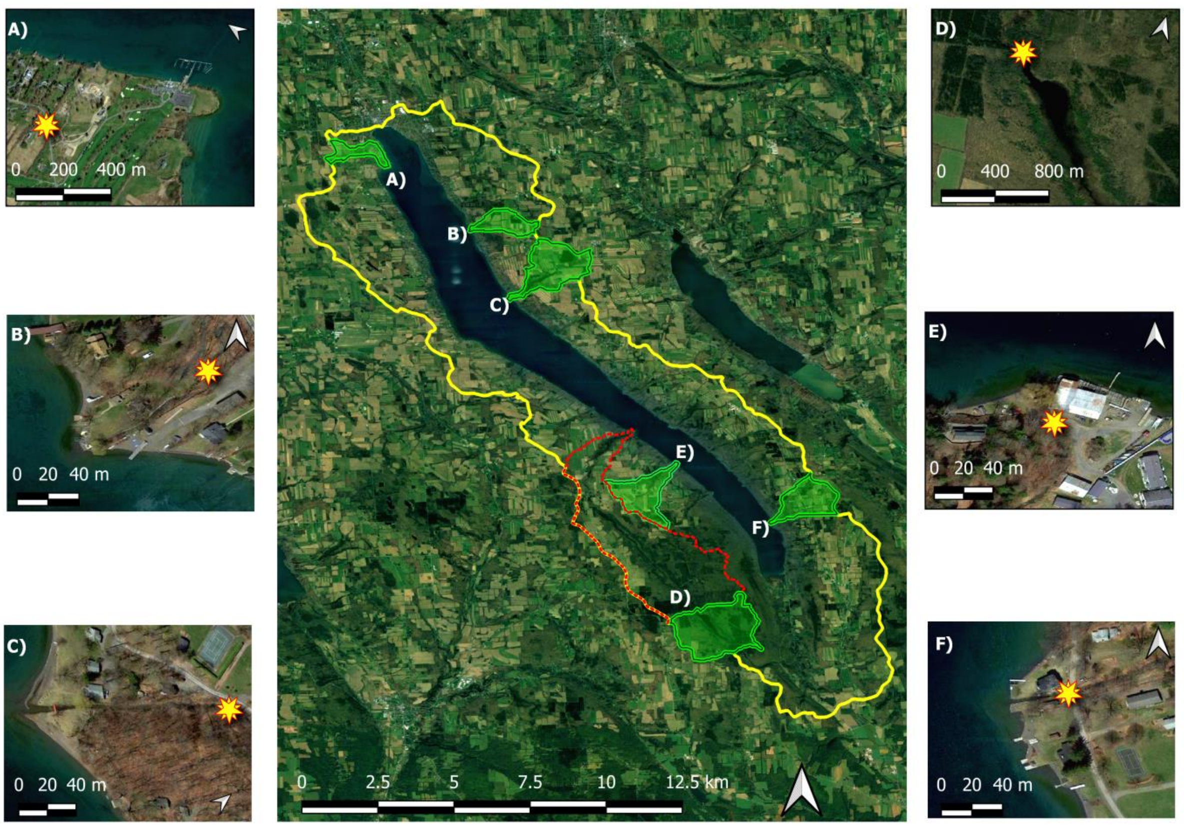

Figure 5. Minor tributaries subwatersheds (green shaded areas) of Skaneateles watershed (yellow line) include One Mile Creek (A), Snow Brook (B), Five Mile Creek (C), upper Bear Swamp Creek (D), Glen Cove (E), and Randall Gulf (F). Bear Swamp Creek is a major tributary (watershed shown in the red dotted line), an upstream sampling point was considered a "minor" tributary for this report. Watersheds delineated with StreamStats (USGS 2016). Satellite imagery from Google Earth (2018).

2.2. Laboratory measurements

Water quality samples were collected as grab samples from accessible areas of the streams (i.e. from bridge, culvert, or wading). Major tributaries were sampled biweekly, whereas minor tributaries were sampled monthly. Both major and minor tributaries were sampled during rain events. Samples were analyzed at UFI's ELAP certified laboratory for the following analytes: total nitrogen (TN), nitrate and nitrite (NO_x), total ammonia (t-NH_3), dissolved organic carbon (DOC), particulate organic carbon (POC), total phosphorus (TP), soluble reactive phosphorus (SRP), total dissolved phosphorus (TDP) dissolved reactive silica (DRSi), total suspended solids (TSS), fixed suspended solids (FSS), volatile suspended solids (VSS), and turbidity (Tn). All analyses were completed using standard methods (Table 5). From these measured parameters, particulate phosphorus (PP) and dissolved organic phosphorus (DOP) were derived as $PP = TP - TDP$ and $DOP = TDP - SRP$.

Table 5. Laboratory analytical methods specification. "SM" refers to Standard Methods (Rice et al. 2012).

Analysis	Method No.
Phosphorus, Orthophosphate (Soluble Reactive Phosphorus as P; SRP)	SM 4500-P G -2011
Phosphorus, Total, Total Dissolved (as P; TP, TDP) low range	SM 4500-P F-H -2011
Nitrogen, Nitrate + Nitrite, Nitrite (as N; NOx, NO2)	SM 4500-NO3 F -2011
Nitrogen, Total Ammonia (as N; T-NH3)	SM 4500-NH3 H -2011
Nitrogen, Total, Total dissolved	SM 4500-N C -2011
Turbidity	SM 2130 B -2011
Particulate organic carbon (as C; POC)	SM 5310 B -2011
Dissolved organic carbon (as C; DOC)	SM 5310 C -2011
Silica, Dissolved Reactive, (as SiO_2;DRSi) high range	SM 4500-SiO2 C -2011
Total Suspended Solids	SM 2540 D -2011
Fixed & Volatile Suspended Solids	SM 2540 E -2011
Specific Conductance	SM 2510- B -2011

2.3. Field measurements

2.3.1. Streamflow

Streamflow (Q; measured in cubic feet per second or cfs) is the product of the cross sectional area (A; measured in ft^2) and velocity (V; measured in ft/s). This is visually represented in Figure 6. Measurements of streamflow are needed during both high and low flow conditions in order to best characterize the flow of the stream. Rating curves, or the statistical relationship between stream depth (stage, S) and streamflow, were developed for each major tributary during this monitoring period using measurements made in the field. Near-continuous flows can be estimated from the rating curves and near-continuous stage measurements collected both in the field and by *in-situ* equipment. Relationships between flow of the minor tributaries and water quality parameters were examined.

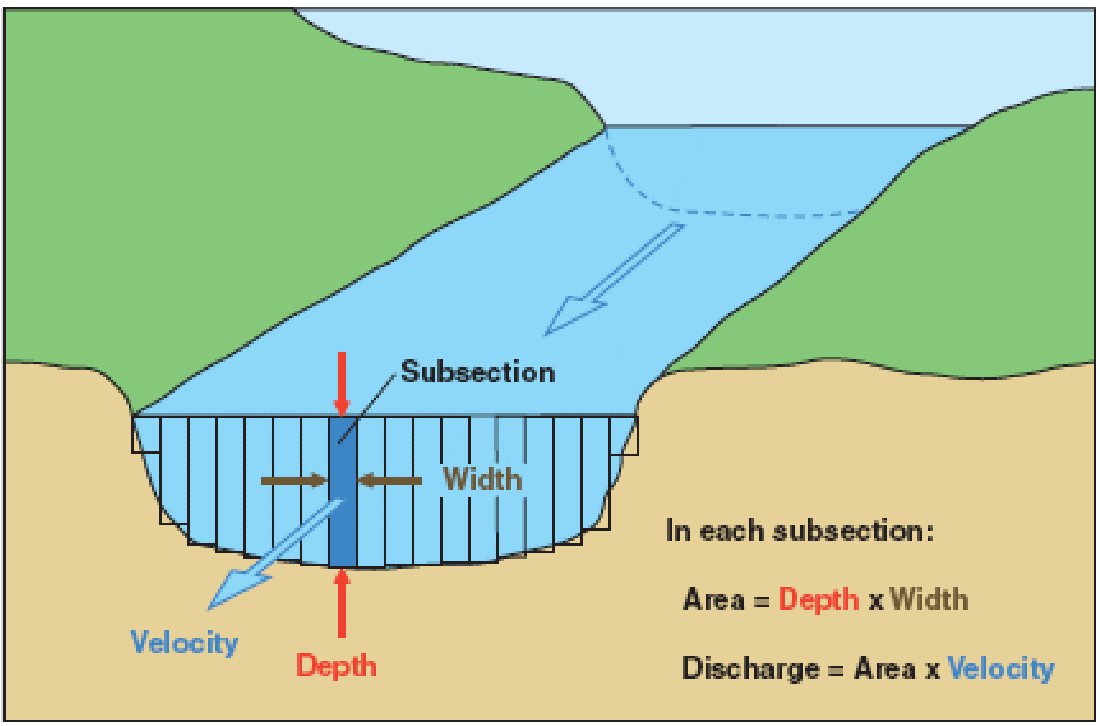

Figure 6. Visual representation of streamflow (discharge) components (Graphic courtesy of USGS).

Cross-sectional area measurements in each tributary were calculated by measuring the depth of the stream at a regular interval across the width of the stream, then geometrically calculating the area for each interval (see Figure 6).

Velocity measurements in the major and minor tributaries were made using a combination of three techniques (float method, electronic velocity meter, and transparent velocity head rod). These methods were chosen in order to provide the most accurate velocity measurements under various conditions (i.e. low and high flow, shallow and deep portions of the streams). When conditions allowed, all three methods of measuring velocity were used in the field. Measurements for each method were attempted at equal intervals across the width of the streams.

2.3.1.a. Float method

The float method is a simple, common technique used to estimate stream velocity (Michaud and Wierenga 2005). A buoyant object, such as a leaf or orange, was timed (in seconds) travelling down the stream over a known distance (in feet). This process was repeated multiple times (typically 5-6) to account for any obstructions or unusual flow patterns. The surface velocity was calculated by dividing the travel time by the reach length. The average flow velocity, or the velocity at the midpoint of the depth of the stream, was estimated by multiplying the surface velocity by 0.85. This adjustment factor is the midpoint of the accepted values of 0.8 and 0.9 (Michaud and Wierenga 2005). The average flow velocity was used for streamflow calculations. This method was not used for all streams because it requires a straight reach.

2.3.1.b. Velocity meter

A Global Water velocity meter (Model FP111) is an electronic instrument that calculates the velocity instantaneously (Global Water Instruments Inc. 2009). The instrument was held perpendicularly to the surface of the stream for 15-30 seconds at multiple points across the width of the stream. The average velocity during this time period was recorded for each point in the stream. An average of the average velocities recorded across the width of the stream was used for comparison to the other methods. This method was not used for all streams because it requires depths greater than or equal to 3 inches and relatively fast flow.

2.3.1.c. Transparent Velocity Head Rod (TVHR)

A transparent velocity head rod (TVHR) is a flat Plexiglas® sheet with two meter sticks attached (Figure 7a). The method and device were based on Fonstad et al. (2005). In order to measure velocity, the TVHR was placed perpendicular to streamflow at multiple points across the width of the stream. At each location, the height of the water (head) was recorded for the upstream, which is visible through the Plexiglas®, and the downstream (Figure 7b). The difference between upstream head and downstream head is used in conjunction with TVHR dimensions to calculate the water velocity. An average velocity of the measurements taken across the width of the stream was used for streamflow calculations. This method was not used during all monitoring events due to safety concerns during high, fast flow events.

Figure 7. Measuring velocity of flow in Shotwell Brook with transparent velocity head rod (TVHR) requires the device to be held upright in stream (a). The difference in the upstream and downstream head (b) is used to calculate the velocity.

2.3.2. *In-situ* equipment – Major tributaries

Measurements at the major tributaries were made nearly-continuously with onsite or *in-situ* monitoring equipment. The equipment was positioned in pools in order to 1) avoid damage during high flow events, 2) maintain position during high flow events, and 3) gather accurate information (Figure 8). *In-situ* measurements of stage were made with a Campbell Scientific model CS450 pressure sensor (Campbell Scientific 2012). A YSI Series 6600 multi-probe datasonde (YSI 2011) positioned near each pressure sensor was used to collect water quality data including temperature, specific conductivity, and turbidity. These instruments were connected to a battery and data logger that recorded data every 15 minutes; the collected data were sent via cellular modem to UFI for storage and analysis. The data from these sensors in addition to measurements from all previous monitoring efforts (2016-2018) were used to create rating curves and estimate near-continuous flow for each major tributary.

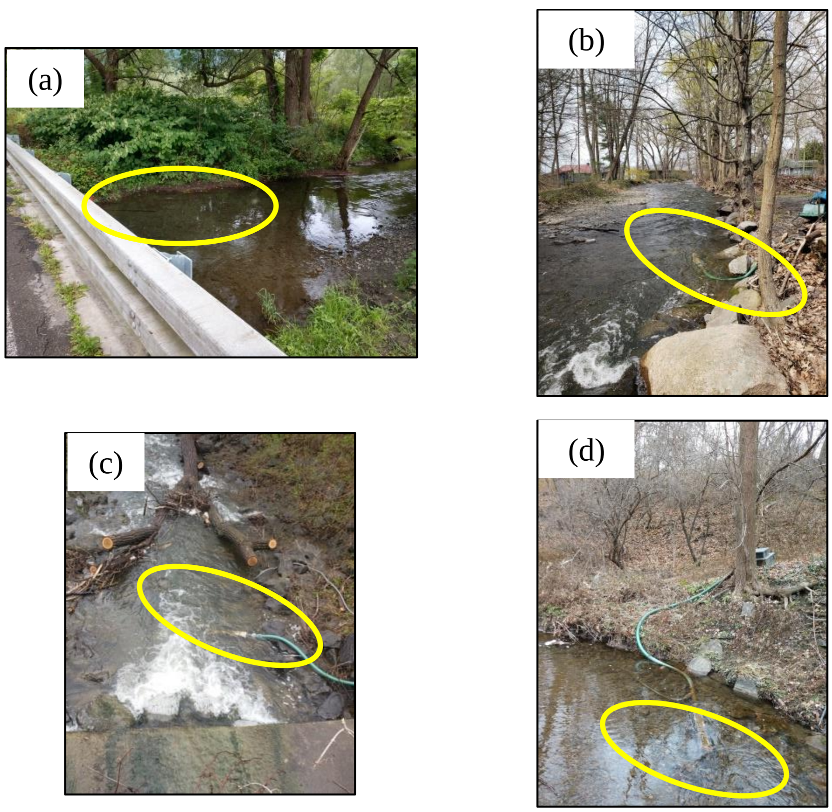

Figure 8. Position of pressure sensor and YSI® data sonde (circled) in the major tributaries of Skaneateles Lake: (a) Grout Brook, (b) Bear Swamp Creek, (c) Shotwell Brook, and (d) Harold Brook.

2.3.3. Instantaneous water quality measurements – Minor tributaries

A YSI Series 6600 multi-probe datasonde (YSI 2011) was used in the minor tributaries during each monitoring event from October to November to collect water quality data including temperature, specific conductivity, and turbidity. If the stream was too shallow for the probes to be properly submerged, water was collected in a metal bucket and parameters were measured in it. These measurements were used to evaluate seasonal patterns and relationships with flow.

2.3.4. Visual Assessments – Minor tributaries

The visual assessment included measuring the width of the tributary and depth at the midpoint in addition to qualitative information regarding presence of flow, flow characteristics, and weather conditions during and prior to the assessment. Streamflow measurements (cross-sectional area and velocity) were conducted approximately every other sampling event during the entire monitoring period.

Figure 9. Upstream Bear Swamp Creek impoundment, June 26.

2.4. 2019 Environmental conditions

Temperature, rainfall, and snowfall data from January through November 18 were obtained from the National Weather Service station in Auburn, NY. This station is approximately 10 km (6 mi) west of the Village of Skaneateles.

2.4.1. 2019 temperature, precipitation and long-term comparisons

Air temperatures during 2019 were lower than the long-term (1980-2018) average in January, March, April, May, June, and November (Figure 10a). Temperatures were slightly greater than the average in July, September, and October. The air temperatures during 2019 followed the general pattern of the long-term average temperatures.

Monthly precipitation during 2019 was above the monthly long-term averages in January, February, May, June, July, August, October, and December (Figure 10b). The greatest amount of precipitation fell in July of 2019 (6.3 in), which is greater than the long-term average, but within the expected range for this month. The summer (June – September) of 2019 was wetter than the average long-term summer with a total of 20.5 inches of rain in 2019 compared to the long-term average of 17.7 inches. Cumulative precipitation in 2019 was almost 5 inches greater than the long-term average (Figure 10c).

2.4.2. 2018 – 2019 winter snowfall and long-term comparisons

Total snowfall in Auburn from November of 2018 through March of 2019 was 115.5 inches, slightly above the average annual snowfall of 102.53 ± 11.27 inches from 1980 to 2017. The total snowfall during the 2018-2019 winter season was less than the 2017-2018 winter season (132.2 inches; UFI 2019). Snowfall can affect water quality by increasing runoff and loading to the tributary during the spring snowmelt period.

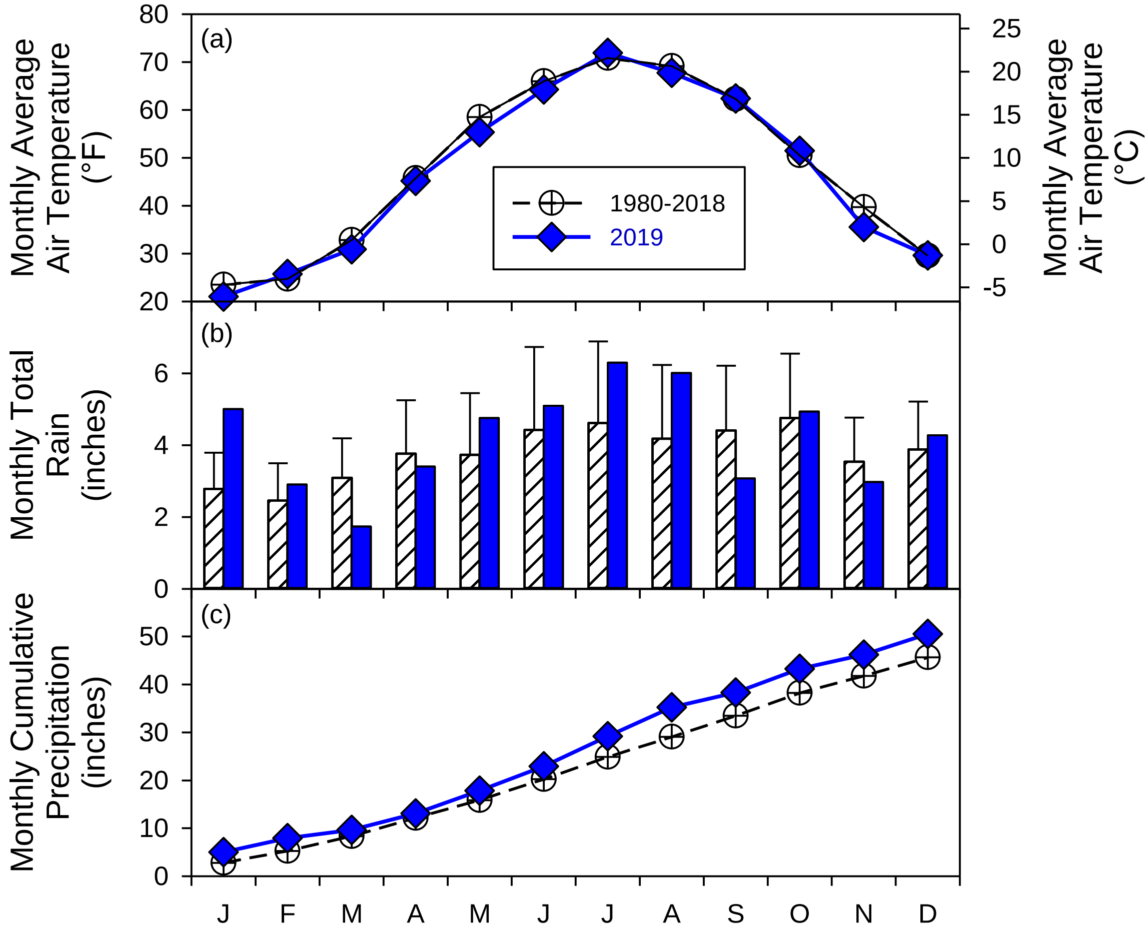

Figure 10. Auburn National Weather Service metrological conditions in 2019 compared with the 1980-2018 average: (a) monthly average air temperature, (b) monthly total rainfall (inches), and (c) monthly cumulative rainfall (inches).

3. Results and Discussion- Major Tributaries

3.1. Streamflow and continuous data

3.1.1. 2019 results – Streamflow

The average velocity of the utilized methods and measured cross-sectional area were used to calculate streamflow. Although there were slight variations in velocity observed between the three methods, the velocity estimations made with these methods were fairly consistent with one another (Figure 11a, 12a, 13a, 14a). Over the course of the monitoring program, the velocity of and cross-sectional areas in each tributary varied (Table 6).

Table 6. Summary of velocity and cross-sectional area measurements of the major tributaries to Skaneateles Lake in 2019. Number of observations shown in parentheses after tributary name.

Tributary	Average velocity (ft/s)	Velocity range (ft/s)	Average cross-sectional area (ft^2)	Cross-sectional area range (ft^2)
Bear Swamp Creek (17)	2.02	1.2 - 3.4	9.5	2.6 - 22.5
Grout Brook (18)	1.7	0.6 - 3.8	15.3	4.6 - 62.8
Shotwell Brook (22)	3.9	1.7 - 7.3	2.2	0.5 - 7.5
Harold Brook (18)	3	1.2 - 5.3	1.4	0.1 - 5.1

For Bear Swamp Creek, Shotwell Brook, and Harold Creek, a cubic polynomial function was fit to the streamflow measurements and average depth of the in-situ pressure sensor during the time period streamflow measurements were taken in the field (Figure 12b, 13b, 14b). The rating curve of Grout Brook was fit with a single parameter, exponential curve (Figure 11b). In addition to UFI pressure sensor stage measurements, flow-gage measurements from the USGS station 1 mile upstream of the UFI site were used to develop the rating curve for Grout Brook. The 15-minute USGS gage height measurements were linearly related to the 15-minute UFI sensor depths (Figure A.1.).

The pressure sensor in Shotwell Brook was installed in a pool below the culvert near a downed tree. The tree may have periodically created a deeper pool with minor backwater effects on the pressure sensor (Figure 8). Near the end of the monitoring period there was a high flow event that moved the tree downstream. Stage measurements and estimated streamflow in Shotwell Brook may be slightly elevated due to the position of the sensor during the majority of the monitoring period.

Pressure sensor measurements at Grout Brook after September 24 were adjusted due to disruption from an excavation project at the monitoring site. Pressure sensor measurements were adjusted by a ratio of 0.57 in order to account for the channel alteration; the original streamflow-stage measurements are shown in Figure 11b. The adjustment ratio (0.57) was calculated as the ratio between pressure sensor depths recorded at similar stream velocities during the pre-excavation and post-excavation periods. Because the pressure sensor was disturbed during the excavation process, measurements between September 24 and October 3 were removed from the near continuous flow estimation. Measurements collected by the USGS gage (#04235890) upstream of the UFI site were substituted for this data gap in the calculation of near-continuous flow.

Within 2019 and between monitoring periods the streamflow-stage relationship in most of the tributaries showed great variability. The two largest tributaries, Grout Brook and Bear Swamp Creek (Figures 11b, 12b), showed weaker relationships compared to Shotwell Brook and Harold Brook (Figures 13b, 14b). This may be due to upstream channel and hydrological differences or the need for more data. Paired t-tests were performed to evaluate the difference between the measured flow and estimated flows (using the rating curve) at the times that field measurements were taken. Flow data were common log transformed prior to statistical testing. The difference between measured and calculated flows at Grout Brook were not significant ($p = 0.07$), and generally calculated flows were less than measured flows (average 14 cfs). The difference between the measured and calculated flows at Bear Swamp Creek were significant ($p = 0.01$), with calculated flows less than measured flows (average 16 cfs). Most flow estimations at Shotwell Brook using the rating curve produced with 2016-2019 data were higher than the measured flows in 2019 (average 6 cfs) with the largest differences observed during high-flow events ($p = 0.0001$). Flow measurements collected at Harold Brook were very similar to flow estimations made using the rating curve, and 5 of 19 pairs were ± 1 cfs of one another ($p = 0.21$).

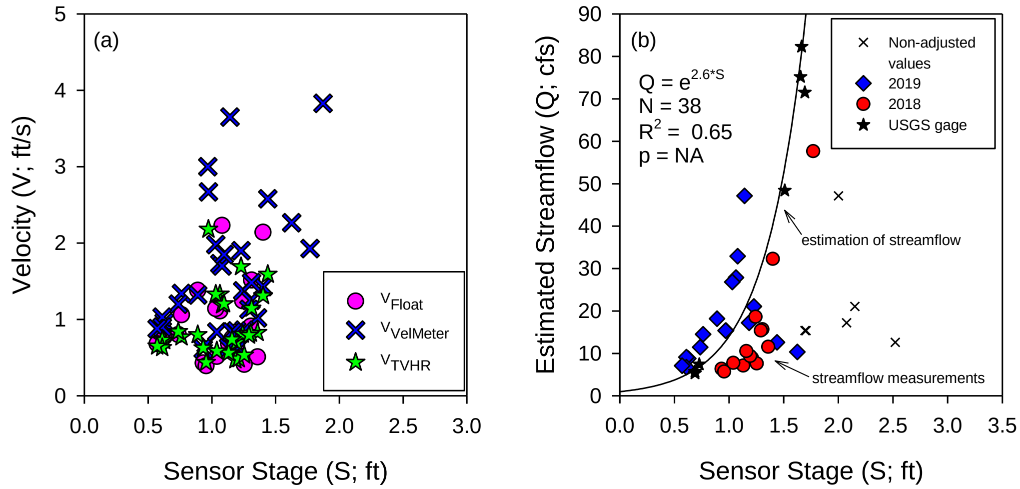

Figure 11. Estimation of streamflow in Grout Brook using data collected in 2018 and 2019: (a) stage-velocity relationships for three velocity estimation methods, and (b) pressure sensor stage-flow relationship (rating curve) with associated equation and statistics. Measurements made after excavation efforts (09/25/19) are marked with an "X"; the depths of the pressure sensor after this date were adjusted by the average ratio of depths pre- and post-excavation with similar measured velocities.

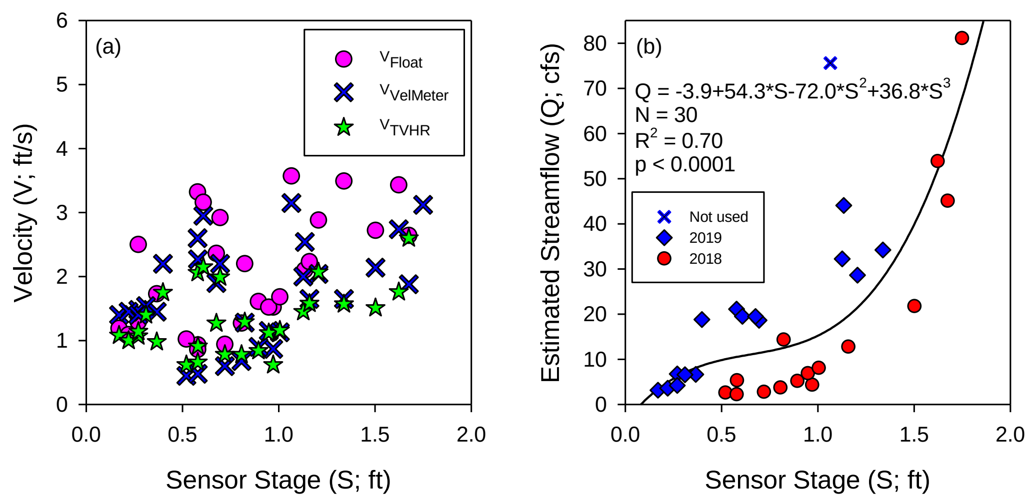

Figure 12. Estimation of streamflow in Bear Swamp Creek using data collected in 2018 and 2019: (a) stage-velocity relationships for three velocity estimation methods, and (b) pressure sensor stage-flow relationship (rating curve) with associated equation and statistics. Measurement made on 5/13/19, marked with "X", was not used to develop the rating curve.

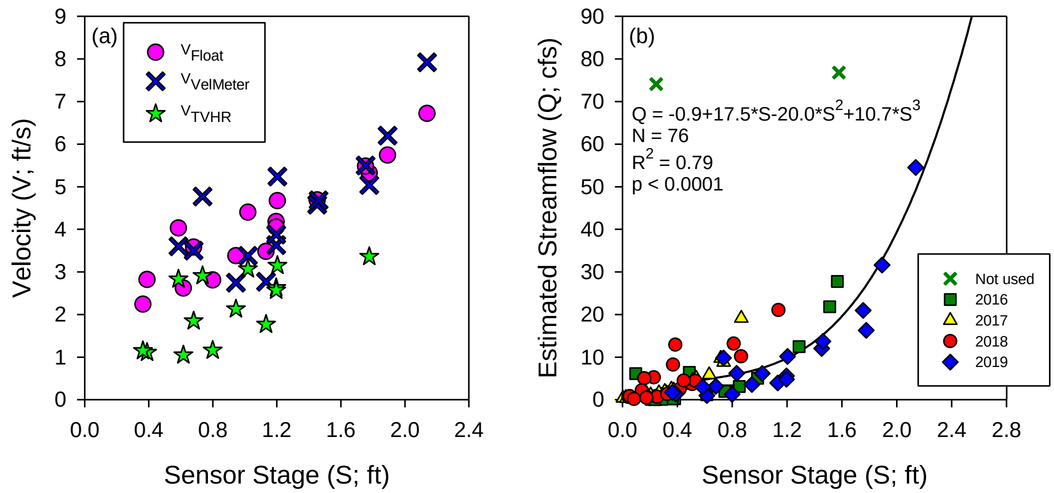

Figure 13 . Estimation of streamflow in Shotwell Brook using data collected 2016-2019: (a) stage-velocity relationships for three velocity estimation methods, and (b) pressure sensor stage-flow relationship (rating curve) with associated equation and statistics. Measurements made on 10/21/16 and 11/03/16, marked with "X", were not used to develop the rating curve.

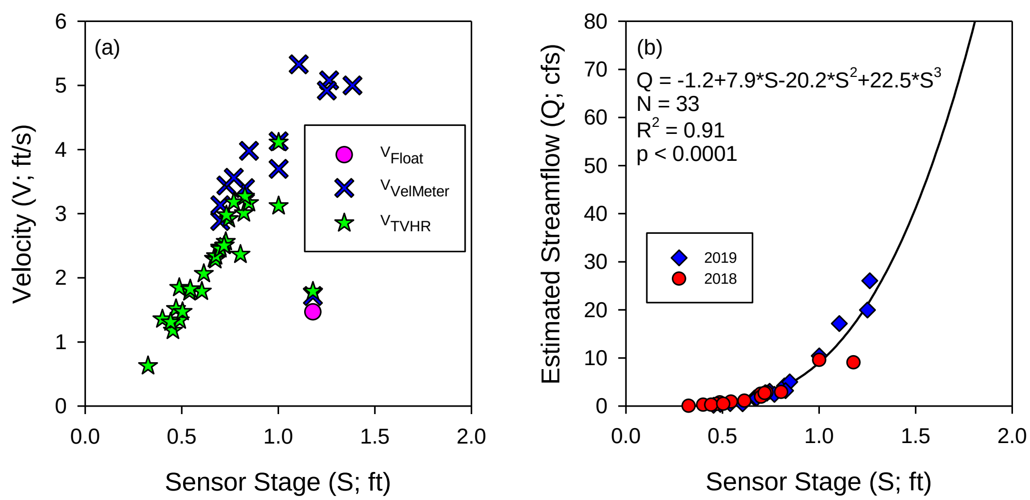

Figure 14. Estimation of streamflow in Harold Brook using data collected in 2018 and 2019: (a) stage-velocity relationships for three velocity estimation methods, and (b) pressure sensor stage-flow relationship (rating curve) with associated equation and statistics.

The *in-situ* equipment was deployed in Shotwell Brook on April 4 and in the other tributaries on May 2. Over 18,000 measurements of stage, temperature, specific conductance, and turbidity were made at each of the tributaries during 2019. In-stream sensors collected high frequency (15-minute) data for 235 days in Shotwell Brook, 207 days in Grout Brook and Harold Creek, and 196 days in Bear Swamp Creek. Early removal of monitoring equipment from Bear Swamp Creek was necessitated by winter conditions on the seasonally maintained access road. Any data that appeared to be the result of disturbance, fouling, etc. or were outside the standard YSI performance ranges (Table A.1).were removed from all analyses.

Stream stages were generally responsive to precipitation and seasonal patterns (e.g. soil saturation, leaf-on/off). The amount of precipitation in 2019 was greater than previous years (Figure 10), which influenced stream stage in each tributary (Figure 15). Each stream responded to major rainfall events, but the magnitude of the responses varied. The stage in the two larger tributaries (Grout Brook and Bear Swamp Creek) were less affected by minor precipitation events, whereas the smaller major tributaries (Shotwell Brook and Harold Brook) had more frequent responses and at a greater magnitude (Figure 15). Stream stage patterns were also affected by the timing of rainfall, antecedent conditions, and season. For example, large increases in stage were apparent in each tributary from September through November when evapotranspiration was low and there was little leaf cover.

The frequency distributions of stream stage and streamflow of the major tributaries show major differences in the hydrology of the four watersheds (Figure 16). Stream stage was elevated in Grout Brook compared to other tributaries throughout the monitoring period with a median stage of 0.9 ft (10.8 inches). Mean stage at Shotwell Brook was similar to Grout Brook; however, the percent occurrence and skew of the distribution indicates the stage in Shotwell Brook was more variable than Grout Brook. The stage of Harold Creek was between 0.6 and 0.8 ft for more than half of the 15-minute observations, which was more consistent than any other tributary. Harold Brook had the greatest change in stream stage of the four major tributaries, with a maximum stage of 5.4 ft measured prior to 2 PM on June 20. The maximum stage in each major tributary was greater in 2019 than in 2018 (UFI 2019). Bear Swamp Creek had the greatest number of low stage measurements. This may be due to the larger channel width compared to the other streams or upstream impoundments altering the course and amount of streamflow of Bear Swamp Creek.

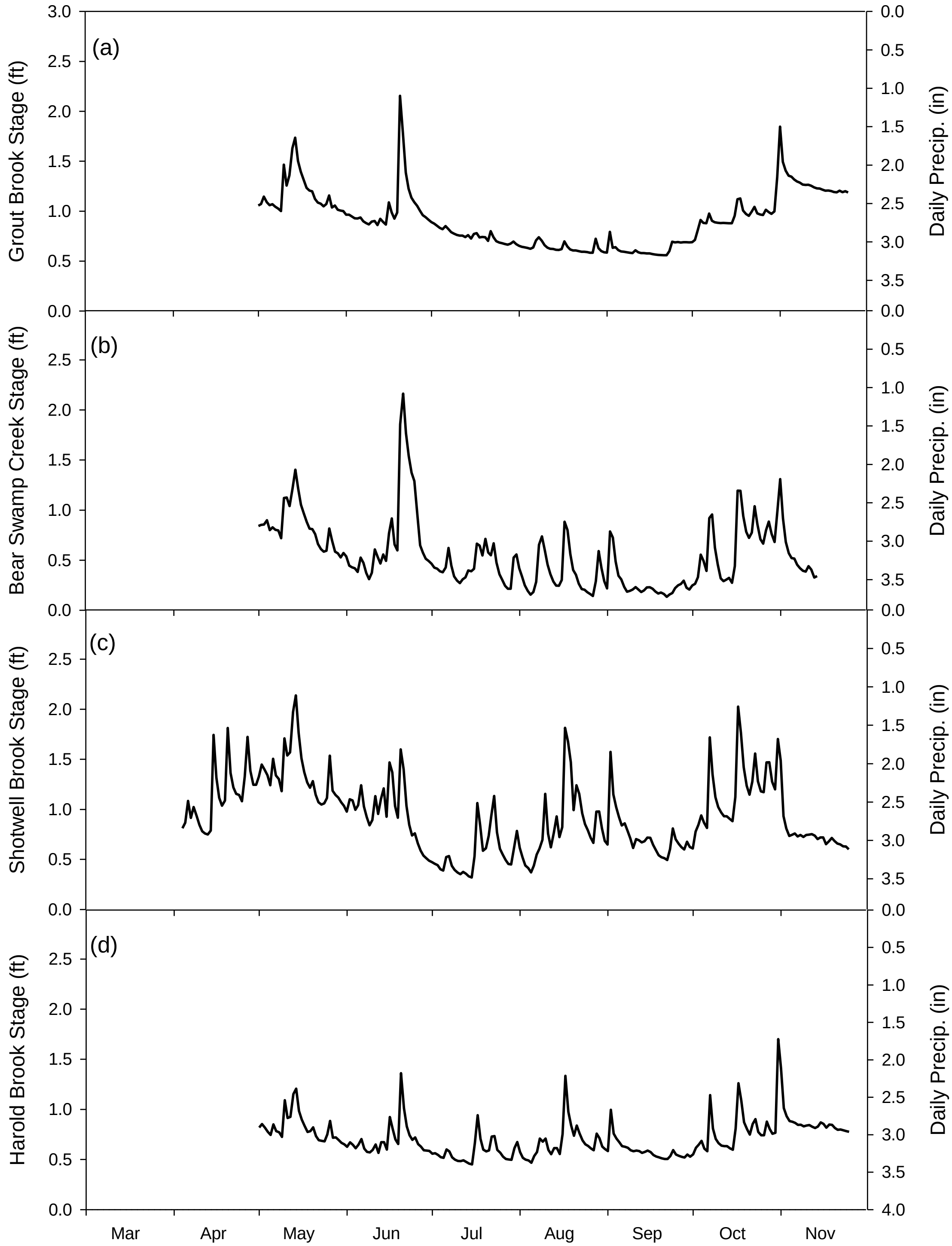

Figure 15. Time series of daily averaged stage (ft) in (a) Grout Brook, (b) Bear Swamp Creek, (c) Shotwell Brook, and (d) Harold Brook and precipitation (in) in 2019. Precipitation data from Auburn National Weather Service station located in Auburn, NY.

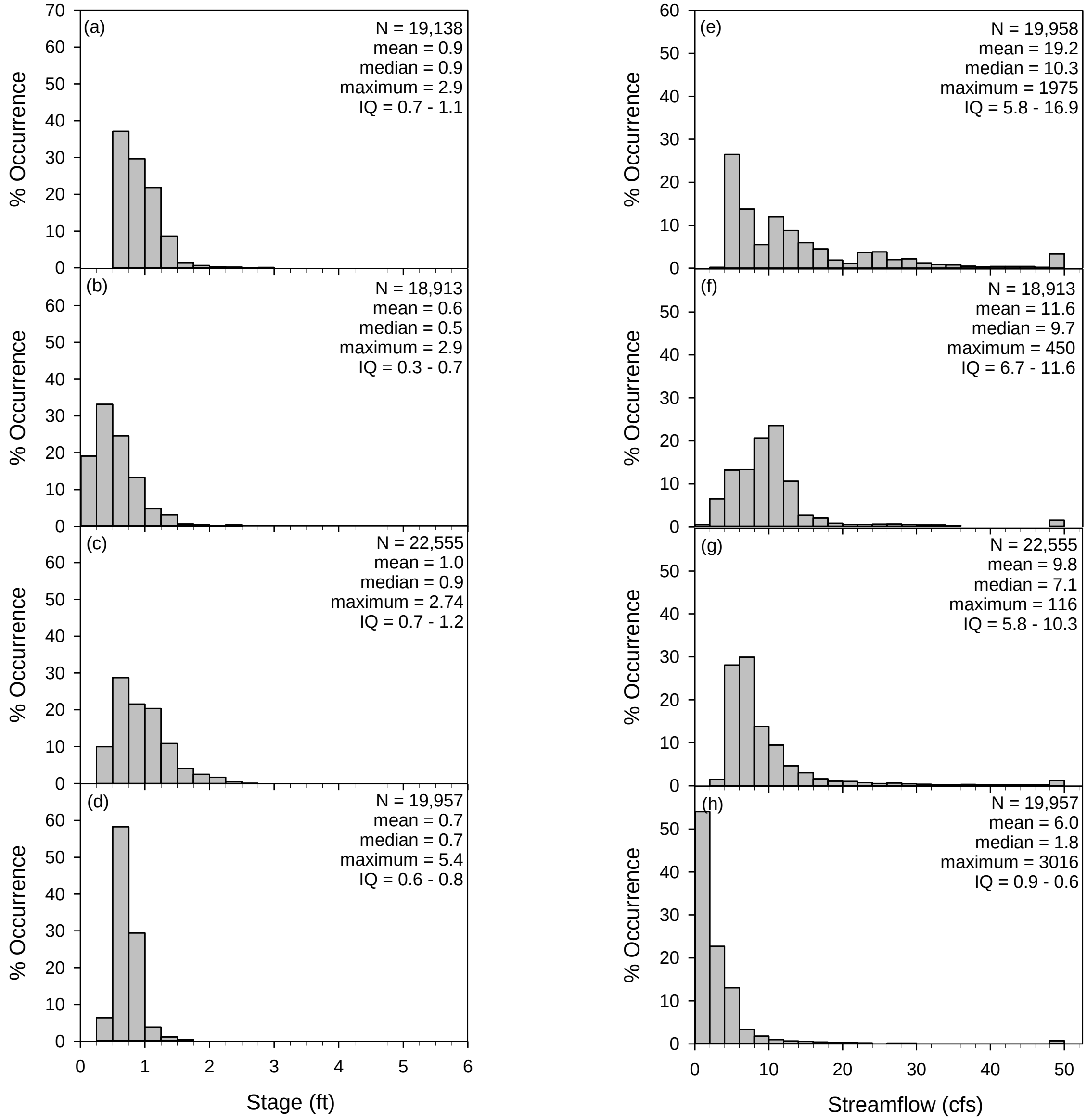

Figure 16. Observation frequency of stage (a-d) and estimated streamflow (e-h) at 15-minute intervals in four major tributaries to Skaneateles Lake: (a,e) Grout Brook, (b,f) Bear Swamp Creek, (c,g) Shotwell Brook, and (d,h) Harold Brook. Associated descriptive statistics shown; IQ represents the 25% - 75% inter quartile range.

3.1.2. 2019 results – In-situ YSI data and relations to streamflow

Daily averages of stage and YSI parameters (temperature, specific conductance, and turbidity) are shown in Figure 17. On November 14 a second YSI handheld data sonde was used to ground truth, or validate measurements made by *in-situ* equipment.

Daily average stream temperatures in all major tributaries were typical of streams in temperate zones, and both high frequency measurements and daily averages supported diel and seasonal patterns. Stream temperatures in Grout Brook were lower than the other streams, even during the warmer summer months (Figure 17, Figure A.2.). Lower temperatures in Grout Brook may be caused by groundwater contributions or shading of the stream channel. The YSI sonde was exposed to the air between October 31 and November 14 in Shotwell Brook and removed from all analyses. Water temperature in all streams was closely related to air temperature (Figure A.2.). Stream temperatures did not fluctuate as widely as air temperatures throughout the monitoring period, though. This is attributed to the buffering effect of thermally stable (not affected by air temperature) groundwater inputs to streamflow and the shading from trees along the stream. Temperature is an important regulator of water density, and the relationships observed between air temperatures and the four tributaries may be important to future modeling of Skaneateles Lake and its watershed.

Specific conductance (SC) is an aggregate measure of ionic content that can indicate relative concentrations of primary ionic species (i.e. Ca^{2+}, Na^{+}, K^{+}, Cl^{-},SO_4^{2-}, HCO_3^{-}). Ionic content within an aquatic system is often regulated by the geology of the watershed; higher levels of specific conductance can also be associated to human activities such as application of road salt. A majority of ionic compounds in a stream are inputted via groundwater; SC values are often higher when groundwater is more dominant than surface water in streamflow. During runoff events, SC typically decreases due to dilution. During high stage/flow events, SC decreased in each tributary by varying magnitudes (Figure 17, Figure A.3.). Shotwell Brook and Harold Brook had higher SC than the larger tributaries during base flows (Figure 17, 18). Bear Swamp Creek had the lowest median SC (215 µS/cm), indicating that either 1) groundwater sources are not as ionically enriched as those for the other tributaries or 2) Bear Swamp Creek is influenced less by groundwater.

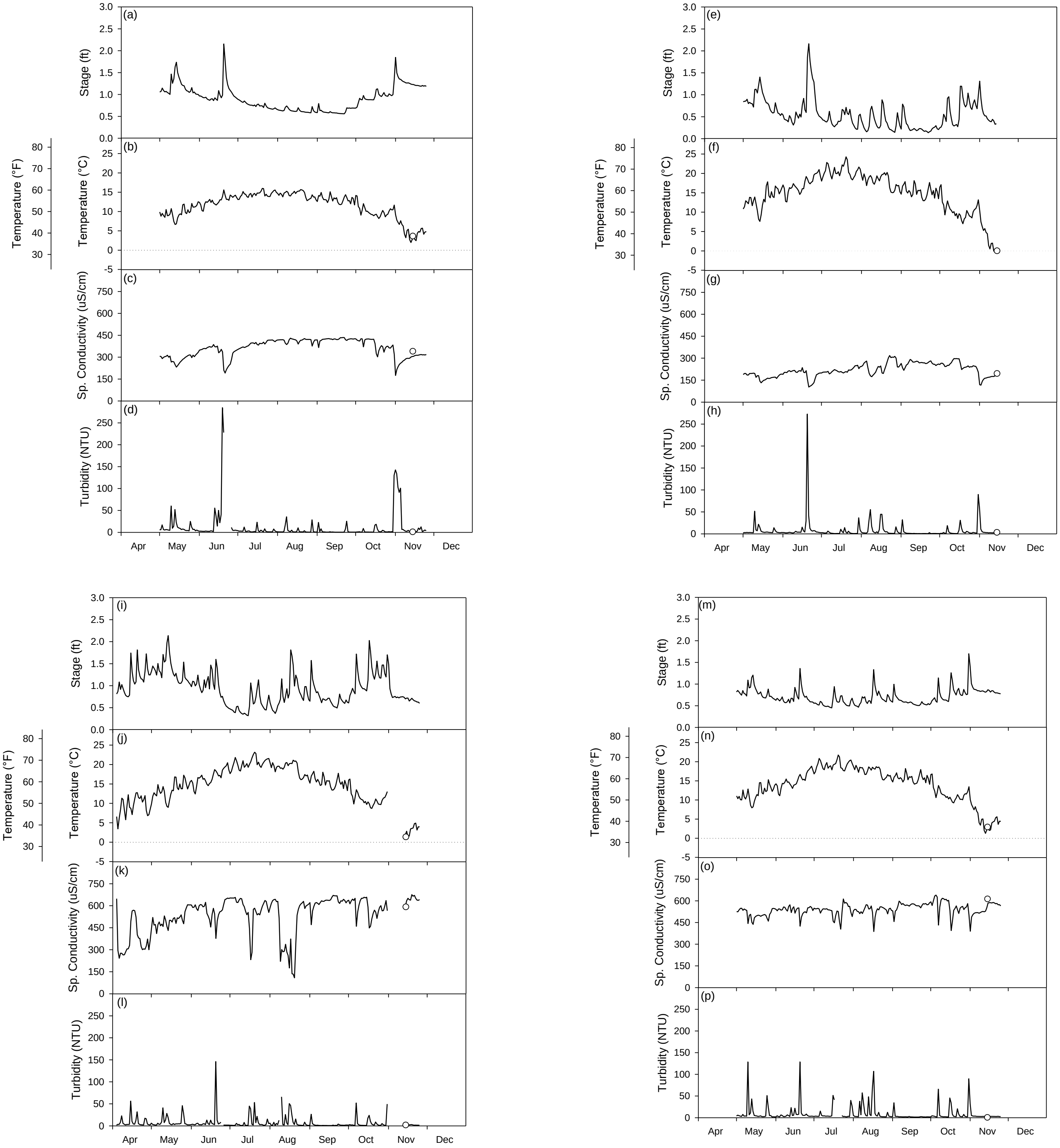

Figure 17. Time series of daily averaged 15-minute observations of stage (a, e, i, m), temperature (b, f, j, n), specific conductance (c, g, k, o) and turbidity (d, h, l, p) of four major tributaries to Skaneateles Lake during 2019 monitoring period: (a-d) Grout Brook, (e-h) Bear Swamp Creek, (i-l) Shotwell Brook, and (m-p) Harold Brook.

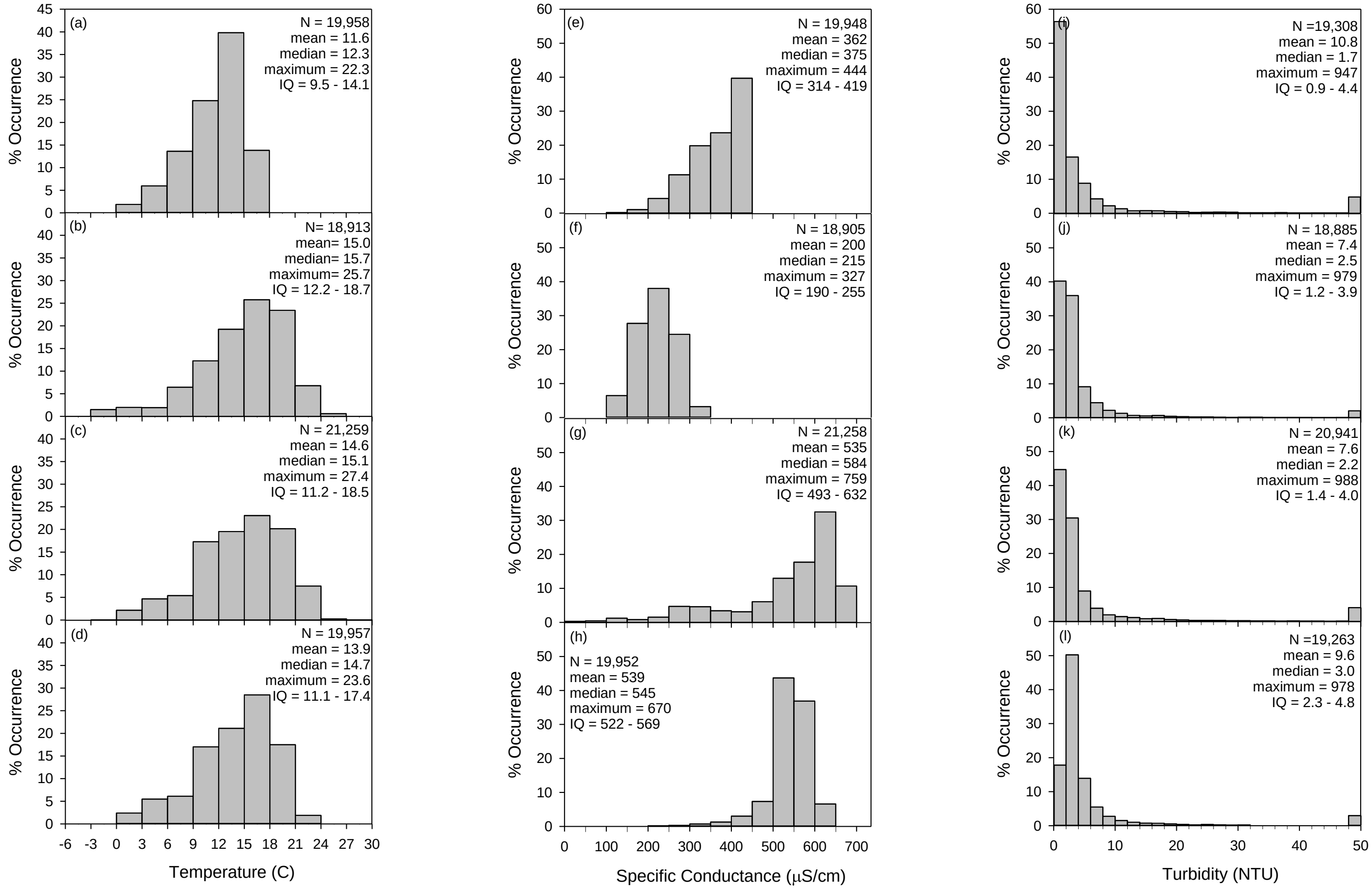

Figure 18. Observation frequency of (a-d) temperature (°C), (e-h) specific conductance (µS/cm), and (i-l) turbidity (NTU) at 15-minute intervals in four major tributaries to Skaneateles Lake in 2019: (a, e, i) Grout Brook, (b, f, j) Bear Swamp Creek, (c, g, k) Shotwell Brook, and (d, h, l) Harold Brook. Associated descriptive statistics shown; IQ represents the 25%- 75% inter quartile range.

Figure 19. Mouth of Randall Gulf on June 20, 2019. Turbid plume from stream visible in Skaneateles Lake.

Turbidity is a measurement of optical properties that is related to the amount and size of particles suspended in the water (see Figure 20 for relative scale; Gelda et al. 2009, Kirk 2011). Turbidity in the four major tributaries was overall quite low, with the range of median values of 1.7 to 3.0 NTU (Figure 17, 18). However, abrupt increases in turbidity were observed in each stream during periods of high flow (Figures 17, 21). These sharp increases in turbidity were often short-lived and values quickly returned to “normal”. Increases in turbidity (and associated sediment loading) are often observed during periods of high flow, and a majority of annual particulate loading to a lake or reservoir can be attributed to these intermittent events (O’Donnell and Effler 2006). Large quantities of particulates like silt or clay are transported from the watershed to Skaneateles Lake and can be seen as plumes entering the lake from the mouth of the streams (Figure 19). Although these suspended particles generally contain phosphorus, the phosphorus is often tightly bound and unavailable to immediately support algal growth (Ellis and Stanford 1988, Reynolds and Davies 2001).

Responses in turbidity during higher flow events ranged across the four major tributaries; turbidity in the smaller tributaries was more responsive to changes in stage (streamflow) than in the larger tributaries. The number of days and 15-minute observations with an average turbidity value greater than 100 NTU also varied (Table 7). Although Grout was one of the least turbid tributaries, it had the greatest number of days with daily average turbidity values greater than 100 NTU (Table 7); these days were consecutive following the two largest precipitation events (June 20 and October 31). Turbidity may remain high in this tributary for multiple days following a storm event and take slightly longer to return to normal compared to the other tributaries. For example, on June 20 massive flooding occurred near the mouths of the two largest tributaries, Grout Brook and Bear Swamp Creek (Figure 22). Flood waters receded within a week, but there were multiple days the streams overflowed the channel banks. Harold Brook was the most turbid of the major tributaries during baseflow conditions with a majority of the observations between 2.3-4.8 NTU (Figure 18).

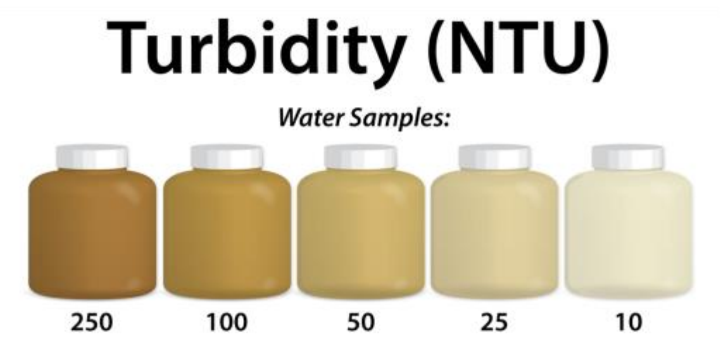

Figure 20. A relative turbidity scale (image courtesy of www.learnnc.org).

Table 7. Summary of high turbidity events of the four major tributaries to Skaneateles Lake in 2019. Number of days with daily average turbidity values greater than 100 shown. Observations greater than 1000 NTU were not included in the total sum of observations greater than 100 NTU and were removed from analyses as it is the upper limit of the YSI probe performance range.

	Daily averages	*15-minute observations*		
Tributary	# Days > 100 NTU	> 100 NTU	500 – 1000	> 1000 NTU
Bear Swamp Creek	1	179	33	25
Grout Brook	7	485	34	10
Shotwell Brook	1	242	23	122
Harold Brook	3	319	36	547

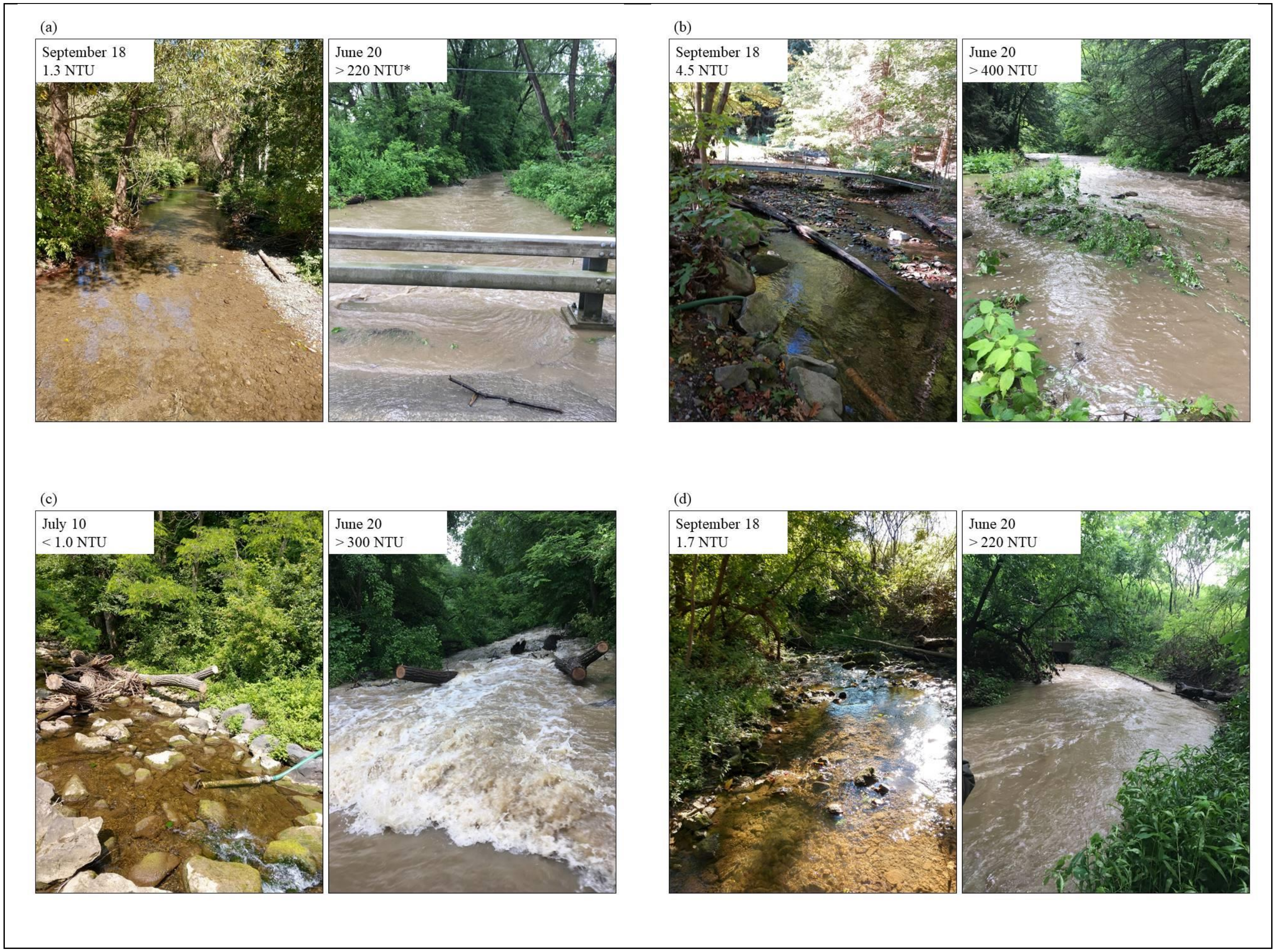

Figure 21. Photographs showcasing the range of turbidity in (a) Grout Brook, (b) Bear Swamp Creek, (c) Shotwell Brook, and (d) Harold Brook in 2019. Date and approximate 15-mintute turbidity value shown. *Turbidity probe non-functional during time photograph taken, estimate based on turbidity values measured prior to malfunction.

Figure 22. Photographs of the flooding near the mouths of (a) Grout Brook and (b) Bear Swamp Creek on June 20, 2019.

3.2. Water quality

Streamflow can greatly affect concentrations of water quality constituents. Several factors, including watershed land use, groundwater sources, and precipitation, can influence streamflow, thus affecting water quality. Mean and median concentrations are reported in order to evaluate the central tendency for water quality parameters. Means or averages can be skewed by observations that are extremely higher or lower than the other values measured over the monitoring period. The median, on the other hand, describes the middlemost value of a dataset, and better describes “normal” conditions in highly skewed distributions. Comparing these values can indicate the effect of streamflow on concentrations; for example, if a mean and median value is similar, it is likely that streamflow does not greatly affect the concentration. High flow conditions are the often the result of runoff after precipitation events. Runoff can temporarily influence water quality in the streams yet greatly affect annual loads to lakes. Typically, water quality constituents that are comprised largely of particulates (e.g. TP, TSS, PP) increase with increasing flows due to greater contributions from the watershed and turbulence within the stream. Meanwhile, some dissolved constituents (e.g. TDP, NO_x) may decrease with flow due to the influx of relatively dilute water. As expected, concentrations of several water quality parameters were observed to increase with increasing flow (Table 8).

Flow relationships were analyzed categorically and numerically in order to best describe the dataset. Daily average flow measurements (calculated using the pressure sensor measurements) were paired with sampling events. Linear relationships were made between concentration and flow for all available data (2016-2019). All concentration and flow data were common log-transformed to normalize variance. To characterize flow regimes, the annual interquartile range of the pressure sensor data was calculated for each year. The daily average flow values for each sampling event were categorized as “high” if they were above the interquartile range for that year or “low” if below the interquartile range. Instantaneous flow measurements were used when calculated daily average flow values were suspicious (i.e. < 0.01).

Table 8. Summary of linear relationships between flow and water quality parameters of the major tributaries to Skaneateles Lake using all available data (2016-2019 Shotwell Brook; 2018-2019 Bear Swamp Creek, Grout Brook, Harold Brook). Numbers within table represent R^2 (fit) between flow and analyte. Shaded values are relationships with p-values < 0.05 with the color indicating a positive (blue) or negative (red) significant relationship.

Tributary	Parameter														
	TP	TDP	SRP	PP	DOP	TN	NO_x	t-NH_3	Tn	TSS	FSS	VSS	Si	DOC	POC
Bear Swamp Creek	0.21	0.02	0.02	0.40	0.01	0.14	0.06	0.00	0.43	0.37	0.55	0.52	0.02	0.12	0.29
Grout Brook	0.53	0.29	0.06	0.57	0.23	0.03	0.48	0.00	0.62	0.59	0.71	0.73	0.27	0.30	0.43
Shotwell Brook	0.14	0.01	0.04	0.23	0.10	0.01	0.01	0.04	0.31	0.20	0.63	0.63	0.02	0.26	0.40
Harold Brook	0.26	0.21	0.13	0.24	0.06	0.02	0.04	0.01	0.29	0.17	0.71	0.64	0.12	0.40	0.39

Key:

	p-value	
	> 0.05	< 0.05
Slope	N/A	Negative
		Positive

3.2.1. Phosphorus

Phosphorus is a crucial nutrient found in water and soils that supports growth of aquatic plants, including algae. Phosphorus is the most limiting nutrient (compared to carbon, nitrogen) in most north temperate lakes, and many management actions are directed towards decreasing phosphorus loading. Phosphorus can be delivered to waterbodies through direct atmospheric deposition, points sources (e.g. wastewater treatment discharge), and nonpoint sources (e.g. runoff, failing septic systems). There are several forms of phosphorus that cycle through the environment and food web, and each form can impact water quality.

The phosphorus cycle in lakes begins with autotrophic organisms (plants or algae) taking up inorganic phosphorus compounds. Primary producers convert this phosphorus into organic forms which is then either directly or indirectly consumed by animals. Upon the decomposition of plants and animals, or through their excretions, the organic phosphorus is released and becomes available for bacteria. Bacteria convert organic phosphorus back into inorganic phosphorus to restart the cycle. Through natural and human-mediated processes, though, additional phosphorus is inputted into the waterbody (often in an inorganic form) that, in turn, supports algal and plant growth. This process not only takes place in lakes, and is commonly referred to as nutrient spiraling in flowing water systems (Webster 1975). Nutrient spiraling takes into account the longitudinal distance it takes for nutrients (such as phosphorus and nitrogen) to undergo a complete cycle, or transform from dissolved inorganic form though particulate forms and back to dissolved inorganic form (Newbold et al. 1981). This process can be affected by streamflow, geomorphology, and presence of producers and decomposers (i.e. algae, plants, bacteria, and fungi; Ensign and Doyle 2006).

Total phosphorus (TP) is a measured constituent that encompasses all organic and inorganic phosphorus compounds in the sample, and these compounds can be in either a particulate or dissolved form. Dissolved forms near the mouth of streams are important to monitor as they are in a form that is readily available for uptake by algae and plants upon entering the lake. Total dissolved phosphorus (TDP) measures the dissolved fractions of phosphorus, and can include inorganic and organic compounds. Soluble reactive phosphorus (SRP) is the dissolved, inorganic fraction of phosphorus that is immediately available for uptake by plants. These measured constituents (TP, TDP, and SRP) can be used to derive other forms of phosphorus including dissolved organic phosphorus (DOP) and particulate phosphorus (PP). Dissolved organic phosphorus is derived by subtracting SRP from TDP, and is indicative of biochemical processes that convert particulate, organic phosphorus to soluble, organic forms (e.g. lysis, decomposition). Particulate phosphorus is a form of phosphate that is contained within organisms (e.g. plant and animal tissues, algae) or attached to inorganic particles (e.g., clays), and derived by subtracting TDP from TP. Although most PP is not readily available for biological uptake, it can be converted to dissolved forms within streams and the lake.

Peak TP concentrations were observed in all of the tributaries on June 20 with the highest value observed in Grout Brook (1020 µg/L; Figure 24). Most TP values greater than the median were observed during high flow regimes, but there were instances of elevated TP when the tributaries were at a normal or “low” flow (Figure 24). Every tributary experienced high TP on June 20 and October 7 (Figure 24); the means and standard deviations of TP in each tributary were likely affected by the event on June 20 more than the event on October 7. There were no high TP values measured in any of the tributaries during September, which may be related to the below average precipitation experienced in that month.

Figure 23. Harold Brook on June 20, 2019.

Grout Brook had the lowest median TP of the major tributaries, and had the lowest individual TP measurements of the major tributaries during 11 sampling events (Table 9; Figure 24). Median phosphorus measurements in Shotwell Brook and Bear Swamp Creek were typically highest or second highest of the major tributaries (Table 9). Grout Brook and Harold Brook had similar overall median and average values, but there were often differences between the two tributaries on any given date. These qualitative observations are similar to those observed in 2018 (UFI 2019; Table 10). Median phosphorus concentrations were similar in the two years, with most 2019 medians slightly higher than 2018 values (Tables 9, 10). Comparisons of the mean and standard deviation values of the two years show higher concentrations of TP and PP in 2019, which could indicate samples were collected at higher flows or flows were generally higher in 2019 than 2018.

Both linear and categorical statistical tests support that TP was higher at higher flows in each of the major tributaries (Figure 25). Total dissolved phosphorus in Grout Brook and Harold Brook significantly increased with increasing flow (Figure 26d, h); Bear Swamp Creek was the only major tributary with decreasing TDP with increasing flow, but the relationship was not significant ($p = 0.48$; Figure 26b). Similarly, SRP concentrations in Grout Brook and Harold Brook increased with increasing flow (Figure 27d, h). In Shotwell Brook and Bear Swamp Creek, SRP concentrations generally decreased with increasing flows, suggesting dilution of a continuous source (e.g., groundwater, wetlands). All linear relationships between PP and flow were statistically significant (Figure 28). Concentrations of DOP in Grout Brook showed a positive relationship with flow (Figure 29d). High and low flow regimes in Harold Brook were indicative of a positive relationship between DOP and flow, but linear analysis did not support this pattern (Figure 29g, h).

Table 9. Mean ± standard deviation (X̅), median (M), and number of observations (n) of total phosphorus (TP), total dissolved phosphorus (TDP), soluble reactive phosphorus (SRP), particulate phosphorus (PP), and dissolved organic phosphorus (DOP) concentrations measured in the major tributaries to Skaneateles Lake in 2019.

Tributary	TP (µg/L)			TDP (µg/L)			SRP (µg/L)			PP (µg/L)			DOP (µg/L)		
	X̅	M	n	X̅	M	n	X̅	M	n	X̅	M	n	X̅	M	n
Bear Swamp Creek	108 ± 231	24	19	22 ± 9	22	19	12 ± 6	12	19	110 ± 248	10	15	10 ± 5	9	19
Grout Brook	84 ± 233	11	19	11 ± 7	9	19	7 ± 5	6	19	108 ± 271	8	13	4 ± 3	4	18
Shotwell Brook	81 ± 134	29	21	30 ± 28	21	21	19 ± 17	14	21	53 ± 115	17	20	12 ± 14	8	20
Harold Brook	71 ± 144	19	19	18 ± 21	10	19	13 ± 18	6	19	59 ± 137	7	17	5 ± 4	5	18

Table 10. Mean ± standard deviation (X̅), median (M), and number of observations (n) of total phosphorus (TP), total dissolved phosphorus (TDP), soluble reactive phosphorus (SRP), particulate phosphorus (PP), and dissolved organic phosphorus (DOP) concentrations measured in the major tributaries to Skaneateles Lake in 2018.

Tributary	TP (µg/L)			TDP (µg/L)			SRP (µg/L)			PP (µg/L)			DOP (µg/L)		
	X̅	M	n	X̅	M	n	X̅	M	n	X̅	M	n	X̅	M	n
Bear Swamp Creek	30 ± 24	23	17	16 ± 6	17	17	11 ± 6	12	16	13 ± 21	5	17	5 ± 2	5	16
Grout Brook	14 ± 9	11	18	8 ± 4	8	18	5 ± 3	5	17	6 ± 6	3	18	4 ± 1	3	15
Shotwell Brook	45 ± 48	35	22	27 ± 16	24	22	22 ± 14	22	17	18 ± 34	8	22	7 ± 3	7	17
Harold Brook	52 ± 119	17	18	14 ± 13	10	18	9 ± 10	6	17	39 ± 107	8	18	5 ± 3	4	17

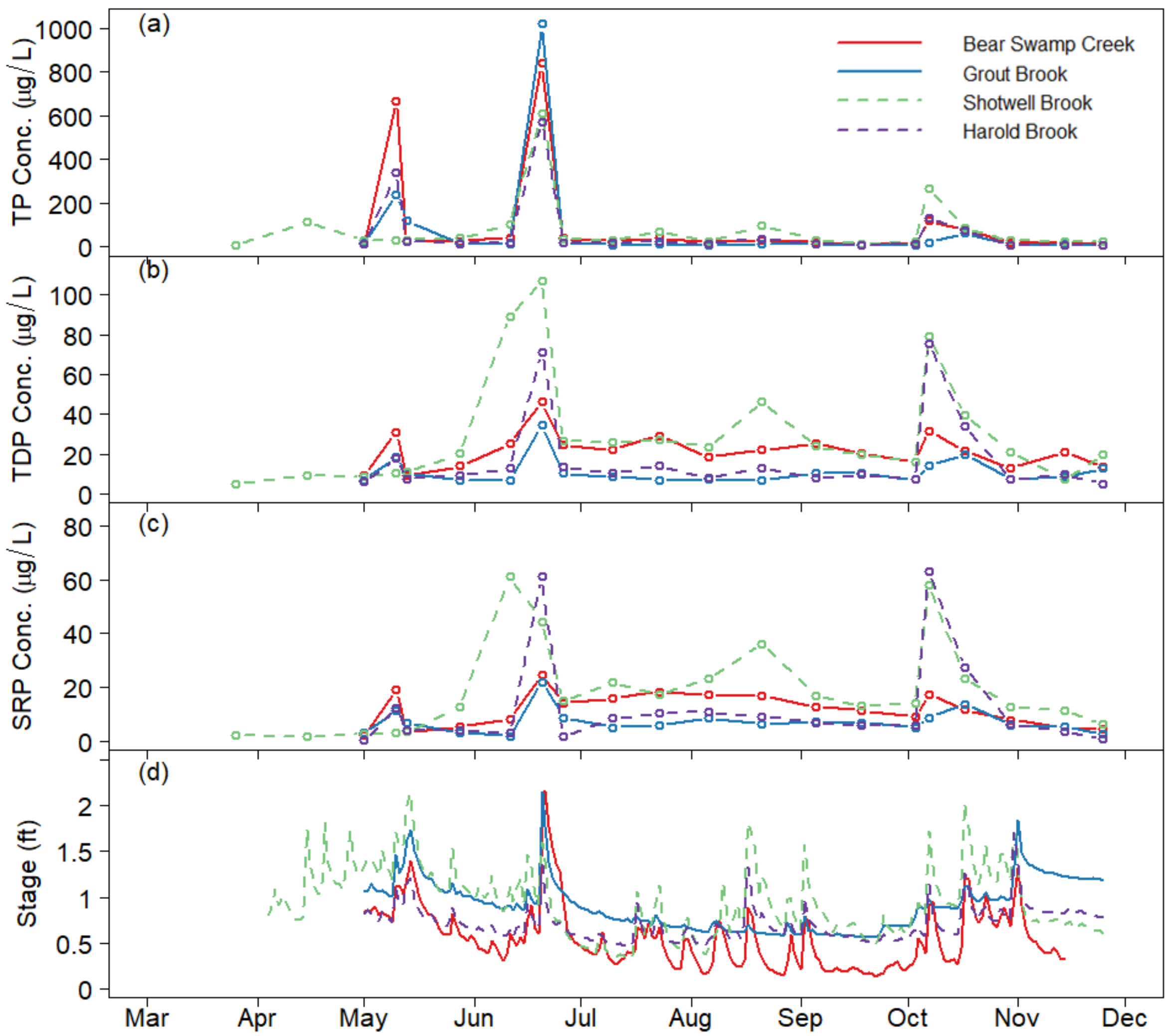

Figure 24. Time series of phosphorus concentrations and stage (ft) of Bear Swamp Creek, Grout Brook, Shotwell Brook, and Harold Brook in 2019: (a) total phosphorus (TP), (b) total dissolved phosphorus (TDP), (c) soluble reactive phosphorus (SRP), and (d) daily average stage.

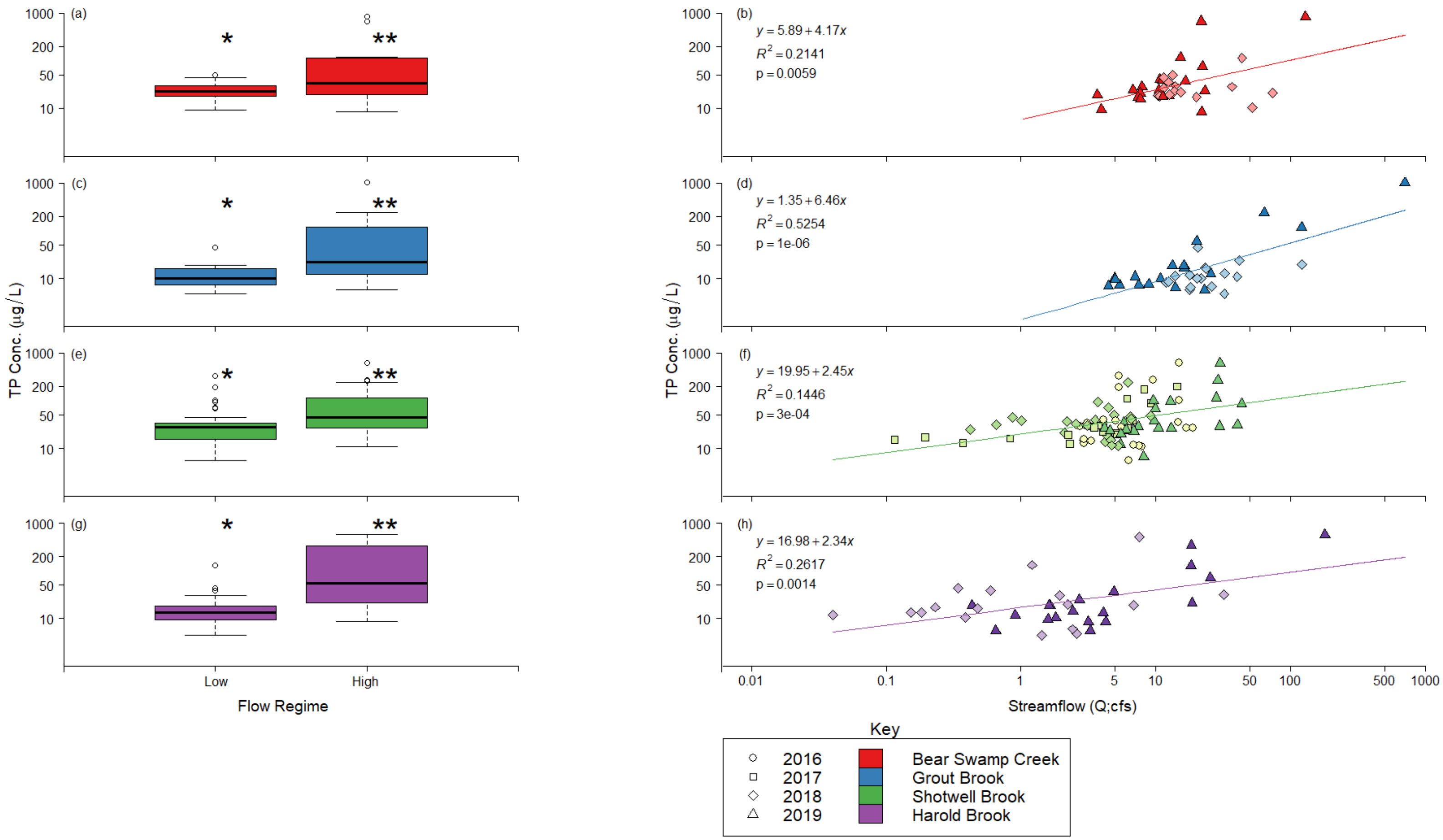

Figure 25. Comparison of total phosphorus (TP) concentration measured during high and low flow regimes (a,c,e,g) and relationship between TP and flow (b,d,f,h) in (a,b) Bear Swamp Creek (2018-2019), (c,d) Grout Brook (2018-2019), (e,f) Shotwell Brook (2016-2019), and (g,h) Harold Brook (2018-2019). Statistically significant differences between concentrations within each tributary is denoted with * and **. Linear relationship equation and statistical significance shown within plot.

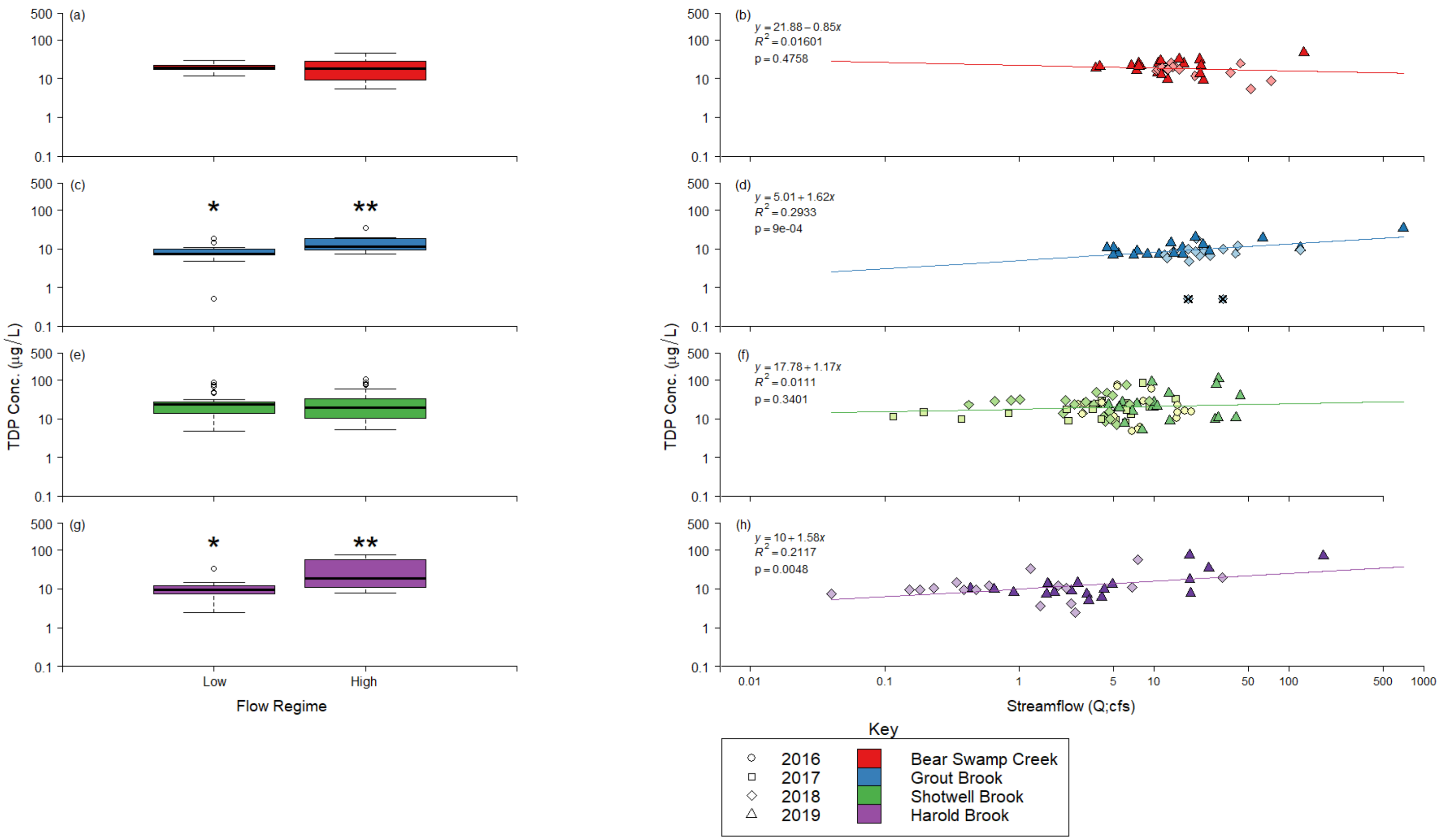

Figure 26. Comparison of total dissolved phosphorus (TDP) concentration measured during high and low flow regimes (a,c,e,g) and relationship between TDP and flow (b,d,f,h) in (a,b) Bear Swamp Creek (2018-2019), (c,d) Grout Brook (2018-2019), (e,f) Shotwell Brook (2016-2019), and (g,h) Harold Brook (2018-2019). Statistically significant differences between concentrations within each tributary is denoted with * and **. Linear relationship equation and statistical significance shown within plot. "X" indicates point not used for regression.

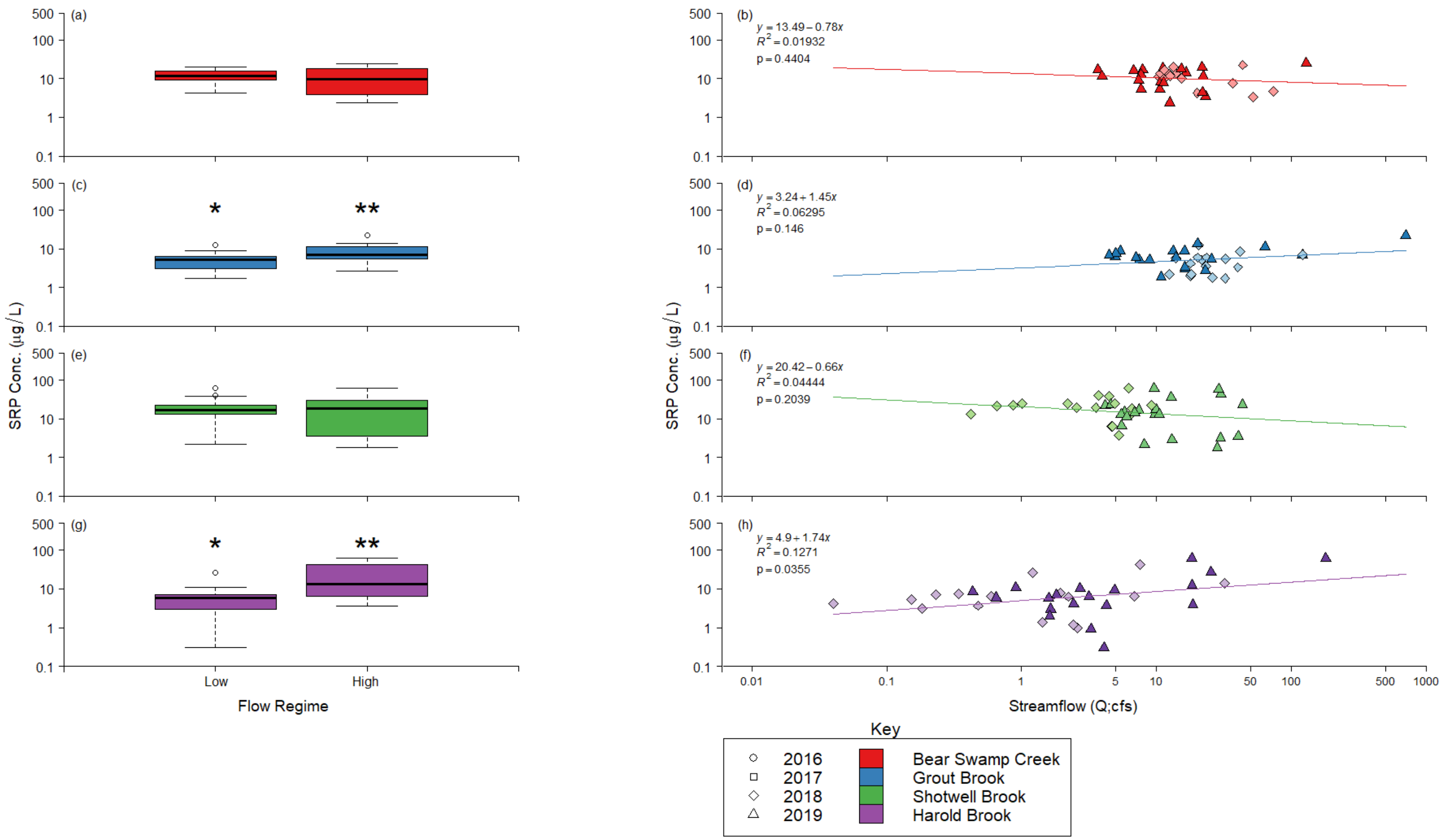

Figure 27. Comparison of soluble reactive phosphorus (SRP) concentration measured during high and low flow regimes (a,c,e,g) and relationship between SRP and flow (b,d,f,h) in (a,b) Bear Swamp Creek (2018-2019), (c,d) Grout Brook (2018-2019), (e,f) Shotwell Brook (2016-2019), and (g,h) Harold Brook (2018-2019). Statistically significant differences between concentrations within each tributary is denoted with * and **. Linear relationship equation and statistical significance shown within plot.

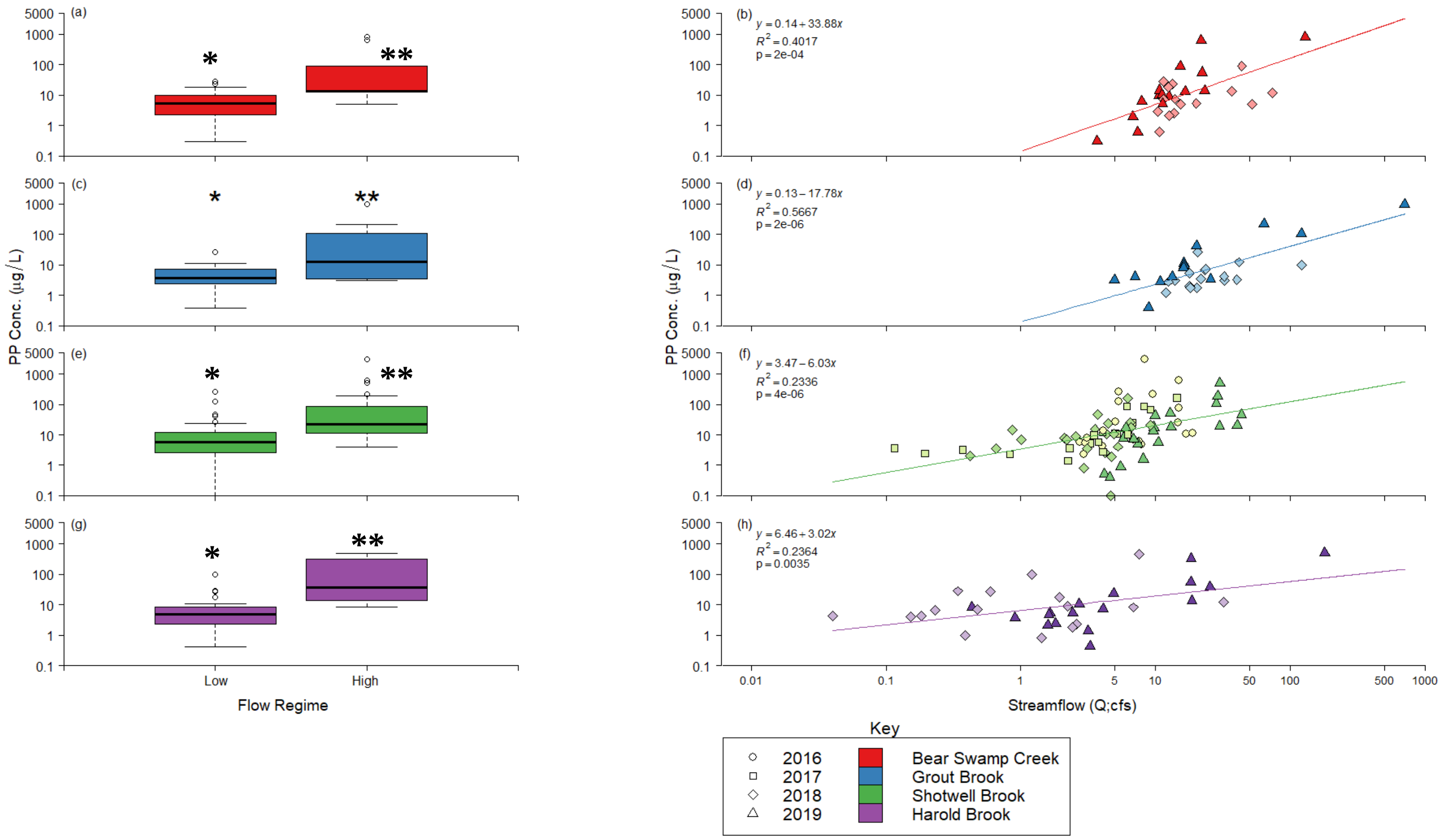

Figure 28. Comparison of particulate phosphorus (PP) concentration measured during high and low flow regimes (a,c,e,g) and relationship between PP and flow (b,d,f,h) in (a,b) Bear Swamp Creek (2018-2019), (c,d) Grout Brook (2018-2019), (e,f) Shotwell Brook (2016-2019), and (g,h) Harold Brook (2018-2019). Statistically significant differences between concentrations within each tributary is denoted with * and **. Linear relationship equation and statistical significance shown within plot.

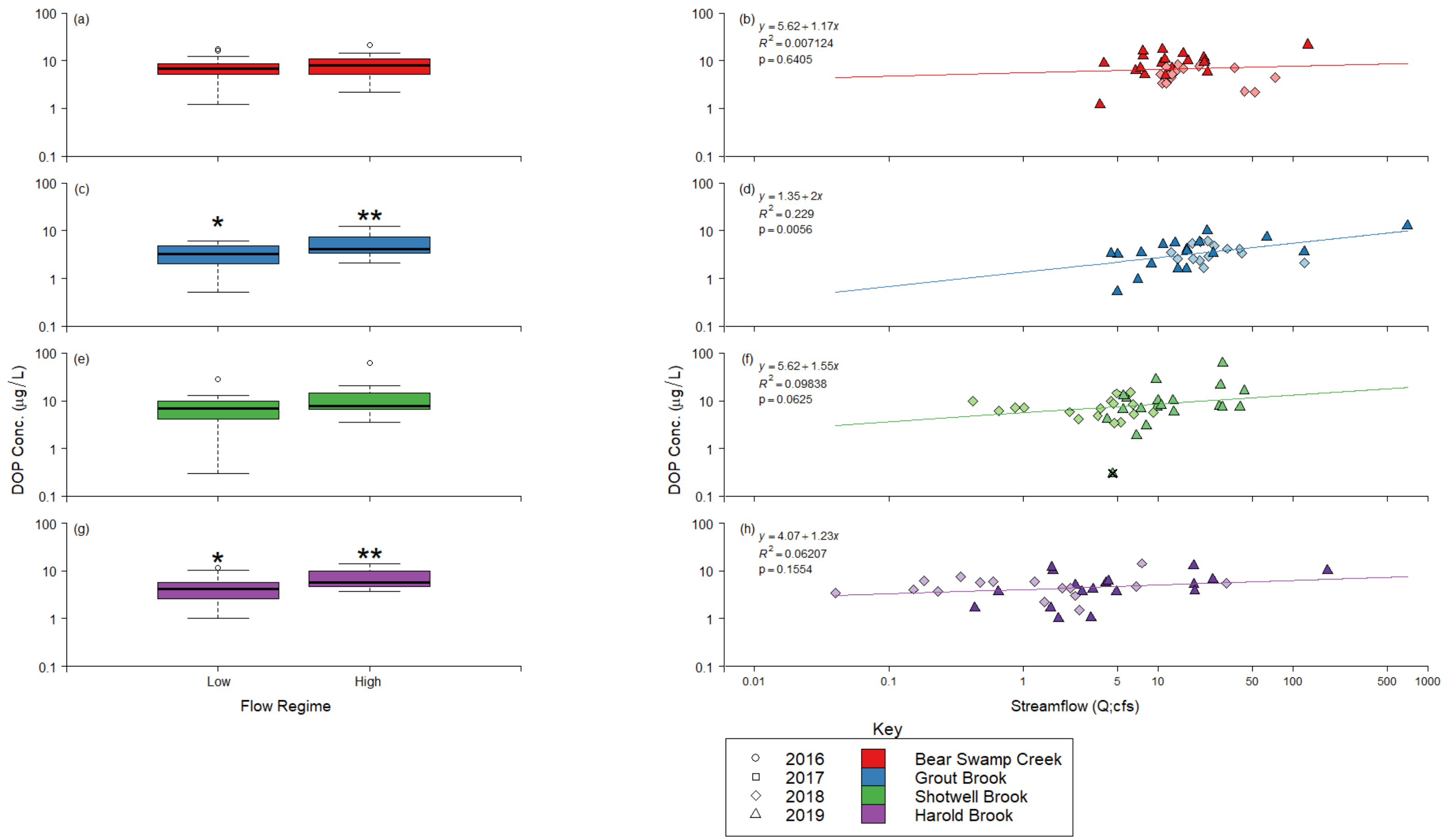

Figure 29. Comparison of dissolved organic phosphorus (DOP) concentration measured during high and low flow regimes (a,c,e,g) and relationship between DOP and flow (b,d,f,h) in (a,b) Bear Swamp Creek (2018-2019), (c,d) Grout Brook (2018-2019), (e,f) Shotwell Brook (2016-2019), and (g,h) Harold Brook (2018-2019). Statistically significant differences between concentrations within each tributary is denoted with * and **. Linear relationship equation and statistical significance shown within plot. "X" indicates point not used to calculate regression.

3.2.2. Nitrogen

Nitrogen is also a crucial nutrient that supports plant and algal growth in lakes. Like phosphorus, nitrogen can be in present in multiple forms and undergoes cycling through physical and biological processes (e.g. nitrification, denitrification). Nitrogen compounds are relatively plentiful compared to phosphorus, and most oligotrophic waterbodies are phosphorus-limited rather than nitrogen-limited (Wetzel 2001). Loading of nitrogenous compounds does occur, though, and can support primary production; typically nitrogen loading is paired with high phosphorus loading. Wastewater treatment plant discharge, runoff from lawns and crops, runoff from animal manure storage areas, and failing septic systems can contribute to nitrogen loads to a waterbody.

Total nitrogen (TN) is comprised of dissolved and particulate forms of nitrogen including nitrate (NO_3^-), nitrite (NO_2^-), and ammonia (t-NH_3). Dissolved forms of N are typically found in higher concentrations than particulate forms. Ammonia is naturally generated by decomposition of organic matter and waste excretions. It can also originate from fertilizers and household cleaning products. Total ammonia (t-NH_3) measures the concentrations of ammonium ions (NH_4^+) and unionized ammonia (NH_3); both of these species are present at any given time, but the quantity of each can fluctuate based on pH and temperature (Wetzel 2001). Unionized ammonia (NH_3) can be toxic to aquatic life under certain environmental conditions and at high concentrations (Oram 2020). Ammonia can either be taken up by plants and phytoplankton or undergo the nitrification process. Nitrification is mediated by chemical, physical, and biological factors within a water body including temperature, oxygen, and presence of nitrifying bacteria. Ammonia is oxidized (chemically combined with oxygen) to form nitrite (NO_2). Nitrite is an uncommon form of nitrogen because it is less chemically stable; it can be toxic to aquatic life under certain conditions (Oram 2020). Nitrate is the ultimate product of the nitrification process, and is often the most dominant fraction of TN. The sum of nitrate and nitrite is determined in the laboratory ($NOx = NO_3^- + NO_2^-$). Nitrates are essential nutrients for plants and often a main component of terrestrial fertilizers. As Skaneateles Lake is located in a highly agricultural watershed (Figure 2), it is prudent to monitor nitrogen loading from tributaries.

The maximum TN (4860 µg/L) was observed at Harold Brook on June 20. The maximum TN in each tributary was also observed on this date (Bear Swamp Creek: 2020 µg/L, Grout

Brook: 2220 µg/L, and Shotwell Brook: 2200 µg/L). A major run off event that occurred on June 20 resulted in distinguishable peaks in TN across each tributary (Figure 30). During this time period crops normally have only just started growing, making it a possible time for increased mobilization of nitrogen from fields. Harold Brook maintained the highest TN concentrations over the monitoring period except on June 11 and October 3 when surpassed by concentrations in Grout Brook (Figure 30). Harold Brook had the highest median TN, followed by Grout Brook and Shotwell Brook (Table 11). Similarly to monitoring results from 2018 (UFI 2019), TN was dominated by the NO_x form (Tables 11, 12). Median values of t-NH_3 were between 1.5 and 2 times greater in 2019 than 2018 in Bear Swamp Creek, Grout Brook, and Shotwell Brook.

Relationships between TN, NO_x and flow were generally weak (e.g. $R^2 < 0.06$; Figures 31, 32). There was a significant difference between TN concentrations in Grout Brook at high and low flow regimes, with lower TN observed at higher flow, but no significant linear trend was present (Figure 31c,d). A positive linear relationship between TN and flow was detected in Bear Swamp Creek (Figure 31b). Nitrate concentrations in Grout Brook were significantly different between the two flow regimes and decreased with flow ($p < 0.005$; Figure 32c,d). While NO_x concentrations decreased with flow in Grout Brook, Shotwell Brook, and Harold Brook, NO_x concentrations in Bear Swamp Creek increased modestly with increasing flows ($p = 0.17$; Figure 32).

Ammonia concentrations were generally low (<100 µg/L) and mostly similar across streams (Figure 30c). Harold Brook had the highest observed t-NH_3 on June 20 (249 µg/L); t-NH_3 concentrations were highest in Harold Brook during 5 sampling events. While each tributary experienced spikes in t-NH_3 concentrations, on October 3 the t-NH_3 concentration in Bear Swamp Creek was 246 µg/L, nearly 6 times greater than the median value (Table 11). Although t-NH_3 responded to high flow events, no statistically significant relationships were identified for any of the major tributaries (Figure A.4.).

Table 11. Mean ± standard deviation ($\bar{X}$), median (M), and number of observations (n) of total nitrogen (TN), nitrate (NO_x), and total ammonia (t-NH_3) concentrations measured in the major tributaries to Skaneateles Lake in 2019.

Tributary	TN (µg/L)			NO_x (µg/L)			t-NH_3 (µg/L)		
	$\bar{X}$	M	n	$\bar{X}$	M	n	$\bar{X}$	M	n
Bear Swamp Creek	865 ± 411	722	19	513 ± 270	441	19	52 ± 54	40	18
Grout Brook	1497 ± 296	1560	19	1194 ± 369	1340	19	36 ± 31	27	18
Shotwell Brook	1310 ± 328	1240	21	876 ± 387	893	21	53 ± 30	50	21
Harold Brook	2113 ± 769	2090	19	1573 ± 681	1820	19	57 ± 72	26	18

Table 12. Mean ± standard deviation ($\bar{X}$), median (M), and number of observations (n) of total nitrogen (TN), nitrate (NO_x), and total ammonia (t-NH_3) concentrations measured in the major tributaries to Skaneateles Lake in 2018.

Tributary	TN (µg/L)			NO_x (µg/L)			t-NH_3 (µg/L)		
	$\bar{X}$	M	n	$\bar{X}$	M	n	$\bar{X}$	M	n
Bear Swamp Creek	836 ± 196	790	17	455 ± 241	423	17	21 ± 14	20	17
Grout Brook	1462 ± 277	1440	18	1191 ± 371	1195	18	19 ± 13	19	18
Shotwell Brook	1972 ± 1749	1470	18	1454 ± 1567	951	18	36 ± 34	27	18
Harold Brook	2494 ± 635	2505	18	2149 ± 748	2180	18	22 ± 14	21	18

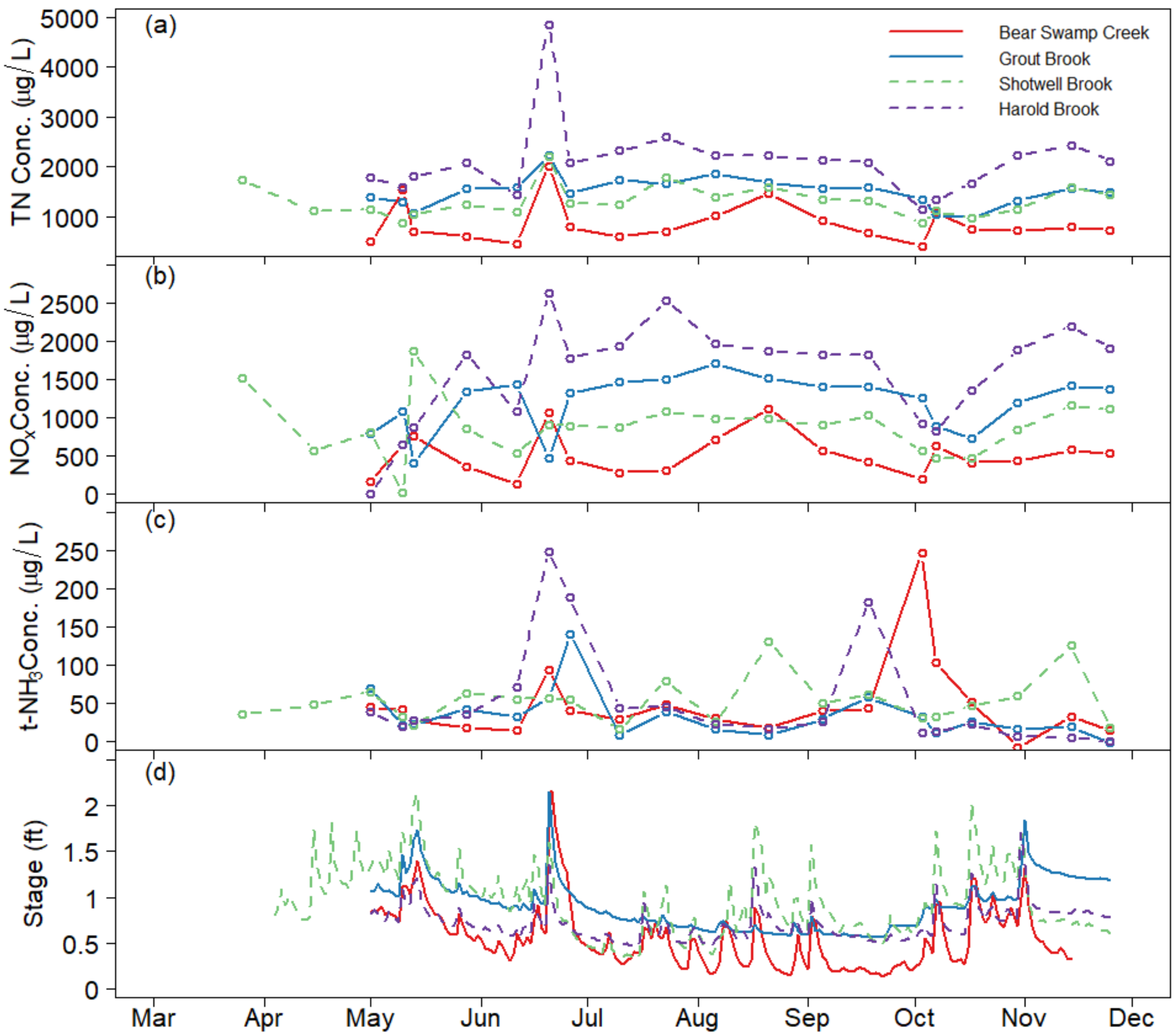

Figure 30. Time series of nitrogen concentrations and stage (ft) of Bear Swamp Creek, Grout Brook, Shotwell Brook, and Harold Brook in 2019: (a) total nitrogen (TN), (b) nitrate+nitrite (NO_x), (c) total ammonia (t- NH_3), and (d) daily average stage.

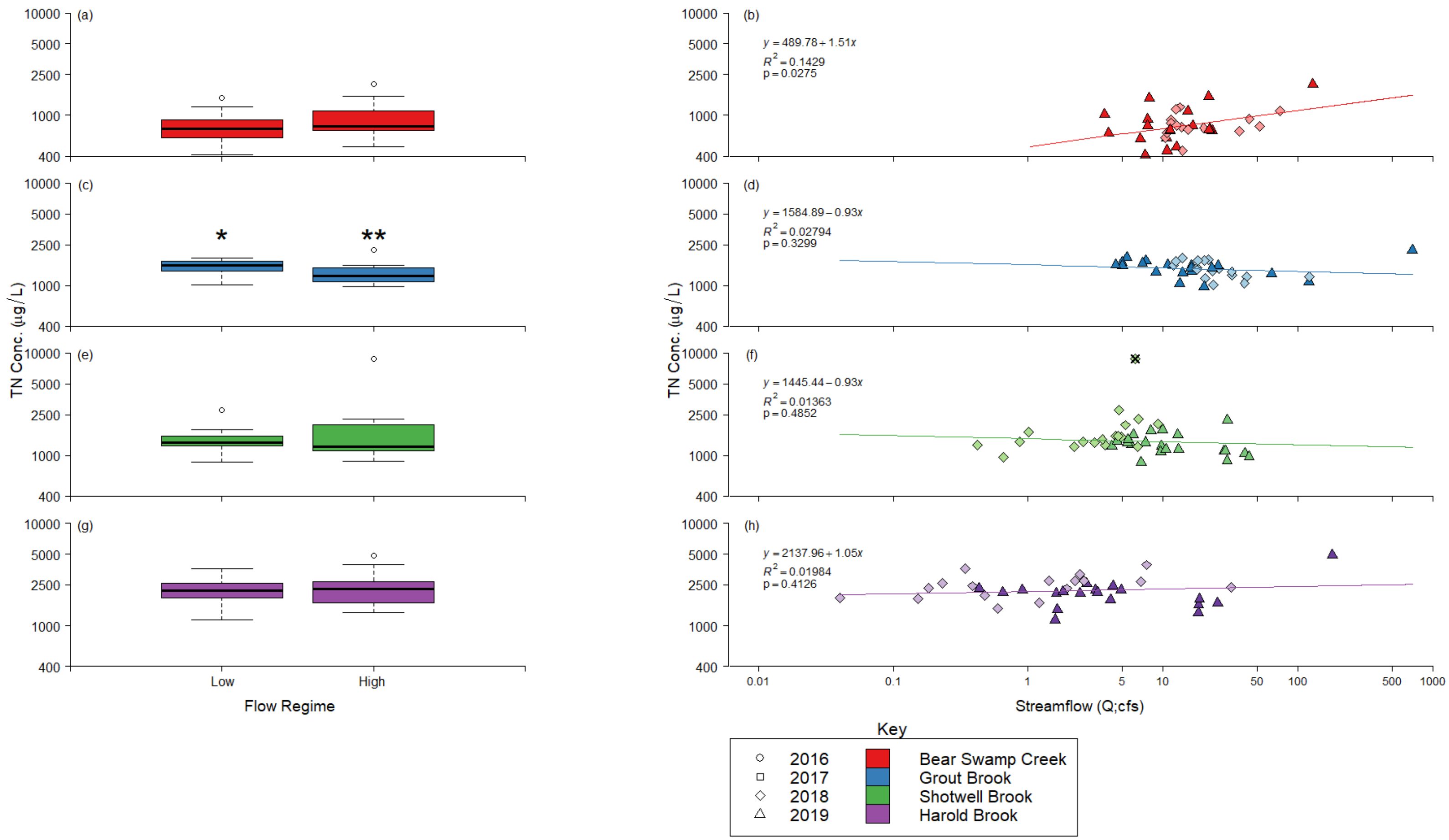

Figure 31. Comparison of total nitrogen (TN) concentration measured during high and low flow regimes (a,c,e,g) and relationship between TN and flow (b,d,f,h) in (a,b) Bear Swamp Creek (2018-2019), (c,d) Grout Brook (2018-2019), (e,f) Shotwell Brook (2016-2019), and (g,h) Harold Brook (2018-2019). Statistically significant differences between concentrations within each tributary is denoted with * and **. Linear relationship equation and statistical significance shown within plot. "X" indicates point not used for regression.

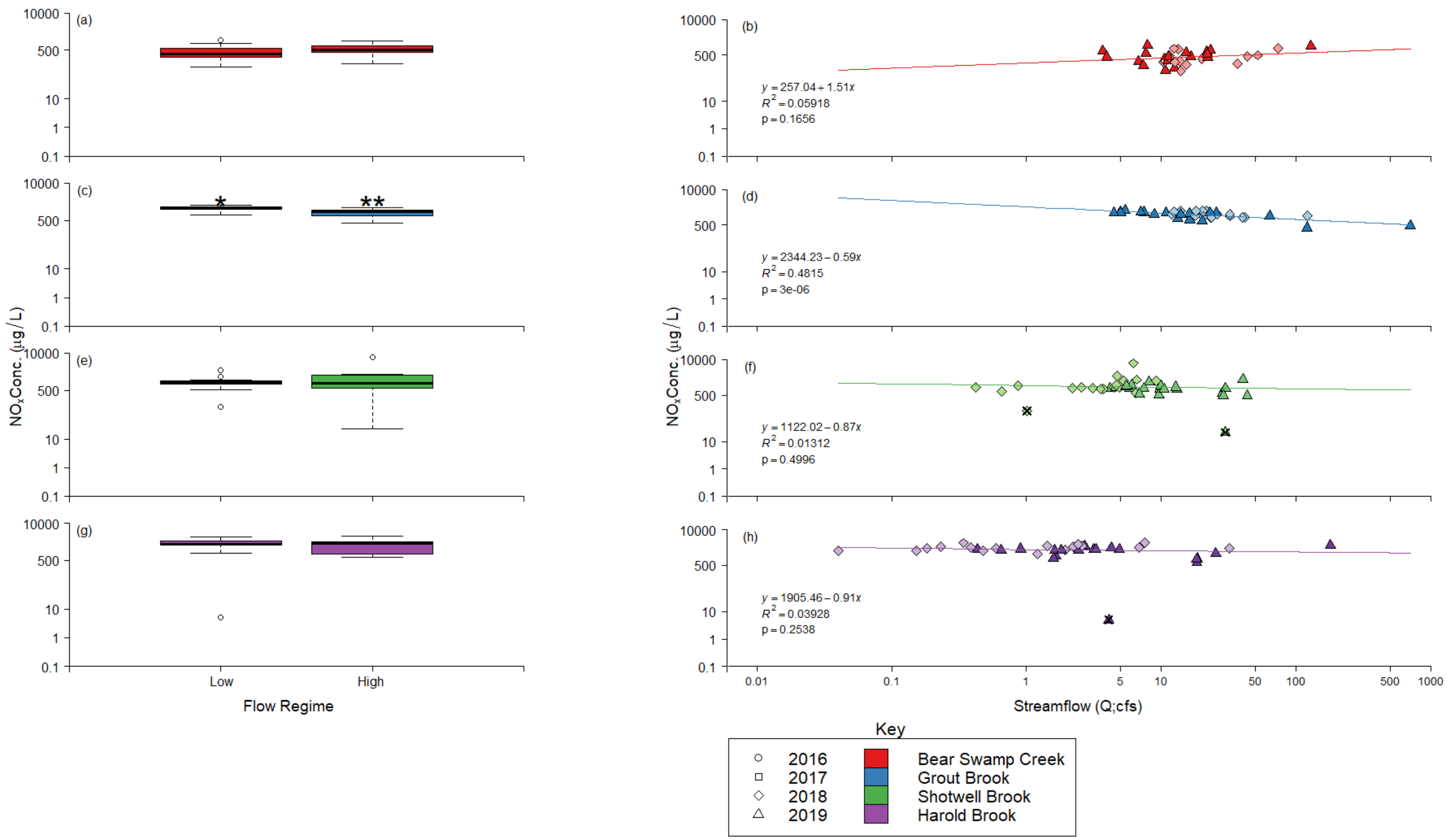

Figure 32. Comparison of nitrate+nitrite (NO_x) concentration measured during high and low flow regimes (a,c,e,g) and relationship between NO_x and flow (b,d,f,h) in (a,b) Bear Swamp Creek (2018-2019), (c,d) Grout Brook (2018-2019), (e,f) Shotwell Brook (2016-2019), and (g,h) Harold Brook (2018-2019). Statistically significant differences between concentrations within each tributary is denoted with * and **. Linear relationship equation and statistical significance shown within plot. "X" indicates points not used for regression.

3.2.3. Carbon

Dissolved and particulate organic carbon (DOC and POC) are two organic carbon fractions that contribute to the food web and can affect water quality. Carbon, like other water quality compounds, cycles and takes on many forms. Dissolved organic carbon is derived from decomposition of plants and other aquatic life. Depending on the complexity of the molecule, DOC can either be consumed by bacteria (e.g. sugars, proteins) or add color to the water (e.g. humic substances; Kalff 2002). Particulate organic carbon can include plankton, bacteria, and detritus. Organic carbon typically has a natural origin, but can also be present in streams where manure is used to fertilize soils. Both DOC and POC are important components of the carbon cycle that support algal growth.

Bear Swamp Creek and Shotwell Brook had similar mean and median DOC concentrations in 2019 (Table 13). Each tributary experienced an increase in DOC during three major rain events (May 10, June 20, and October 7; Figure 33); DOC remained elevated 10 days after the event on October 7 in all tributaries. Grout Brook had the lowest DOC concentrations compared to the other major tributaries throughout the monitoring period (Table 13). This may be related to groundwater inputs or relationships with land use. Concentrations of POC in the major tributaries were typically below or around 1 mg/L, and increased on days with elevated streamflow (Figure 33). The high POC concentrations observed this year (especially in May and June) were orders of magnitude greater than the highest values observed in 2018, thus affecting the mean POC concentrations observed (UFI 2019; Tables 13, 14). Greater POC values were observed in 2019 most likely due to sampling higher flows (e.g. Figure 35f, h). Significant, positive relationships between DOC and POC and flow were detected in all of the major tributaries (Figures 34, 35).

Table 13. Mean ± standard deviation ($\bar{X}$), median (M), and number of observations (n) of dissolved organic carbon (DOC) and particulate organic carbon (POC) concentrations measured in the major tributaries to Skaneateles Lake in 2019.

Tributary	DOC (mg/L)			POC (mg/L)		
	$\bar{X}$	M	n	$\bar{X}$	M	n
Bear Swamp Creek	5.2 ± 1.1	5.2	19	1.3 ± 3.1	0.3	19
Grout Brook	2.2 ± 1.4	1.6	19	2.9 ± 6.9	0.3	19
Shotwell Brook	5.6 ± 1.5	5.2	21	1.1 ± 1.6	0.7	21
Harold Brook	3.9 ± 1.8	3.1	19	2.1 ± 4.9	0.3	19

Table 14. Mean ± standard deviation ($\bar{X}$), median (M), and number of observations (n) of dissolved organic carbon (DOC) and particulate organic carbon (POC) concentrations measured in the major tributaries to Skaneateles Lake in 2018.

Tributary	DOC (mg/L)			POC (mg/L)		
	$\bar{X}$	M	n	$\bar{X}$	M	n
Bear Swamp Creek	6.0 ± 1.9	5.7	17	0.3 ± 0.2	0.2	16
Grout Brook	2.1 ± 1.1	1.7	18	0.2 ± 0.2	0.2	17
Shotwell Brook	5.7 ± 2.2	5.3	18	0.4 ± 0.4	0.2	17
Harold Brook	3.8 ± 1.8	3.1	18	0.4 ± 0.3	0.4	17

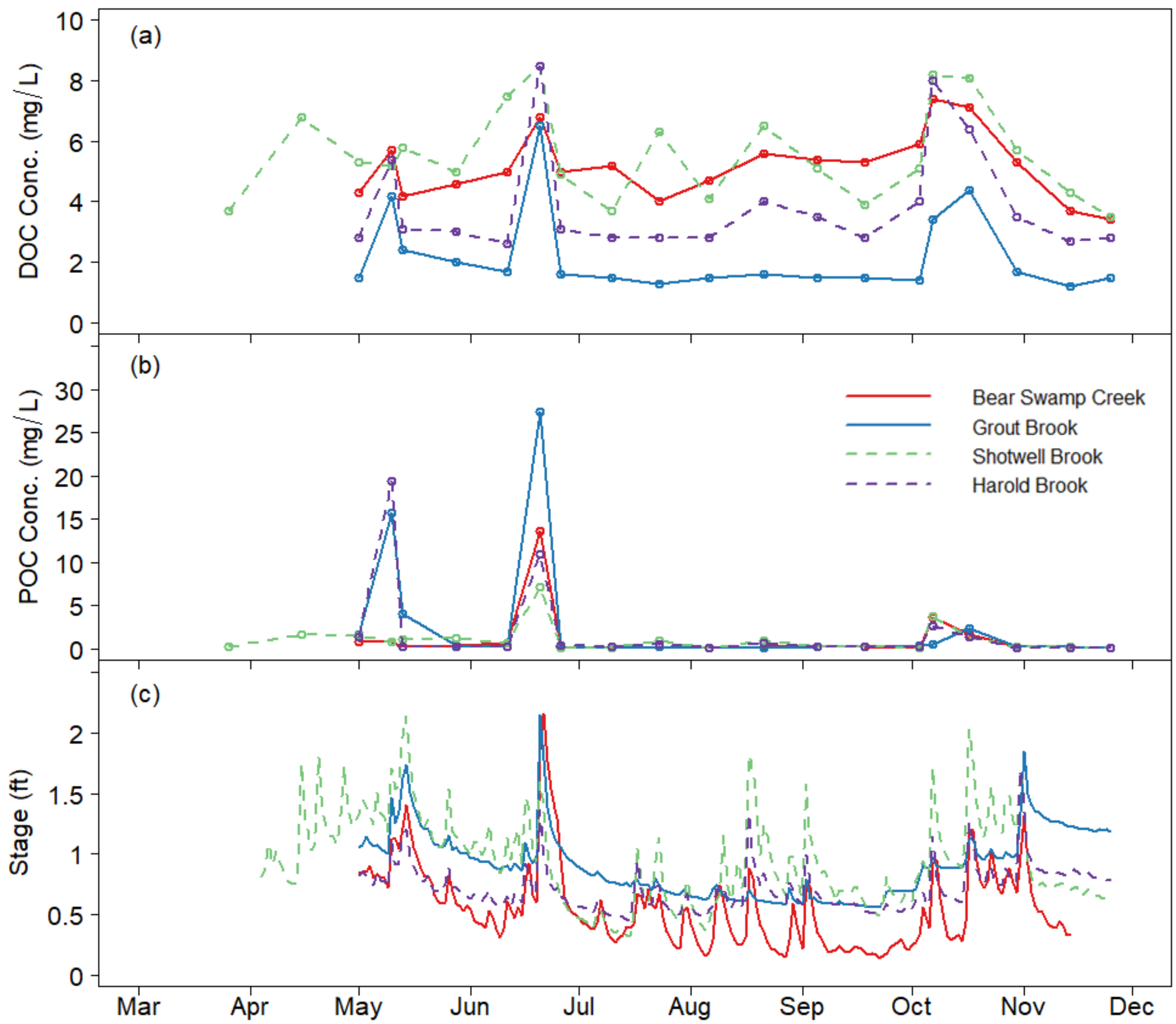

Figure 33. Time series of carbon concentrations of Bear Swamp Creek, Grout Brook, Shotwell Brook, and Harold Brook in 2019: (a) dissolved organic carbon (DOC), (b) particulate organic carbon (POC), and (c) daily average stage.

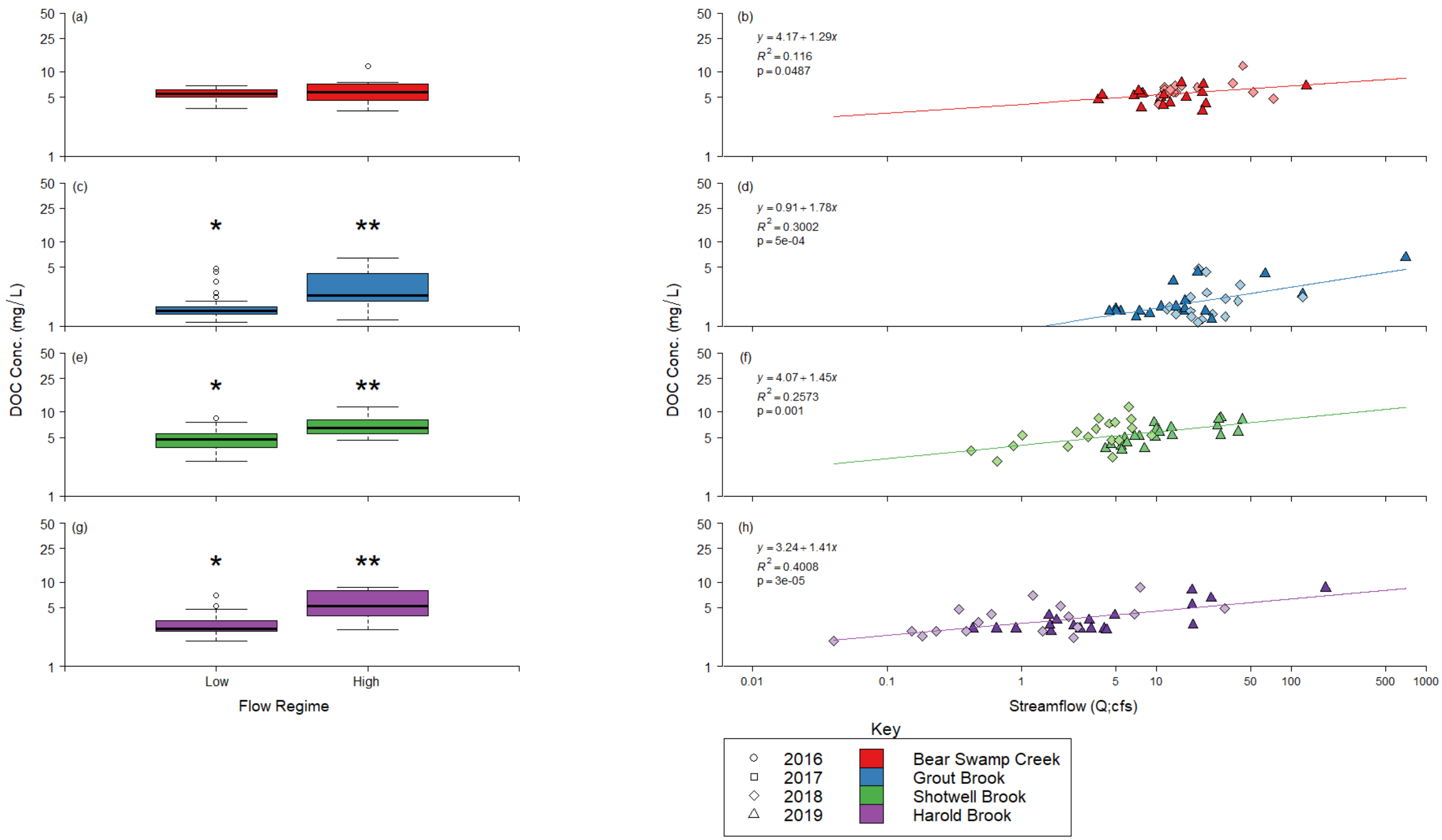

Figure 34. Comparison of dissolved organic carbon (DOC) concentration measured during high and low flow regimes (a,c,e,g) and relationship between DOC and flow (b,d,f,h) in (a,b) Bear Swamp Creek (2018-2019), (c,d) Grout Brook (2018-2019), (e,f) Shotwell Brook (2016-2019), and (g,h) Harold Brook (2018-2019). Statistically significant differences between concentrations within each tributary is denoted with * and **. Linear relationship equation and statistical significance shown within plot.

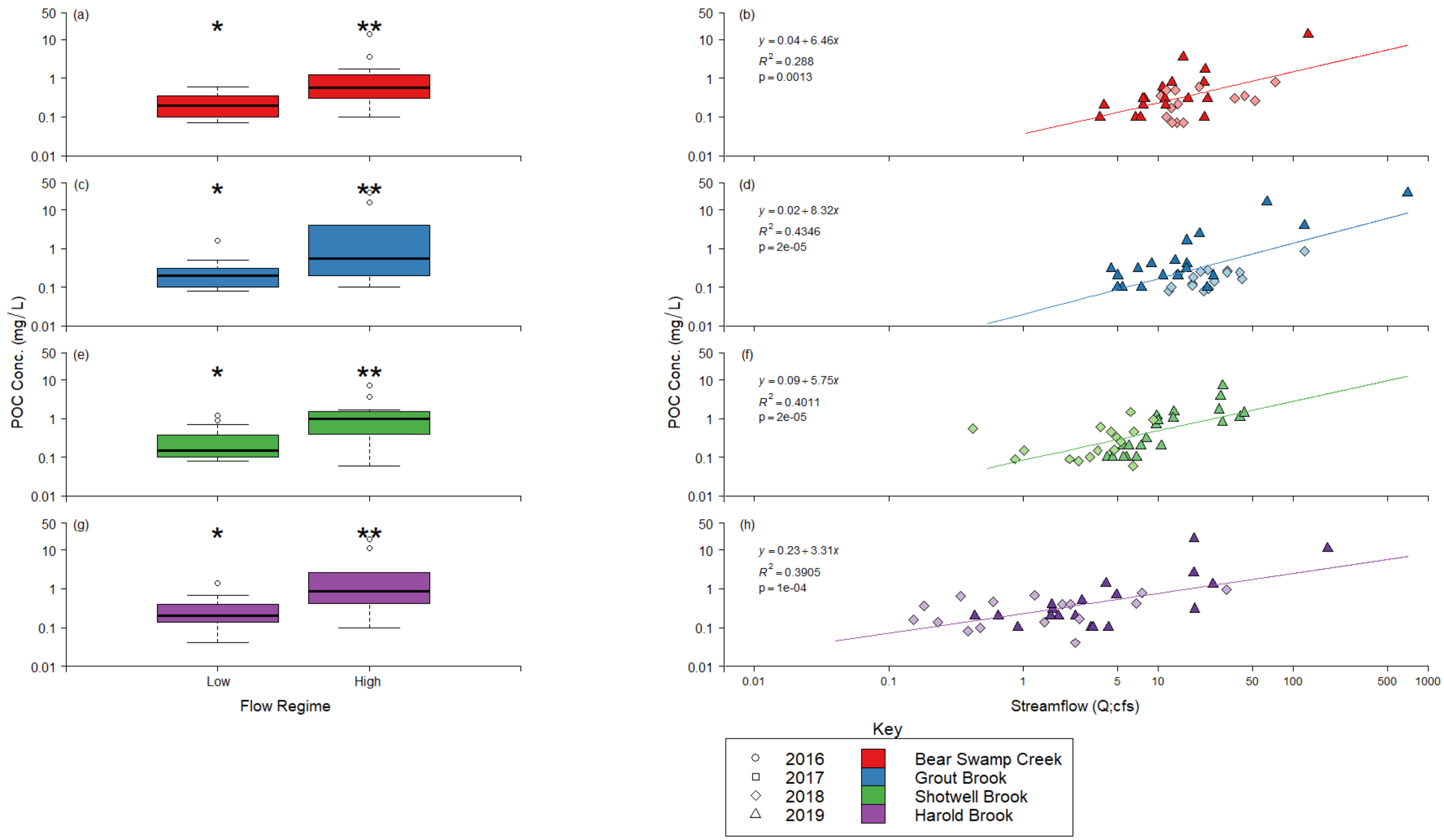

Figure 35. Comparison of particulate organic carbon (POC) concentration measured during high and low flow regimes (a,c,e,g) and relationship between POC and flow (b,d,f,h) in (a,b) Bear Swamp Creek (2018-2019), (c,d) Grout Brook (2018-2019), (e,f) Shotwell Brook (2016-2019), and (g,h) Harold Brook (2018-2019). Statistically significant differences between concentrations within each tributary is denoted with * and **. Linear relationship equation and statistical significance shown within plot.

3.2.4. Silica, turbidity, total suspended sediments

Total suspended solids (TSS) include clay and silt particles, plankton, small organic fragments, and other particulates that often originate from the watershed. Turbidity (Tn) is an optical measurement that measures the presence of suspended particles. Turbidity and suspended solids measurements are both related to the quantity of particles suspended in the water. Solids can originate from eroded land/streambanks, wastewater discharges, fertilizers, and road runoff. Not only can the particulates that enter the lake contribute to nutrient loading, but high TSS or Tn can affect water clarity and temperature, which can subsequently alter aquatic macrophyte and animal communities. Additionally, solids can affect palatability and safety of drinking water drawn from the lake. This monitoring period was the first to measure FSS and VSS, which are subcomponents of TSS. Fixed suspended solids describe the particulates that are inorganic (e.g. undissolved salts and silt), whereas volatile suspended solids are particles that are organic. Together, FSS and VSS make up the total suspended solids (TSS); the fraction of each part can be indicative of erosion, runoff, or biological processes.

Silica is a micronutrient that is important to certain algal groups (i.e. diatoms) and some aquatic plants. Silica (Si) concentrations can influence algal succession within a waterbody, therefore affecting the overall productivity of the waterbody (Wetzel 2001). Typically, in lakes, Si concentrations are higher in the spring then gradually decline over the summer as they are used by diatoms. Diatoms are often prevalent during these times when Si is plentiful, and then they are replaced by other algal groups (e.g. green algae, cyanobacteria) who do not rely on Si to create outer coverings when Si concentrations decline. In streams, silica originates from natural weathering of rocks and sediments or groundwater.

Throughout the monitoring program, we observed similar, expected temporal relationships with increased turbidity and suspended solids observed during periods of higher flow in each tributary (Figure 37). The maximum turbidity, TSS, FSS, and VSS were observed on June 20 in each tributary (Figure 37b, c, d). Grout Brook and Bear Swamp Creek experienced severe flooding on June 20 so high turbidity and solids concentrations were expected. Turbidity was often low, though, with over 75% of each tributary’s samples less than 10 NTU. As expected, a majority of the TSS concentrations in each tributary were also low (under 10 mg/L); of these samples, more than half of the low-TSS samples from Grout Brook and Shotwell Brook were less than 1 mg/L. Median turbidity and TSS values in 2019 were similar to those observed in 2018 (Tables 15, 16). The mean values in Bear Swamp Creek and Grout Brook in 2019 were greater than the 2018 mean (+ 1 standard deviation), though.

Flow regime greatly affected turbidity and TSS concentrations in the streams, and a positive linear trend was identified in most of the major tributaries (Figures 38, 39). The range in VSS (as a percentage of TSS) was similar in Bear Swamp Creek (7-100%) and Grout Brook (10-100%). VSS did not get as high in Shotwell Brook and Harold Brook (maximum 86% and 82%). On October 3 and 30 in Shotwell Brook, and August 6 in Grout Brook, VSS exceeded TSS. Relationships between flow and suspended solids support that increased concentrations of solids (i.e. FSS and VSS) were related to increased flows (Figures 40, 41); however, it is important to mention that the contributions of FSS and VSS to TSS change with flow as well. There were significant decreases in the VSS contribution to TSS with increasing flow in Bear Swamp Creek, Grout Brook, and Shotwell Brook (Figure 42).

Silica concentrations generally increased during the late spring then decreased in the fall (Figure 43). Most of the peak concentrations in the major tributaries were observed in late July and/or in early October. Grout Brook had the highest Si concentration over the monitoring period, but values were similar to those observed in the other tributaries (Table 15). Silica concentrations were mostly similar to those measured in 2018 (Table 16). The only significant relationship between Si and flow was in Grout Brook, with Si decreasing in conjunction with increasing flows ($p < 0.05$; Figure 44).

Figure 36. Shotwell Brook on November 25, 2019.

Table 15. Mean ± standard deviation ($\bar{X}$), median (M), and number of observations (n) of turbidity (Tn), total suspended solids (TSS), fixed suspended solids (FSS), volatile suspended solids (VSS), and silica (Si; derived from SiO_2) concentrations measured in the major tributaries to Skaneateles Lake in 2019.

Tributary	Tn (NTU)			TSS (mg/L)			FSS (mg/L)			VSS (mg/L)			Si (mg/L)		
	$\bar{X}$	M	n	$\bar{X}$	M	n	$\bar{X}$	M	n	$\bar{X}$	M	n	$\bar{X}$	M	n
Bear Swamp Creek	45 ± 131	2	19	82 ± 230	3	19	78 ± 216	2	18	8 ± 21	1	18	2.4 ± 0.6	2.5	19
Grout Brook	65 ± 237	1	19	70 ± 231	2	19	69 ± 220	2	17	9 ± 23	1	18	2.9 ± 0.8	3.1	19
Shotwell Brook	18 ± 50	4	21	23 ± 72	3	21	23 ± 72	2	16	4 ± 10	1	17	2.5 ± 0.8	2.9	21
Harold Brook	28 ± 72	2	19	36 ± 90	2	18	30 ± 77	1	18	6 ± 14	1	18	2.7 ± 0.8	2.9	19

Table 16. Mean ± standard deviation ($\bar{X}$), median (M), and number of observations (n) of turbidity (Tn), total suspended solids (TSS), and silica (Si; derived from SiO_2) concentrations measured in the major tributaries to Skaneateles Lake in 2018.

Tributary	Tn (NTU)			TSS (mg/L)			Si (mg/L)		
	$\bar{X}$	M	n	$\bar{X}$	M	n	$\bar{X}$	M	n
Bear Swamp Creek	11 ± 29	2	17	21 ± 48	3	15	2.5 ± 0.6	2.5	17
Grout Brook	3 ± 3	1	18	4 ± 6	2	17	3.1 ± 0.5	3.2	18
Shotwell Brook	10 ± 30	2	22	15 ± 46	2	17	3.0 ± 0.7	3.3	18
Harold Brook	25 ± 67	3	17	33 ± 86	5	17	2.8 ± 0.5	2.9	18

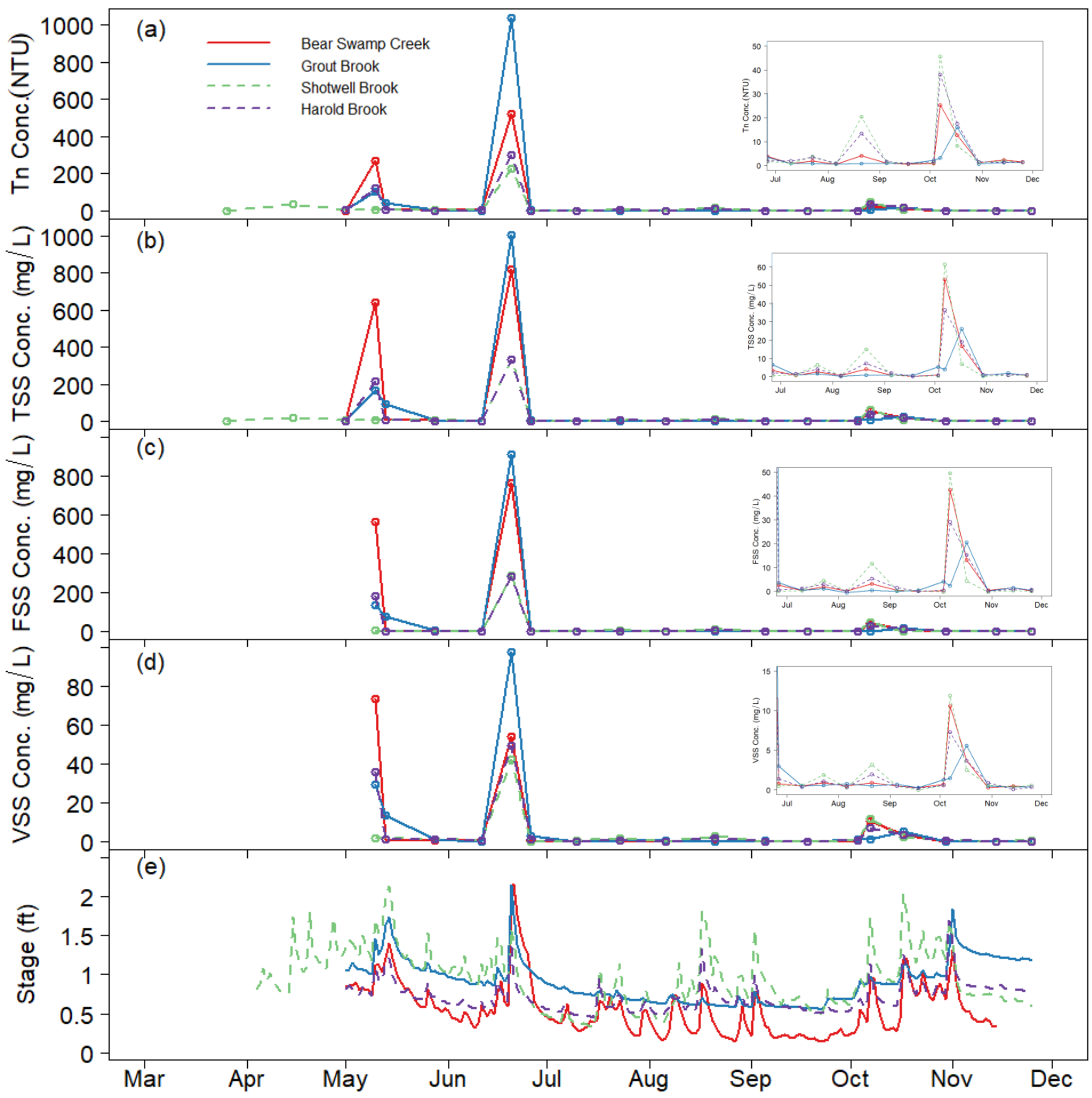

Figure 37. Time series of (a) turbidity (Tn), (b) total suspended solids (TSS), (c) fixed suspended solids (FSS), (d) volatile suspended solids (VSS), and (d) daily average stage in the 4 major tributaries to Skaneateles Lake, 2019. Inset plots show values from July 1 through December at a different scale.

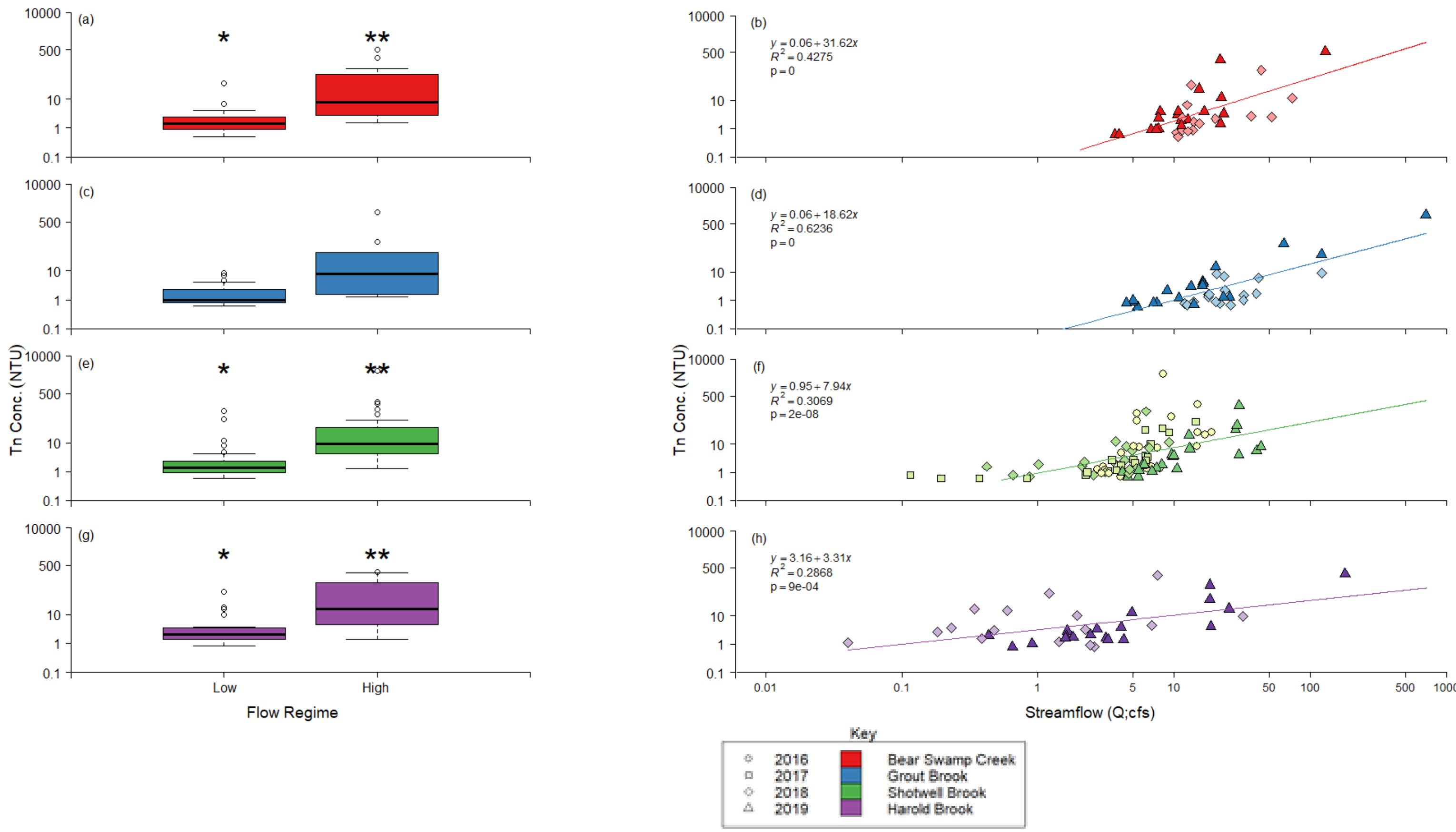

Figure 38. Comparison of turbidity (Tn) concentration measured during high and low flow regimes (a,c,e,g) and relationship between turbidity and flow (b,d,f,h) in (a,b) Bear Swamp Creek (2018-2019), (c,d) Grout Brook (2018-2019), (e,f) Shotwell Brook (2016-2019), and (g,h) Harold Brook (2018-2019). Statistically significant differences between concentrations within each tributary is denoted with * and **. Linear relationship equation and statistical significance shown within plot.

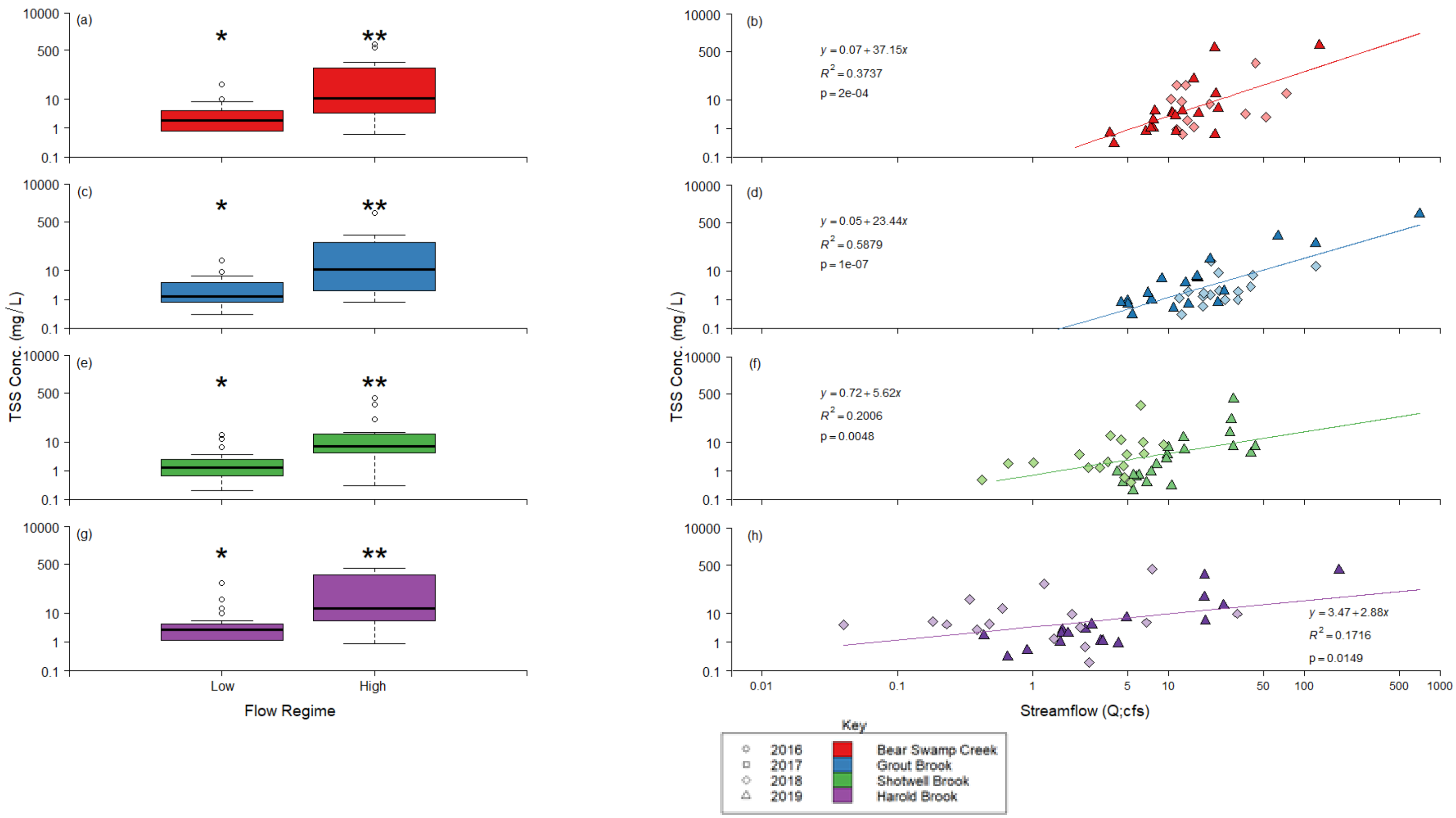

Figure 39. Comparison of total suspended solids (TSS) concentration measured during high and low flow regimes (a,c,e,g) and relationship between TSS and flow (b,d,f,h) in (a,b) Bear Swamp Creek (2018-2019), (c,d) Grout Brook (2018-2019), (e,f) Shotwell Brook (2016-2019), and (g,h) Harold Brook (2018-2019). Statistically significant differences between concentrations within each tributary is denoted with * and **. Linear relationship equation and statistical significance shown within plot.

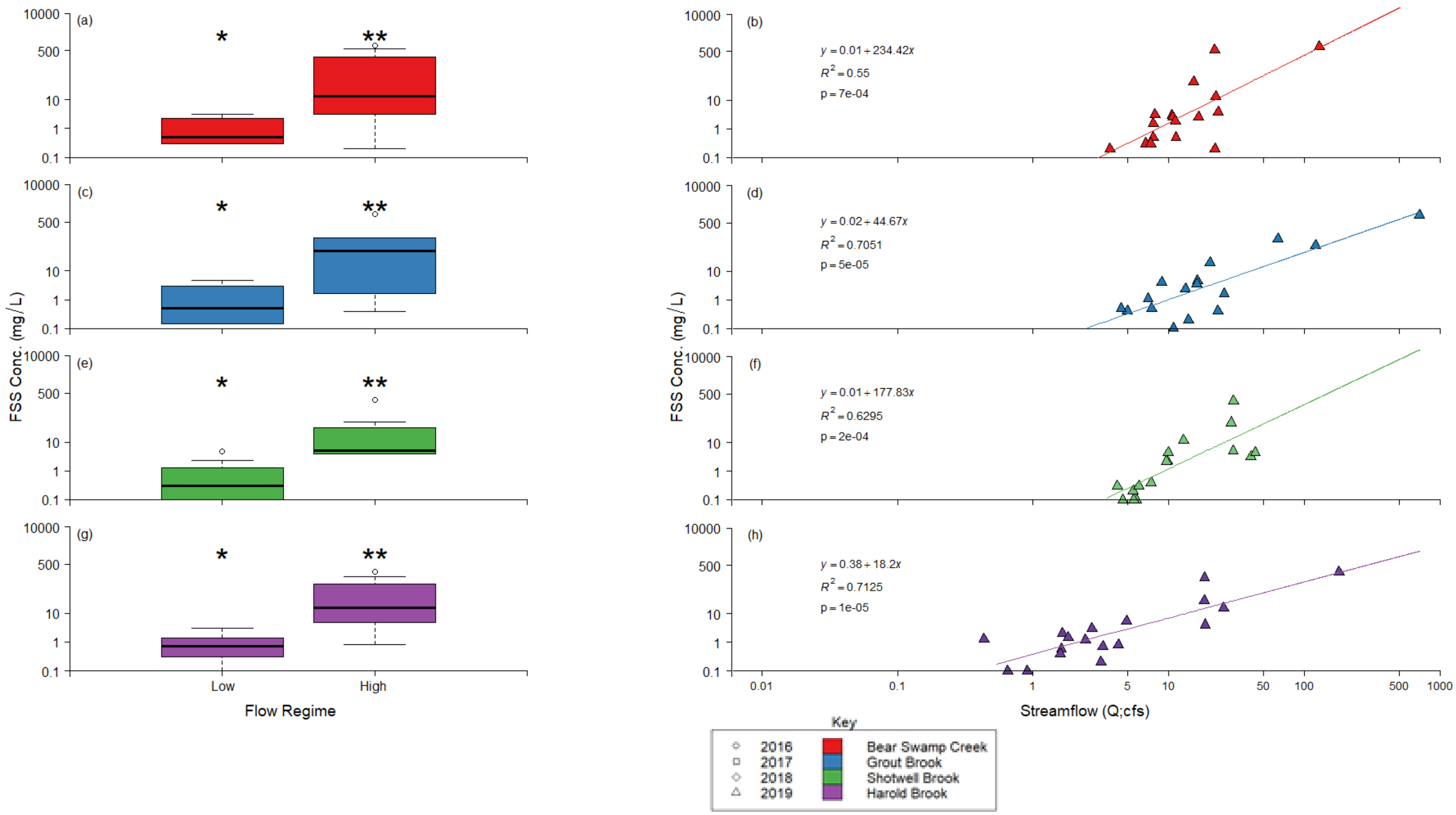

Figure 40. Comparison of fixed suspended solids (FSS) concentration measured during high and low flow regimes (a,c,e,g) and relationship between FSS and flow (b,d,f,h) in (a,b) Bear Swamp Creek (2018-2019), (c,d) Grout Brook (2018-2019), (e,f) Shotwell Brook (2016-2019), and (g,h) Harold Brook (2018-2019). Statistically significant differences between concentrations within each tributary is denoted with * and **. Linear relationship equation and statistical significance shown within plot.

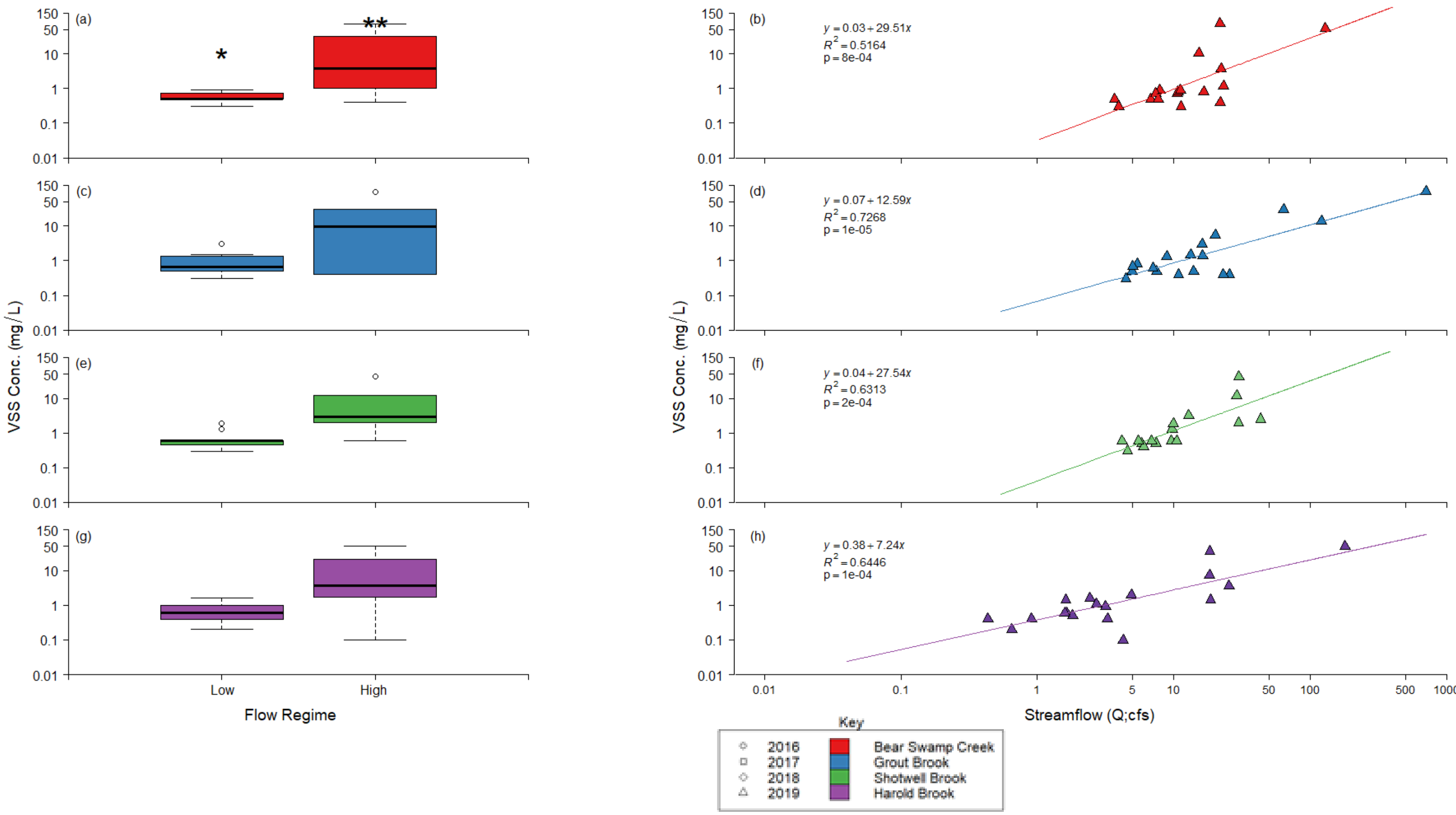

Figure 41. Comparison of volatile suspended solids (VSS) concentration measured during high and low flow regimes (a,c,e,g) and relationship between VSS and flow (b,d,f,h) in (a,b) Bear Swamp Creek (2018-2019), (c,d) Grout Brook (2018-2019), (e,f) Shotwell Brook (2016-2019), and (g,h) Harold Brook (2018-2019). Statistically significant differences between concentrations within each tributary is denoted with * and **. Linear relationship equation and statistical significance shown within plot.

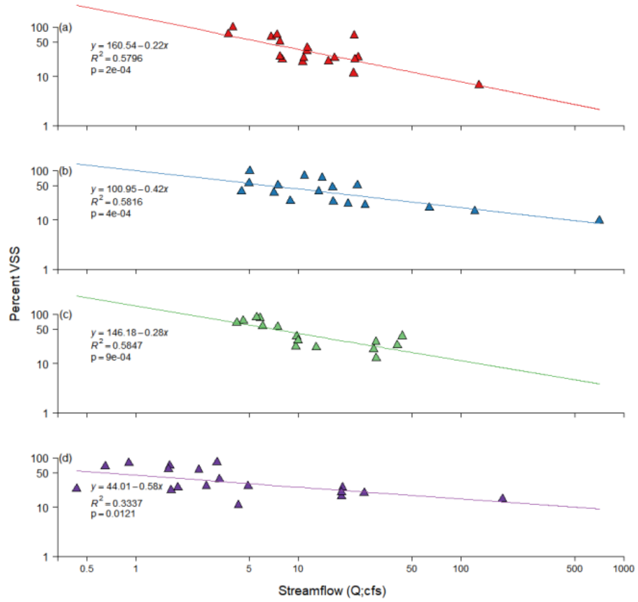

Figure 42. Composition of TSS, as VSS (%), related to flow with average predicted value shown in (a) Bear Swamp Creek, (b) Grout Brook, (c) Shotwell Brook, and (d) Harold Brook. Summary statistics shown within plot.

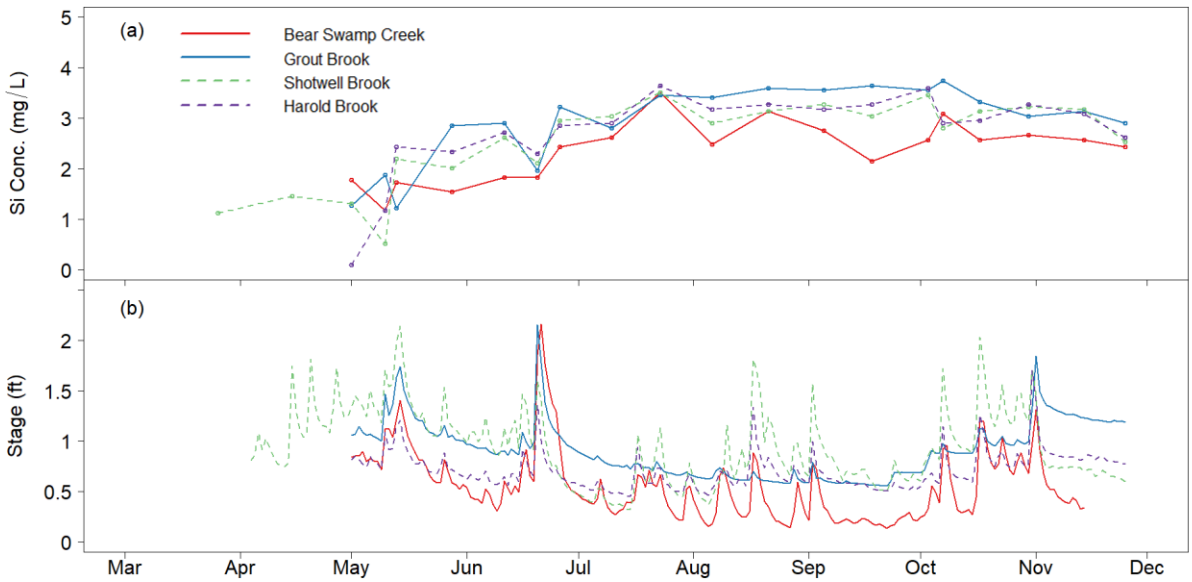

Figure 43. Time series of (a) silica (Si; derived from SiO_2) and (b) stage (ft) in the major tributaries to Skaneateles Lake, 2019.

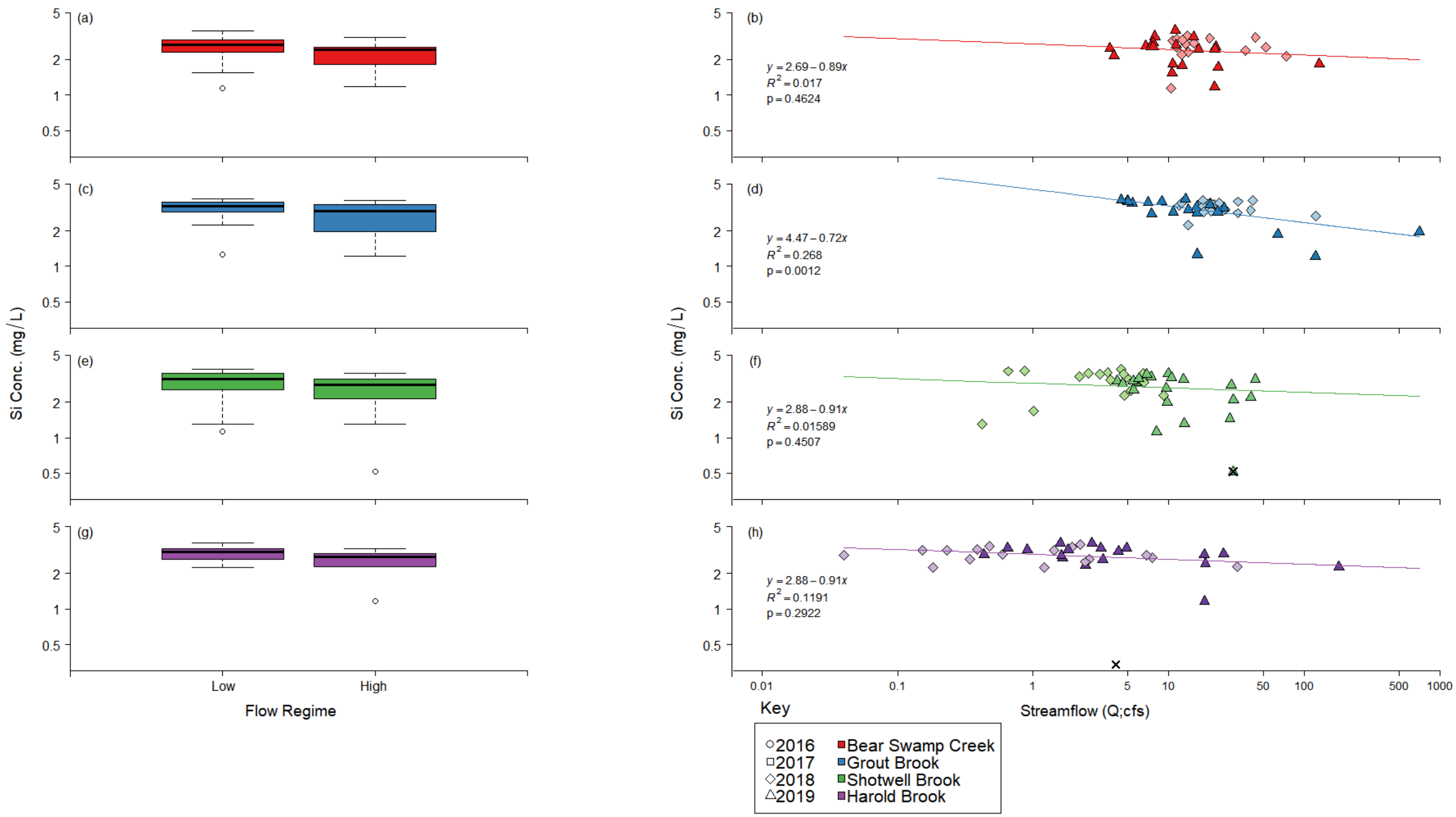

Figure 44. Comparison of silica (Si) concentration measured during high and low flow regimes (a,c,e,g) and relationship between Si and flow (b,d,f,h) in (a,b) Bear Swamp Creek (2018-2019), (c,d) Grout Brook (2018-2019), (e,f) Shotwell Brook (2016-2019), and (g,h) Harold Brook (2018-2019). Statistically significant differences between concentrations within each tributary is denoted with * and **. Linear relationship equation and statistical significance shown within plot. "X" indicates points not used for regression.

4. Results and Discussion – Minor Tributaries

4.1. Visual Assessments and Streamflow

The minor tributaries to Skaneateles Lake varied in size and hydrology throughout the monitoring period, sometimes appearing very different from one week to the next (Figure 46). These streams could be classified as "permanent with interstitial flow" or "intermittent". Intermittent streams have portions that may receive water from a ground water and/or surface source during certain periods of the year, and at low flow may contain dry segments. Ephemeral streams, on the other hand, flow only in response to precipitation within the subwatershed and do not have any influence from ground water (Levick et al. 2008). Perennial or permanent streams contain continuous flow. Perennial streams with interrupted or interstitial flow have dry streambeds with isolated pools that are connected via water flow beneath the surface of the streambed (Ohio EPA 2009). Upper Bear Swamp, Five Mile Creek, and Snow Brook were always observed with some flow (although it may not have been across the width of the channel). One Mile Creek was often observed with low, continuous flow, but it was also seen ponded once during the monitoring period. The streambeds of Glen Cove and Randall Gulf were dry on 1 and 2 days, respectively. It is likely that portions of the streams were dry or severely ponded for multiple days during the monitoring period, especially during the hottest and driest periods, that could not be observed with the monitoring schedule. Averaged streamflows include periods of ponded/dry conditions and high flow conditions, so more information is needed to best characterize these streams.

Upper Bear Swamp was the deepest minor tributary and had the second greatest streamflow (Tables 17, 18). Measurements were taken below the culvert on Hartnett Road and throughout the monitoring period build-up of debris against the upstream culvert and downstream beaver activity caused this section to become more impounded. Fish were present in this upstream portion of the major tributary. The greatest estimated flow at this site (33.14 cfs) was measured on June 20. Five Mile Creek was often observed at low, continuous flow. The rocky substrate within the streambed sometimes caused the flow to not be continuous across the entire width of the stream. On November 14, Five Mile Creek was partially frozen over. The highest flow in this tributary was observed on June 20 at 31.16 cfs. Glen Cove was noted for clarity during periods of low flow and was nearly covered in ice in early November. This site had the second greatest average depth following Upper Bear Swamp (Table 17). Despite its depth, the estimated flow was the second lowest of the minor tributaries (Table 18). Glen Cove flow was mostly low and continuous, but the flow was not always continuous across the width of the channel. Geese were observed at the mouth of the tributary in Skaneateles Lake, and a duckling was found at the monitoring site once. One Mile Creek was the smallest tributary monitored and, as expected, had the smallest streamflow (Tables 17, 18). Flow was often very low yet continuous across the width of the stream. Randall Gulf was one of the most dynamic streams monitored. It had dry periods in addition to a large, flashy event (June 20) that transferred a large amount of rock near the mouth of the tributary (See Figure 45 for relative amount excavated material). In early November, the stream was covered with ice except for a small channel of flowing water. Despite being dry/severely ponded twice during the monitoring period, Randall Gulf had the highest estimated average streamflow (11.82 cfs; Table 18). Snow Brook was often observed at low, continuous flow. Even though Snow Brook was narrower than the tributary at Glen Cove (Table 17), it had a greater average streamflow than Glen Cove and the third lowest average streamflow of the monitored minor tributaries (Table 18).

Figure 45. Rocks deposited during June 20 storm and removed from streambed (on both sides of bridge) at the mouth of Randall Gulf. For scale, man shown is approximately 5’11” tall.

Figure 46. Range of flow conditions in the minor tributaries of Skaneateles Lake in 2019. Top panel shows conditions on August 6 and bottom panel shows conditions on June 20. On August 6, maximum temperature of 82 °F (average 68 °F) and approximately cumulative 1 in. precipitation occurring 1 week prior. On June 20, maximum temperature of 80 °F (average 71 °F) and greater than 1 in. precipitation over course of 3 days.

Table 17. Summary of stream width and depth measurements taken for the visual assessments of minor tributaries to Skaneateles Lake in 2019. Number of measurements shown in parentheses next to tributary name.

Tributary	Average width (m)	Average depth (m)	Minimum width (m)	Maximum width (m)	Minimum depth (m)	Maximum depth (m)
Upper Bear Swamp (8)	2.92	0.24	2.18	3.28	0.06	0.50
Five Mile Creek (9)	2.98	0.10	1.22	5.18	0.03	0.22
Glen Cove (9)	2.90	0.15	2.13	3.96	0.06	0.38
Randall Gulf (8)	2.65	0.08	0.81	6.55	0.03	0.10
Snow Brook (9)	1.23	0.13	0.99	1.57	0.08	0.24
One Mile Creek (8)	1.06	0.06	0.25	1.35	0.01	0.09

Table 18. Summary of velocity, cross-sectional area, and estimated streamflow of minor tributaries to Skaneateles Lake in 2019. Number of measurements shown in parentheses.

Tributary	Average velocity (ft/s)	Average cross-sectional area (ft^2)	Average flow (cfs)
Upper Bear Swamp	0.75 (8)	8.8 (9)	7.86 (8)
Five Mile Creek	1.54 (9)	3.4 (8)	7.28 (8)
Glen Cove	0.81 (8)	3.3 (8)	3.54 (8)
Randall Gulf	2.01 (7)	5.5 (7)	11.82 (7)
Snow Brook	1.47 (9)	2.5 (9)	5.60 (9)
One Mile Creek	0.94 (8)	2.2 (9)	2.70 (8)

4.2. Water quality

Over 100 tributaries, mostly smaller than those that were selected for this monitoring program, enter Skaneateles Lake. Although these tributaries are small, in aggregate they can affect the water quality of Skaneateles Lake. Most annual loading from tributaries is done in short, bursts typically following rain events (O'Donnell and Effler 2006). Due to their smaller catchment areas, minor tributaries typically are more likely to rapidly respond to localized rain events than larger tributaries. This could result in multiple opportunities for loading in smaller tributaries throughout the year. Until recent efforts by UFI, Syracuse University, and SUNY-ESF, the flow and water quality of the minor tributaries to Skaneateles Lake have never been intensely monitored. The data presented here may serve as baseline measurements for future monitoring efforts and will help provide more accurate total loading estimates for watershed and water quality models for Skaneateles Lake.

Similarly to the major tributaries, water quality within the minor tributaries varied throughout the monitoring season. Relationships between water quality parameters and flow may be present; however, with the limited data set, there were fewer statistically significant relationships (significance level set as $p < 0.1$), and the relationships were generally weak (e.g., $R^2 < 0.50$; Table 19). Continued monitoring would help identify significant trends and potential areas for best management practices such as flow regulation or riparian buffer zones. This monitoring program focused on sampling during periods of high flow, and the mean and median values should not be directly compared with results from the major tributaries (which included more dry weather samples).

Figure 47. Snow Brook on October 3, 2019.

Table 19. Summary of linear relationships between flow and water quality parameters of the minor tributaries to Skaneateles Lake in 2019. Numbers within table represent R^2 (fit) between flow and analyte. Lightly shaded values are relationships with p-values between 0.1 and 0.2, and darkly shaded represents values < 0.1. The color indicates a positive (blue) or negative (red) significant relationship.

Tributary	Parameter															
	TP	TDP	SRP	PP	DOP	SC	TN	NO_x	t-NH_3	Tn	TSS	FSS	VSS	Si	DOC	POC
Upper Bear Swamp	0.00	0.01	0.01	0.03	0.09	0.06	0.05	0.00	0.16	0.00	0.00	0.49	0.00	0.06	0.22	0.24
Five Mile Creek	0.50	0.70	0.25	0.28	0.49	0.04	0.87	0.44	0.10	0.40	0.43	0.40	0.45	0.33	0.66	0.48
Glen Cove	0.70	0.13	0.01	0.54	1*	0.57	0.10	0.12	0.26	0.24	0.19	0.14	0.33	0.14	0.47	0.22
Randall Gulf	0.56	0.09	0.00	0.97	0.42	0.63	0.02	0.67	0.01	0.73	0.54	0.53	0.57	0.81	0.31	0.70
Snow Brook	0.72	0.60	0.25	0.76	0.69	0.53	0.15	0.30	0.09	0.87	0.80	0.76	0.84	0.33	0.83	0.80
One Mile Creek	0.43	0.18	0.18	0.50	0.24	0.45	0.33	0.03	0.00	0.73	0.59	0.65	0.47	0.32	0.23	0.37

*p-value on "perfect fit" not available

Key:

	p-value		
	> 0.2	0.1-0.2	< 0.1
Slope	NA	Positive	Positive
		Negative	Negative

4.2.1. Temperature, specific conductance, turbidity

Temperature, specific conductance, and turbidity were measured *in-situ* with a handheld YSI datasonde 6 times from October to November. Values that were outside the YSI performance ranges (Table A.1.) or were suspect of malfunction were removed from analysis. Specific conductance and turbidity were also analyzed in the laboratory between June and November. One Mile Creek was the warmest on average of the minor tributaries, and was the warmest minor tributary observed for half of the monitoring events over the six month period (Table 20). The temperatures of the minor tributaries generally followed the air temperature pattern with slight variations that are most likely attributed to thermal buffering or other characteristics of the streams. Specific conductance (SC) was on average highest in One Mile Creek and lowest in Upper Bear Swamp (Table 20). The low SC observed at Upper Bear Swamp is similar to the SC observed at the mouth of the tributary (median 215 µS/cm); the stream only becomes slightly more ionically enriched as it reaches the lake. All tributaries showed slight decreases in SC with increased flow; the SC in Glen Cove and Snow Brook had the most significant decrease observed ($p < 0.1$; Figure A.5.). The average specific conductance measured using the YSI was similar to the average specific conductance observed in the laboratory (Table 20).

The highest turbidity at Five Mile Creek was 262.5 NTU on October 17. Five Mile Creek was on average the most turbid of the minor tributaries using both the YSI and laboratory methods (Table 21). Glen Cove had the highest observed laboratory turbidity of 822 NTU on June 20. The highest turbidities for other tributaries was also observed on this date in Randall Gulf (169 NTU) and Snow Brook (264 NTU). Upper Bear Swamp was the least turbid throughout the monitoring period (Figure 48). The turbidity of Upper Bear Swamp was not greatly affected by rain events, as evidenced by the negligible increase observed between the median and average turbidity values observed in the laboratory. Five Mile Creek, Randall Gulf, Snow Brook, and One Mile Creek had significant positive relationships between flow and turbidity ($p < 0.1$; Figure A.6.). More data is necessary to determine the actual significance of these relationships between turbidity and specific conductance and flow.

Table 20. Summary of temperature and specific conductance measured using YSI (October – November 2019) and laboratory methods (June – November 2019) in minor tributaries to Skaneateles Lake. Number of observations shown in parentheses.

Tributary	Average Temperature (°C; YSI)	Average Specific Conductance (µS/cm; YSI)	Average Specific Conductance (µS/cm; Lab)
Upper Bear Swamp	8.99 (5)	178 (5)	180 (8)
Five Mile Creek	9.00 (6)	506 (6)	469 (8)
Glen Cove	8.30 (6)	310 (6)	344 (8)
Randall Gulf	8.37 (6)	365 (6)	364 (7)
Snow Brook	9.24 (6)	429 (6)	429 (8)
One Mile Creek	10.09 (6)	557 (6)	528 (8)

Table 21. Summary of turbidity measured in the laboratory (June – November 2019) in minor tributaries to Skaneateles Lake. Number of observations shown in parentheses.

Tributary	Average Turbidity (NTU; Lab)	Median Turbidity (NTU; Lab)
Upper Bear Swamp	2.4 (9)	2.3 (9)
Five Mile Creek	139.6 (9)	27.0 (9)
Glen Cove	134.2 (9)	11.9 (9)
Randall Gulf	26.6 (8)	1.2 (8)
Snow Brook	64.4 (9)	11.3 (9)
One Mile Creek	30.1 (9)	6.5 (9)

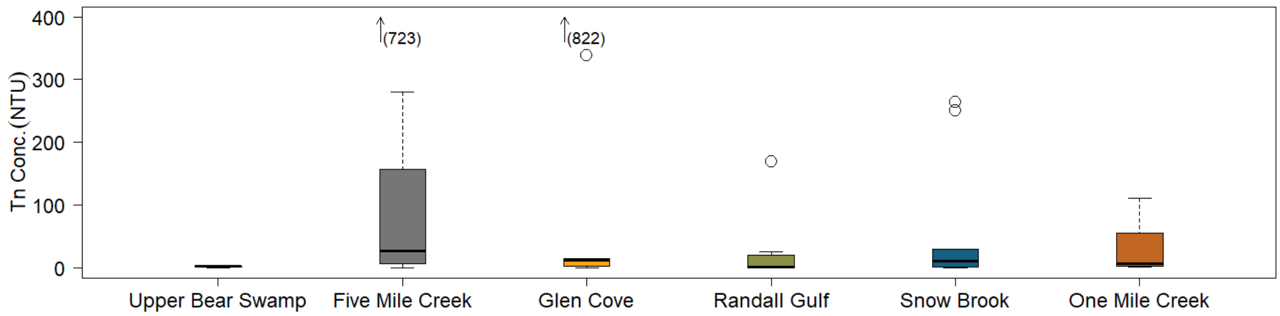

Figure 48. Boxplot of laboratory turbidity (Tn) measurements from the minor tributaries to Skaneateles Lake in 2019.

4.2.2. Phosphorus

The maximum TP concentration observed in the minor tributaries was 1275 µg/L in Five Mile Creek on May 10. The mean and median TP and TDP concentrations in Five Mile Creek were the greatest of the minor tributaries (Table 22; Figure 49). The maximum TDP in Five Mile Creek was on June 20 at 303 µg/L (Figure 50). Both May 10 and June 20 were rain events. Total phosphorus concentrations were often higher in Five Mile Creek than the other minor tributaries throughout the monitoring period (Figures 49, 50). Despite the small size of Snow Brook, it had the second greatest average TP (199.2 µg/L; Table 22). The minimum TP concentration was 6 µg/L in Glen Cove on September 18 (Figure 50). Upper Bear Swamp had the most consistent and low TP concentrations despite changes in season or flow (Figures 49, 50). In relation to flow, TP increased with flow in all tributaries ($p < 0.1$) except Upper Bear Swamp ($p > 0.2$; Table 19). Total dissolved phosphorus significantly increased with flow in Five Mile Creek and Snow Brook ($p < 0.1$).

The median SRP in Upper Bear Swamp was almost an order of magnitude lower than in the other minor tributaries (Table 22). Notable increases in SRP with flow only occurred in Snow Brook (Table 19). The lowest median PP and DOP concentrations (derived from measured concentrations of TP, TDP, and SRP) were in Upper Bear Swamp and Randall Gulf; this may be due to watershed influences (i.e. topography and geology or land use) or phosphorus uptake by organisms within the streams. Particulate phosphorus concentrations in Randall Gulf, Snow Brook, and One Mile Creek increased with increased flow, while increased flow in Five Mile Creek, Glen Cove, and Snow Brook supported increased concentrations of DOP (Table 19).

Table 22. Mean ± standard deviation ($\bar{X}$), median (M), and number of observations (n) of total phosphorus (TP), total dissolved phosphorus (TDP), soluble reactive phosphorus (SRP), particulate phosphorus (PP), and dissolved organic phosphorus (DOP) concentrations measured in the minor tributaries to Skaneateles Lake in 2019.

Tributary	TP (µg/L)			TDP (µg/L)			SRP (µg/L)			PP (µg/L)			DOP (µg/L)		
	$\bar{X}$	M	n	$\bar{X}$	M	n	$\bar{X}$	M	n	$\bar{X}$	M	n	$\bar{X}$	M	n
Upper Bear Swamp	25 ± 7	24	9	11 ± 2	12	9	3 ± 1	3	8	14 ± 8	14	9	8 ± 3	8	9
Five Mile Creek	400 ± 430	223	9	111 ± 99	99	8	73 ± 81	37	9	379 ± 368	353	7	37 ± 25	41	7
Glen Cove	198 ± 299	65	9	56 ± 37	46	9	53 ± 24	48	9	163 ± 277	21	8	18 ± 12	18	4
Randall Gulf	57 ± 80	22	8	21 ± 7	20	8	19 ± 7	22	8	47 ± 84	12	6	4 ± 3	4	5
Snow Brook	199 ± 257	104	9	64 ± 33	75	8	41 ± 14	38	9	155 ± 250	26	8	31 ± 15	37	6
One Mile Creek	144 ± 122	115	9	80 ± 87	33	9	53 ± 60	25	9	86 ± 77	89	7	32 ± 36	15	8

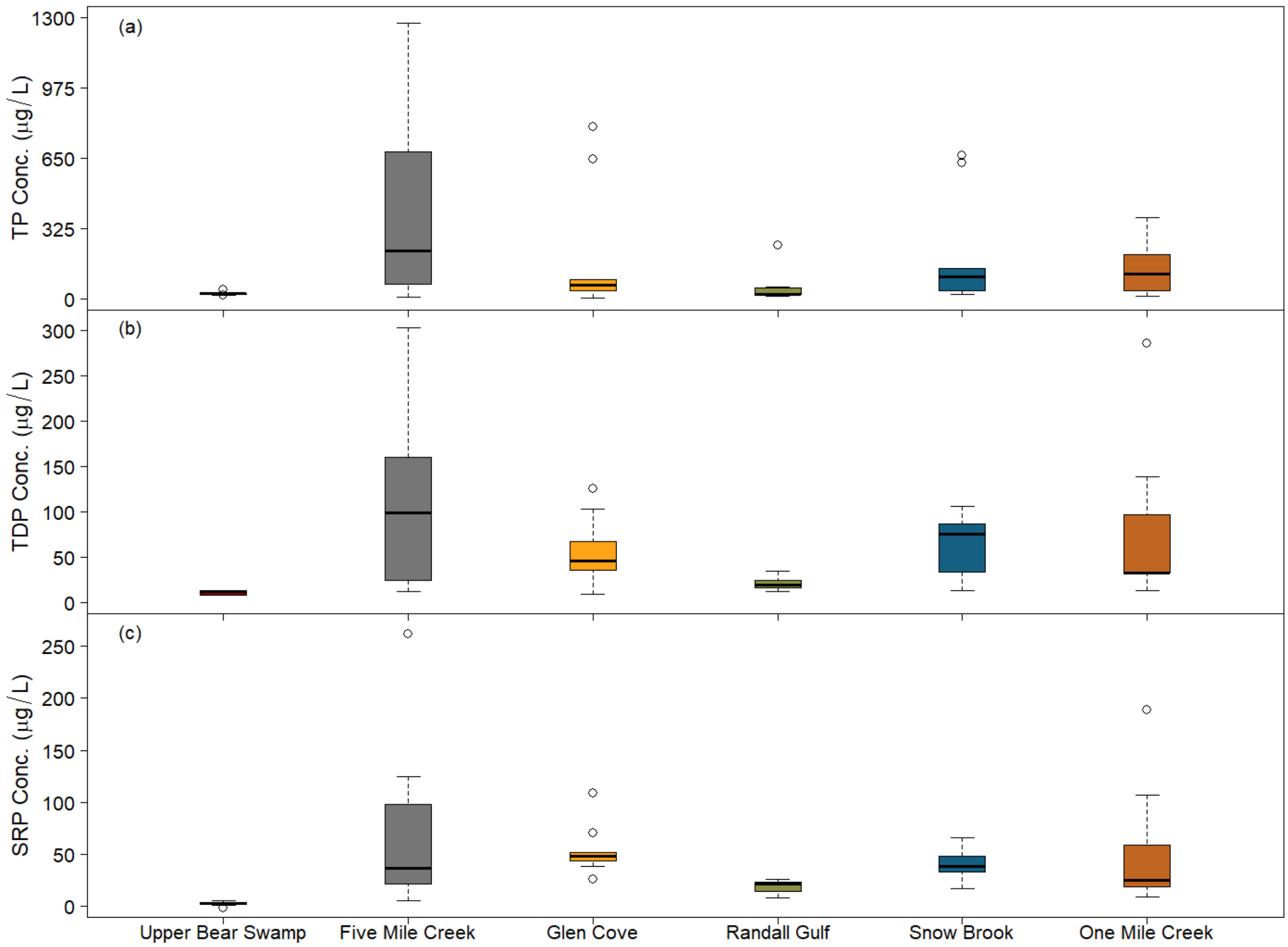

Figure 49. Boxplots of measured phosphorus concentrations in the minor tributaries to Skaneateles Lake in 2019: (a) total phosphorus (TP), (b) total dissolved phosphorus (TDP), and (c) soluble reactive phosphorus (SRP).

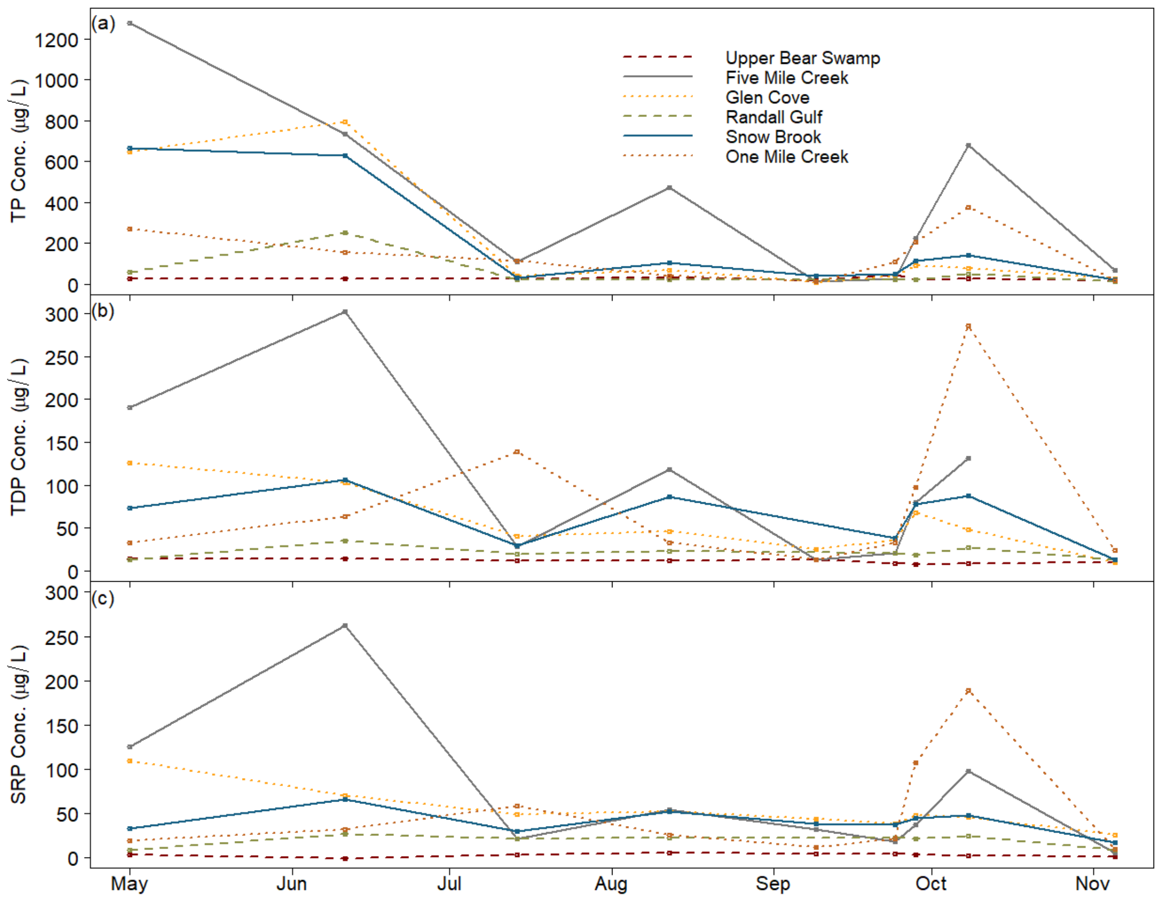

Figure 50. Time series of measured phosphorus concentrations in the minor tributaries to Skaneateles Lake in 2019: (a) total phosphorus (TP), (b) total dissolved phosphorus (TDP), and (c) soluble reactive phosphorus (SRP).

4.2.3. Nitrogen

Similarly to the observed TP concentrations, TN concentrations in Five Mile Creek were often elevated compared to the other minor tributaries (Figures 51, 52). The maximum TN observed in the minor tributaries was 9000 µg/L in Five Mile Creek on June 20 (Figure 52). Snow Brook had the highest median TN over the monitoring period (Table 24; Figure 51). Five Mile Creek had significant increases in TN with increased flow while Snow Brook did not, though ($p < 0.1$; Table 19). Concentrations also notably increased with flow in One Mile Creek ($0.1 < p < 0.2$). The minimum TN was observed in Upper Bear Swamp on November 14 (322 µg/L; Figure 52); this site also had the lowest mean and median TN concentrations of the minor tributaries (Table 23).

Snow Brook and Five Mile Creek had the highest average NO_x concentrations of the minor tributaries (Table 23), but the concentrations within these streams reacted differently to higher flows. As flow increased, NO_x in Five Mile Creek increased ($p < 0.1$) while concentrations slightly decreased in Snow Brook ($0.1 < p < 0.2$). The decrease observed in Snow Brook may be due to dilution of a continuous source of NO_x (e.g., groundwater).

Total ammonia concentrations were relatively similar across the minor tributaries (Table 23); however, marked increased concentrations were observed in Five Mile Creek and Glen Cove during one of the 3 rain events (June 20; Figure 52). There were no statistically significant relationships between flow and t-NH_3 observed within any tributary in the monitoring program (Table 19). Concentrations of t-NH_3 in Upper Bear Swamp were more similar to the other minor tributaries than the other nitrogenous compounds (TN, NO_x), possibly due to presence of aquatic life and beavers within the forested/wetland area.

Table 23. Mean ± standard deviation ($\bar{X}$), median (M), and number of observations (n) of total nitrogen (TN), nitrate (NO_x), and total ammonia (t-NH_3) concentrations measured in the minor tributaries to Skaneateles Lake in 2019.

Tributary	TN (µg/L)			NO_x (µg/L)			t-NH_3 (µg/L)		
	$\bar{X}$	M	n	$\bar{X}$	M	n	$\bar{X}$	M	n
Upper Bear Swamp	479 ± 92	478	9	31 ± 38	14	9	48 ± 41	39	9
Five Mile Creek	3594 ± 2242	2650	9	2177 ± 1841	1850	9	104 ± 104	47	9
Glen Cove	1969 ± 791	1720	9	1452 ± 595	1340	9	69 ± 73	35	9
Randall Gulf	634 ± 174	622	8	398 ± 100	345	8	22 ± 13	19	8
Snow Brook	3258 ± 1357	3530	9	2579 ± 1389	2580	9	46 ± 35	32	9
One Mile Creek	1111 ± 739	881	9	408 ± 575	194	9	43 ± 34	29	9

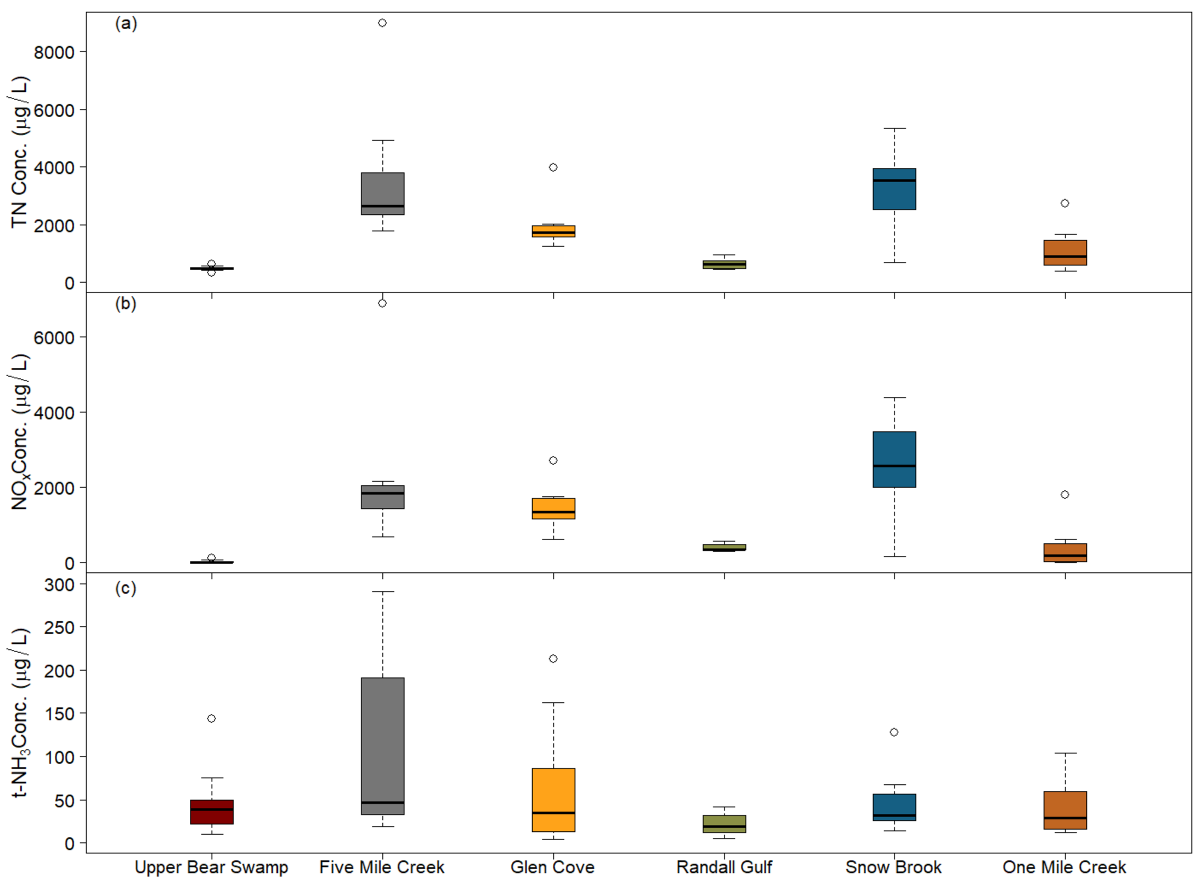

Figure 51. Boxplots of measured nitrogen in the minor tributaries to Skaneateles Lake in 2019: (a) total nitrogen (TN), (b) nitrate+nitrite (NO_x), and (c) total ammonia (t-NH_3).

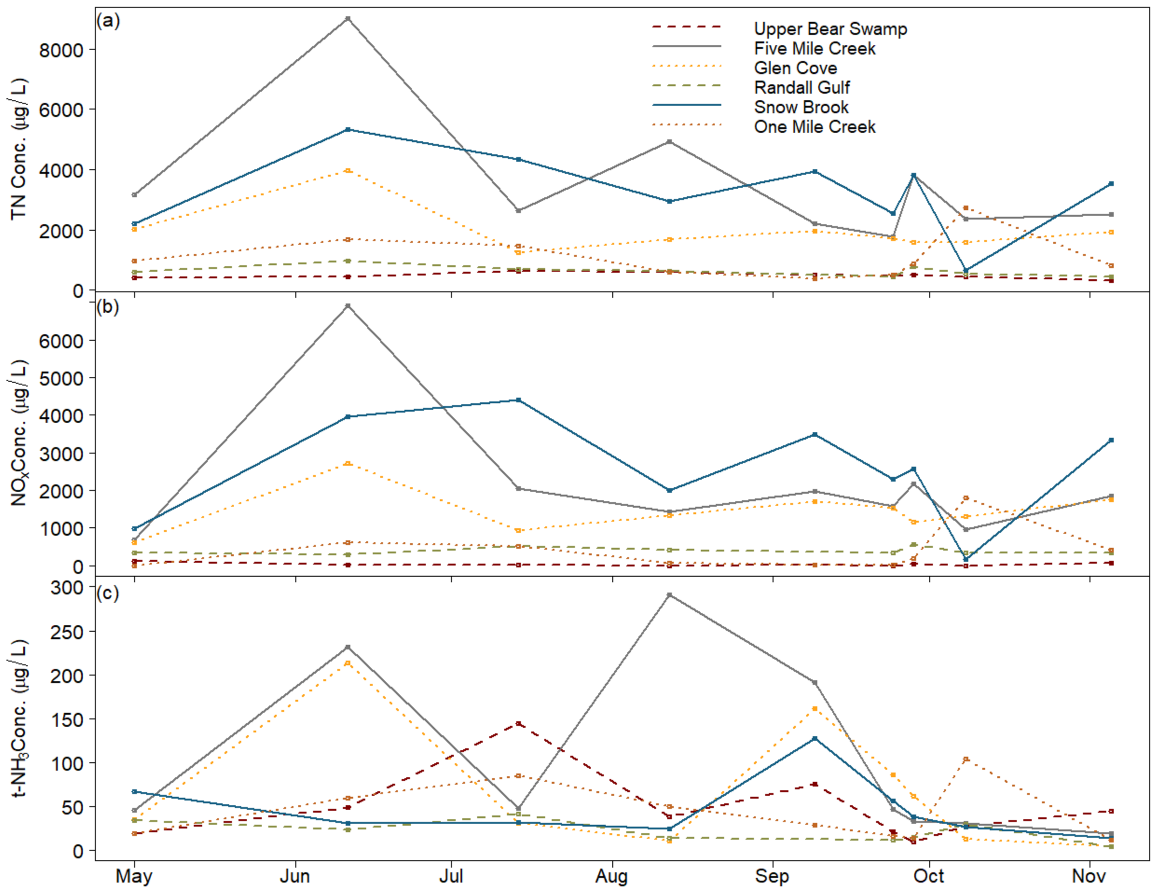

Figure 52. Time series of measured nitrogen concentrations in the minor tributaries to Skaneateles Lake in 2019: (a) total nitrogen (TN), (b) nitrate + nitrite (NO_x), and (c) total ammonia (t-NH_3).

4.2.4. Carbon

Five Mile Creek had the highest average and median DOC and POC concentrations of the minor tributaries to Skaneateles Lake (Table 24; Figure 53). The highest DOC concentration (14.3 mg/L) and POC concentration (22 mg/L) were both observed in Five Mile Creek on June 20 and May 10, respectively (Figure 54). Dissolved organic carbon and flow had a positive relationship in Five Mile Creek, Glen Cove, and Snow Brook (Table 19). Between July and September, DOC concentrations in Glen Cove, Randall Gulf, and One Mile Creek were lower than concentrations observed in the spring and the early fall (Figure 54). Dissolved organic carbon slightly increased then stayed at a consistent level in Upper Bear Swamp during this time period, though.

Generally, POC concentrations across all tributaries decreased during the summer, then slightly increased in October (Figure 54). Five Mile Creek, Randall Gulf, and Snow Brook had significant ($p < 0.1$), positive relationships between POC and flow (Table 19). Positive trends were also observed in Upper Bear Swamp and One Mile Creek ($0.1 < p < 0.2$). Median DOC and POC in all of the minor tributaries, except Randall Gulf, were equal to or higher than all of the major tributaries (Tables 13, 24); this may be the result of targeting runoff events and capturing only times of high concentrations in the minor tributaries.

Table 24. Mean ± standard deviation ($\bar{X}$), median (M), and number of observations (n) of dissolved organic carbon (DOC) and particulate organic carbon (POC) concentrations measured in the minor tributaries to Skaneateles Lake in 2019.

Tributary	DOC (mg/L)			POC (mg/L)		
	$\bar{X}$	M	n	$\bar{X}$	M	n
Upper Bear Swamp	5.9 ± 0.9	6.5	9	1.2 ± 0.5	1.2	9
Five Mile Creek	8.1 ± 4.7	9.3	9	5.4 ± 6.8	2.7	9
Glen Cove	4.6 ± 2.0	5.2	9	4.4 ± 7.8	0.7	9
Randall Gulf	3.7 ± 2.3	2.9	8	1.1 ± 1.8	0.2	8
Snow Brook	5.9 ± 3.3	6.7	9	2.6 ± 4.0	0.7	9
One Mile Creek	7.7 ± 2.2	7.5	9	3.0 ± 4.7	1.1	9

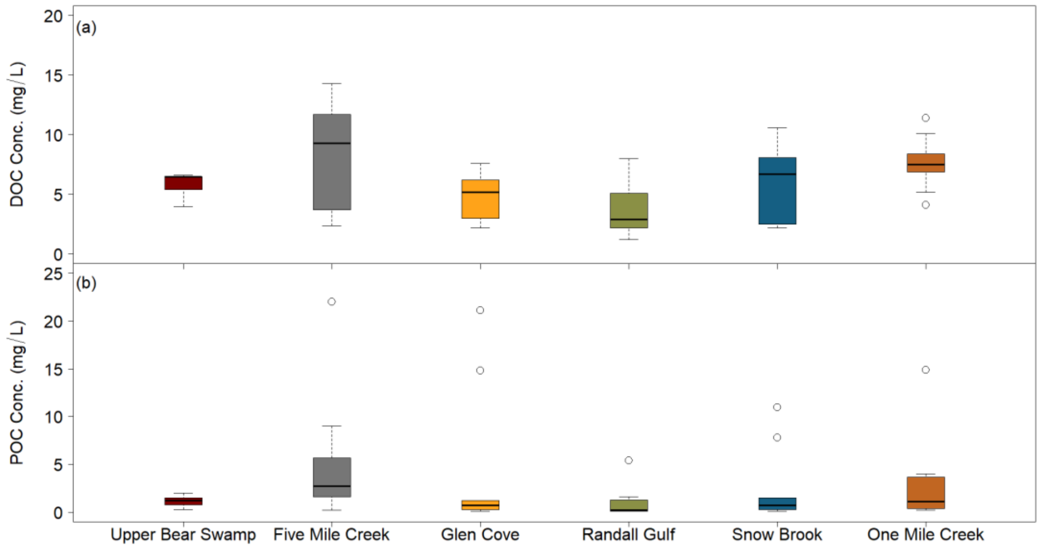

Figure 53. Boxplots of measured carbon in the minor tributaries to Skaneateles Lake in 2019: (a) dissolved organic carbon (DOC) and (b) particulate organic carbon (POC).

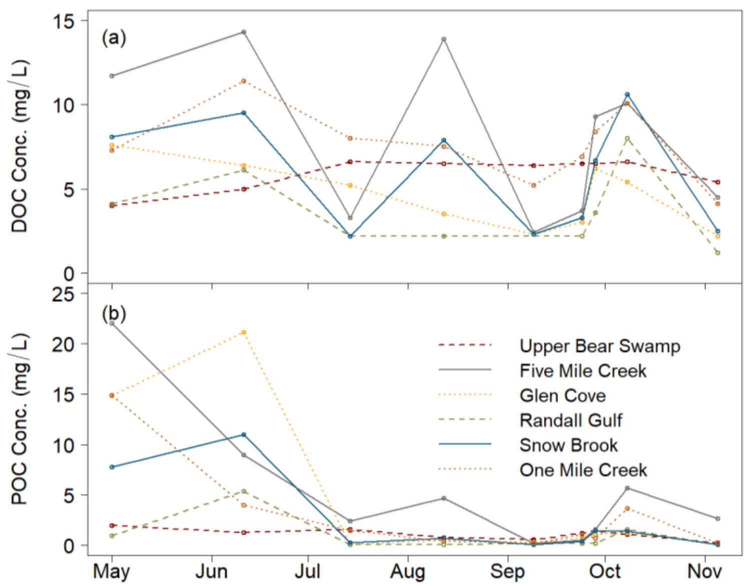

Figure 54. Time series of measured carbon concentrations in the minor tributaries to Skaneateles Lake in 2019: (a) dissolved organic carbon (DOC), (b) particulate organic carbon (POC).

4.2.5. Silica and Suspended Solids

Although Five Mile Creek had the highest mean and median TSS and FSS (Table 25; Figure 55), the greatest TSS and FSS were observed in Glen Cove on June 20 (1093.8 mg/L, 1006.2 mg/L; Figure 56). Despite its small size, One Mile Creek had the second highest median TSS, FSS, and VSS concentrations of the minor tributaries (Table 25). The greatest VSS was observed in Five Mile Creek on May 10 (102.4 mg/L; Figure 56). Five Mile Creek, Randall Gulf, Snow Brook, and One Mile Creek all had notable increases in TSS, FSS, and VSS with increased flow ($0.1 < p < 0.2$; Table 19). Unlike the other tributaries, Upper Bear Swamp had a significantly negative relationship between FSS and flow ($p < 0.1$). Suspended solids (i.e. TSS, FSS, and VSS) were generally low in Upper Bear Swamp (Figure 55, 56).

Silica concentrations were very similar across all minor tributaries, with the median concentration in Upper Bear Swamp slightly lower than the others (Table 25). Concentrations of silica varied most in One Mile Creek (Figure 55a). Silica significantly decreased with flow in Randall Gulf ($p < 0.1$), and showed similar trends in Five Mile Creek, Snow Brook, and One Mile Creek (Table 19). Dissolved silica most likely is diluted in these streams during periods of higher flow volume.

Table 25. Mean ± standard deviation ($\bar{X}$), median (M), and number of observations (n) of total suspended solids (TSS), fixed suspended solids (FSS), volatile suspended solids (VSS), and silica (Si; derived from SiO_2) concentrations measured in the major tributaries to Skaneateles Lake in 2019.

Tributary	TSS (mg/L)			FSS (mg/L)			VSS (mg/L)			Si (mg/L)		
	$\bar{X}$	M	n	$\bar{X}$	M	n	$\bar{X}$	M	n	$\bar{X}$	M	n
Upper Bear Swamp	4 ± 2	4	9	2 ± 1	1	8	2 ± 1	2	9	2.4 ± 0.9	2.0	9
Five Mile Creek	145 ± 246	33	9	120 ± 214	16	9	25 ± 32	17	9	2.7 ± 1.0	2.7	9
Glen Cove	186 ± 381	8	9	169 ± 350	7	9	17 ± 32	2	9	2.6 ± 0.4	2.8	9
Randall Gulf	42 ± 92	2	8	43 ± 88	3	7	5 ± 9	1	8	2.8 ± 0.5	2.9	8
Snow Brook	76 ± 135	7	9	72 ± 117	6	9	11 ± 17	2	8	2.8 ± 0.6	2.9	9
One Mile Creek	39 ± 56	18	9	32 ± 48	15	9	7 ± 8	3	9	3.1 ± 1.4	2.9	9

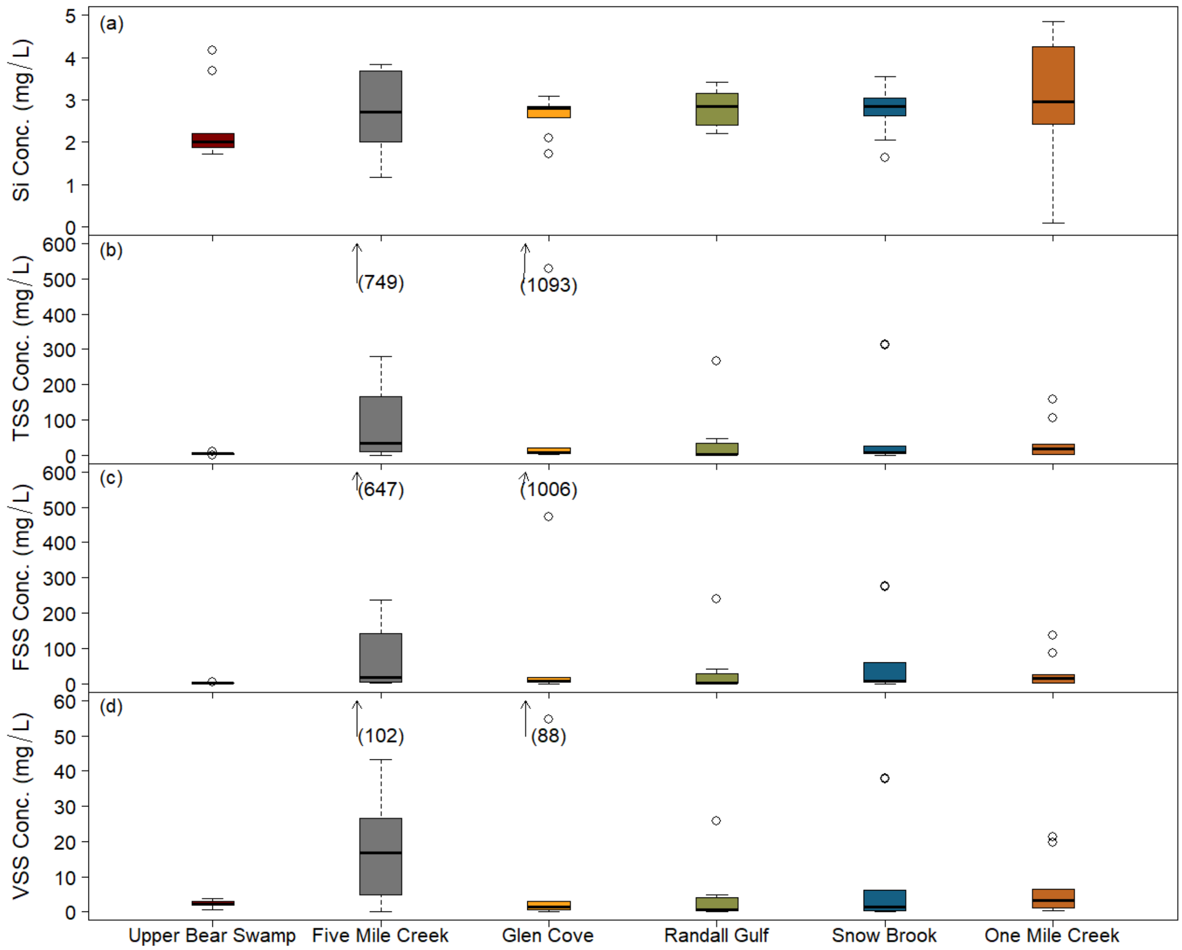

Figure 55. Boxplots of measured silica and suspended solids in the minor tributaries to Skaneateles Lake in 2019: (a) silica (Si; derived from SiO_2), (b) total suspended solids (TSS), (c) fixed suspended solids (FSS), and (d) volatile suspended solids (VSS).

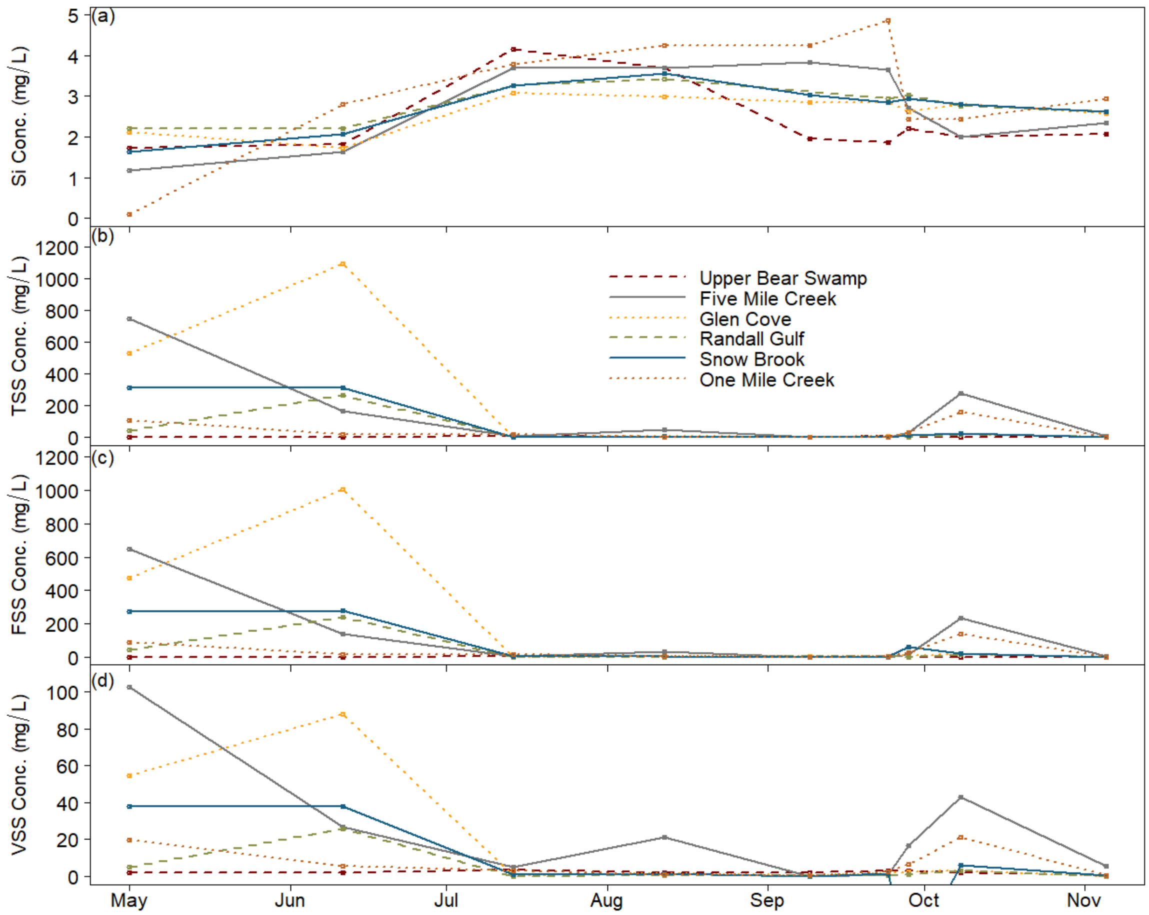

Figure 56. Time series of silica and suspended solids in the minor tributaries to Skaneateles Lake in 2019: (a) silica (Si; derived from SiO_2), (b) total suspended solids (TSS), (c) fixed suspended solids (FSS), and (d) volatile suspended solids (VSS).

4.3. Bear Swamp Creek longitudinal relationships

Bear Swamp Creek has the second largest drainage area (24 km^2) of the major tributaries to Skaneateles Lake. The stream flows through forested, agricultural, and lightly developed areas, which can contribute to the flow and water quality observed in the stream. Additionally, this stream has been affected by beaver dams, especially in the most upmost parts of the tributary. Ponded areas created by beavers allow for nutrients to cycle into bioavailable or unreactive forms as well as be sequestered by plants, bacteria, and fungi. However, when beaver dams are breeched during high flow events, additional nutrients may enter the stream and be transported downstream. By monitoring at two sites, we can begin to understand if/how water quality is affected before it enters the lake. Significant differences between concentrations of the sites were determined by performing paired, two-tailed t-tests for each constituent over the entire monitoring period. T-tests were also performed on subsets of the data based on the downstream flow regime (high or low). Additionally, ratios of the downstream concentration to the upstream concentration were calculated for each sampling date to assess any possible trends.

Ten of the 15 constituents measured at the upstream and downstream sites of Bear Swamp Creek were not significantly different from one another (Table 26). Over all flows, TDP, SRP, DOP, TN, and NO_x were significantly different between the two locations ($p < 0.05$). Each of these parameters, except for DOP, had median ratios greater than two (Table 27), meaning that the concentration measured at the downstream location was typically at least two times greater than the upstream location. TDP, SRP, NO_x, DOC, POC, and VSS were statistically different between the two sites during low flows (Table 26). The dissolved phosphorus forms (TDP and SRP) were typically 1.5 to 6 times greater at the downstream location during low flows. In contrast, DOC, POC, and VSS were reduced at the mouth of Bear Swamp Creek compared to Upper Bear Swamp. During high flow, constituents were typically observed at greater magnitude at the downstream location (Table 27). Significant differences at high flow were observed between the two sites for TDP, SRP, TN, NO_x, and DOC (Table 26).

These relationships are important because they indicate which nutrients are continuously supplied to the lake through natural processes. For example, we are aware that the upstream region has impoundments and it is possible that NO_x may be supplied to the upper region not through runoff, but rather via nitrification of t-NH_3. During low flows, we observed slightly greater t-NH_3 in Upper Bear Swamp ($p = 0.83$), and greater t-NH_3 at the mouth during high flows ($p = 0.07$). There were similar and significant trends observed for the dissolved phosphorus fractions (Table 27). These trends may support the idea that nutrients (i.e. nitrogen, phosphorus, carbon) undergo cycling or storage in the upstream region, therefore affecting downstream water quality (e.g. Puttock et al. 2017).

Figure 57. Photographs of (a) Upper Bear Swamp Creek and (b) near mouth of Bear Swamp Creek on July 23, 2019.

Table 26. Results (p-values) of paired, 2-tailed t-tests between concentrations at low, high, and all flow regimes. Values shaded and bolded indicate significant differences between upstream and downstream concentrations ($p < 0.05$).

Downstream Regime	TP	TDP	SRP	PP	DOP	TN	NO_x	$t\text{-}NH_3$	Tn	DOC	POC	TSS	FSS	VSS	DRSi
Low	0.55	**< 0.01**	**0.02**	0.22	0.20	0.15	**0.04**	0.83	0.57	**0.02**	**0.05**	0.16	0.26	**0.02**	0.93
High	0.13	**0.01**	**0.02**	0.14	0.17	**0.05**	**0.02**	0.07	0.19	**0.04**	0.34	0.16	0.16	0.15	0.51
All Flows	0.14	**< 0.01**	**< 0.01**	0.15	**0.04**	**0.01**	**< 0.01**	0.39	0.17	0.67	0.44	0.16	0.16	0.17	0.57

Table 27. Ratios of concentrations between downstream and upstream monitoring locations of Bear Swamp Creek (Down:Up) with characterized flow regime (high or low) of downstream location based on near continuous flow measurements, 2019. Ratios that were statistically significant (Table 28) are shaded.

Date	Downstream Regime	TP	TDP	SRP	PP	DOP	TN	NO_x	$t\text{-}NH_3$	Tn	DOC	POC	TSS	FSS	VSS
5/10/2019	High	28.5	2.2	5.6	67.0	1.1	3.6	5.4	2.2	83.6	1.4	0.4	188.2	471.9	33.5
6/20/2019	High	32.4	3.4	-	65.0	-	4.6	106.0	1.9	231.4	1.4	10.5	263.7	636.0	28.6
7/23/2019	Low	1.5	2.4	6.2	0.7	1.2	1.1	22.1	0.3	0.5	0.6	0.2	0.3	0.4	0.2
8/21/2019	Low	1.0	1.8	2.8	0.4	0.8	2.5	190.8	0.5	1.7	0.9	0.4	1.1	2.3	0.4
9/18/2019	Low	0.5	1.5	2.4	-	1.1	1.3	19.9	0.6	0.2	0.8	0.4	0.1	0.0	0.1
10/03/2019	Low	0.4	2.0	2.3	0.0	1.7	0.9	31.0	11.4	0.3	0.9	0.1	0.2	0.1	0.2
10/07/2019	High	5.3	4.0	5.5	6.1	3.0	2.2	17.7	10.6	12.5	1.1	2.5	13.3	53.2	3.3
10/17/2019	High	3.2	2.6	4.9	3.5	1.7	1.7	64.1	1.8	7.1	1.1	1.6	5.3	10.1	1.9
11/14/2019	Low	1.0	2.2	4.8	-	1.9	2.5	9.1	0.7	3.1	0.7	1.0	6.7	-	0.8
Median Down:Up		1.5	2.2	4.9	3.5	1.4	2.2	22.1	1.8	3.1	0.9	0.4	5.3	6.2	0.8

5. Relationships between water quality and land use within Skaneateles watershed

The topography, geology, hydrology, and land use of a watershed can alter the water quality and amount of water entering the system. As management strategies are developed to protect the water quality of Skaneateles Lake, it is important to consider the impacts of land use on water quality. Areal loading of nutrients and sediment is typically elevated in areas dominated by agricultural and developed land uses. In contrast, undisturbed areas, such as forests and wetlands, typically contribute fewer nutrients because vegetation and soils can sequester nutrients and slow runoff. We were interested in exploring relationships between land use and concentrations of water quality indicators measured in the major and minor tributaries of Skaneateles Lake in 2019. The relationships reported here offer some support to possible correlations between concentrations and land cover; however, there are other factors that could affect the relationships reported here. Flow is extremely important in delivering nutrient. As we observed for many of the tributaries, concentrations typically increase with increasing flows. Relationships between water quality and land use are best made using flow-weighted concentrations and/or areal load rates, but since estimating loads was beyond the scope of this project, mean values were used to represent transport of nutrients and sediment from these subwatersheds.

An increased percentage of cultivated crop area supported significant ($p < 0.05$) increases in mean TP, TDP, SRP, PP, TN, NO_x, Tn_L and FSS (Table 28). These results are not surprising given that these areas are typically fertilized and tilled. Silica concentrations significantly decreased with increasing percentage of wetlands ($p < 0.05$). Notable relationships ($p < 0.1$) include decreased DOP with increased percentage of wetlands, decreased Si with increased percentage of forest, and increased Si with increased percentage of developed lands. Although not statistically significant, each analyte decreased with increasing land cover of forests, and all but t-NH_3 decreased with increasing wetland cover. In contrast, all analytes increased with increasing percentage of developed and cultivated crop land cover. Relationships between pasture and hay land use were not significant ($p > 0.1$), and unlike the other land cover classes, the majority of the relationships were not unidirectional.

Table 28. R^2 values of relationships between mean water quality parameters and percent land use for the major and minor tributaries of Skaneateles Lake. Shaded values indicate significant relationships.

Land Use	Analyte														
	TP	TDP	SRP	DOP	PP	TN	NO_x	t-NH_3	Tn_L	TSS	FSS	VSS	DOC	POC	Si
Developed	0.07	0.19	0.17	0.18	0.02	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.10	0.11	0.31
Pasture/Hay	0.02	0.03	0.12	0.00	0.02	0.01	0.03	0.05	0.10	0.10	0.13	0.01	0.05	0.02	0.25
Cultivated Crops	0.46	0.40	0.55	0.18	0.40	0.66	0.77	0.11	0.43	0.37	0.41	0.31	0.03	0.18	0.14
Forest/grasslands	0.08	0.29	0.25	0.27	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.08	0.40
Wetlands	0.22	0.32	0.31	0.35	0.14	0.18	0.13	0.08	0.12	0.09	0.09	0.09	0.04	0.21	0.55

Key:

	p-value		
	> 0.1	0.05-0.1	< 0.05
Slope	NA	Positive	Positive
		Negative	Negative

6. Summary and Conclusions

With support from New York State Department of State, Central New York Regional Planning and Development Board, and the Town of Skaneateles, UFI conducted an expansive monitoring program of the four largest tributaries (Bear Swamp Creek, Grout Brook, Shotwell Brook, and Harold Brook) and six minor tributaries (Upper Bear Swamp, Five Mile Creek, Glen Cove, Randall Gulf, Snow Brook, One Mile Creek) to Skaneateles Lake between May and late November 2019. Measurements of stream stage, cross-sectional area, and velocity were added to previous data to support the development of rating curves, which were used to estimate streamflow in the major tributaries. Additionally, measurements of stage, temperature, specific conductance, and turbidity were made at 15-minute intervals within the major tributaries. Water samples were collected at the major tributaries biweekly and during three rain events. Water samples were also collected at the six minor tributaries on a monthly basis and during major rain events. These samples were analyzed for a suite of water quality parameters including: total phosphorus (TP), total dissolved phosphorus (TDP), soluble reactive phosphorus (SRP), total nitrogen (TN), nitrate+nitrite (NO_x), total ammonia (t-NH_3), dissolved organic carbon (DOC), particulate organic carbon (POC), silica (SiO_2), total suspended solids (TSS), fixed suspended solids (FSS), volatile suspended solids (VSS) and turbidity (Tn).

The results of this monitoring program were analyzed in the context of local meteorological conditions and land use. Ultimately, these results are intended to be useful in future modeling efforts and a Nine Element Plan for Skaneateles Lake. Noteworthy findings from the 2019 program are listed below.

- Stream stage in the major tributaries was responsive to short-term rainfall events and longer-term seasonal patterns. Streamflow generally increased during the late summer and fall in response to rainfall events and the seasonal decrease in evapotranspiration. Streamflow in the major tributaries was greater in 2019 than in 2018.
- Grout Brook and Bear Swamp Creek both experienced major flooding after a major rainfall event on June 20, and most of the highest concentrations of each water quality parameter in each tributary monitored were measured on this date.
- During major rain events, streamflow and turbidity increased in the major tributaries while specific conductivity generally decreased.

- Phosphorus concentrations were greatly affected by flow with TP, TDP, and SRP generally increasing with increasing flow; however, SRP slightly decreased with flow in Bear Swamp Creek.
- Nitrogen concentrations in the major tributaries were similar to those collected in previous years. Harold Brook most frequently had the highest nitrogen levels of the major tributaries.
- In each of the major tributaries, carbon (DOC and POC) increased with increasing flows. Concentrations of DOC were similar in 2018 and 2019. Likely due to higher flows, POC was greater in 2019 than in 2018.
- Suspended solids (i.e. TSS, FSS, VSS) generally increased with increasing flows in the major tributaries. Although VSS concentrations increased with flow, the percentage of VSS to TSS decreased in the major tributaries at high flows.
- The minor streams monitored in 2019 are permanent/intermittent. No surface water flow was observed in Glen Cove and Randall Gulf during the late summer.
- Five Mile Creek and Snow Brook typically experienced the highest nutrient concentrations observed in the minor tributaries. One Mile Creek, though, had the second greatest carbon (DOC and POC), TSS, and FSS median concentrations observed in the minor tributaries.
- Relationships between water quality constituents and flow were generally weak in the minor tributaries, due to limited data collection on these streams.
- Significant differences in nutrient concentrations were observed between Upper Bear Swamp and the mouth of Bear Swamp Creek. These differences in dissolved forms of phosphorus (i.e. TDP, SRP), nitrogen (i.e. NO_x), and carbon (i.e. DOC, POC) indicate the potential for storage and cycling occurs between the upstream site and the mouth of the stream. The differences could also be affected by inputs (e.g. agricultural runoff) downstream of the upstream monitoring site, especially during storm events.
- Preliminary relationships between land use and water quality in the streams support that the amount of cultivated cropland in the watershed of the tributaries greatly affects many nutrient export.

With the completion of this monitoring program, UFI recommends the following actions:

1) Continued monitoring of the major and minor tributaries is recommended to add to the historical data set and provide additional information that would benefit future modeling efforts. A more robust rating curve needs to be developed for Bear Swamp Creek and Grout Brook to better estimate streamflow over several years. We have collected at least two years' worth of data on the major tributaries to establish a rating curve, but an additional year may solidify the relationship. Rainfall and snowmelt during the spring often trigger major runoff events that deliver a large fraction of the annual material load to lakes. Spring monitoring in Shotwell Brook, Harold Brook, Snow Brook, and One Mile Creek began in February 2020. Continued spring monitoring in these tributaries and inclusion of the remaining tributaries should be considered to support a Nine Element Plan and watershed and lake models. Further investigation of upstream and downstream differences of Bear Swamp Creek may increase understanding of nutrient inputs to Skaneateles Lake and support localized best management practices and conservation efforts.
2) Develop load estimates for the streams in to support watershed and water quality modeling. Loads can help prioritize streams that could benefit from watershed remediation projects and best management practices. It is important to remember though that loads are primarily driven by the volume of water entering the lake, thus larger tributaries (e.g. Grout Brook and Bear Swamp Creek) will have larger loads than smaller tributaries. Actions taken at smaller streams may provide a more substantial improvement to local water quality than the same amount of action taken at larger streams.

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8. Appendix

Table A.1. Performance ranges for the YSI datasonde probes used for the *in-situ* measurements.

Probe	Range of Detection	Resolution	Accuracy
Turbidity	0 – 1000 NTU	.1 NTU	2 NTU or +/- 5 % of reading, whichever is greater
Temperature	-5 – 45 °C	0.01 °C	+- 0.15
Conductivity	0 – 100 mS/cm	0.001 to 0.1 mS/cm (range dependent)	+- 0.5 % of reading + 0.001 mS/cm

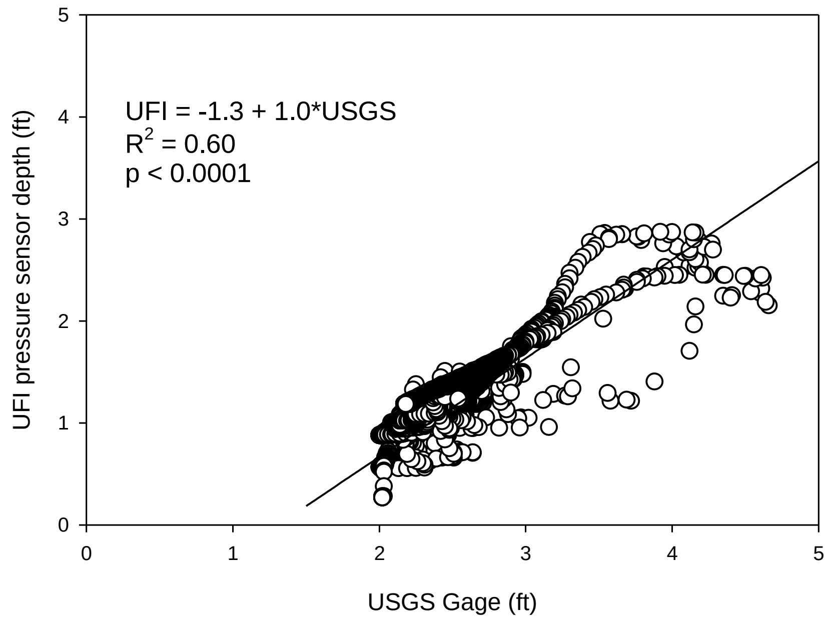

Figure A.1. Relationship between UFI pressure sensor measurements (ft) and upstream USGS gage (ft). Pressure sensor depths after 9/24 adjusted by 0.57 due to channel disturbance.

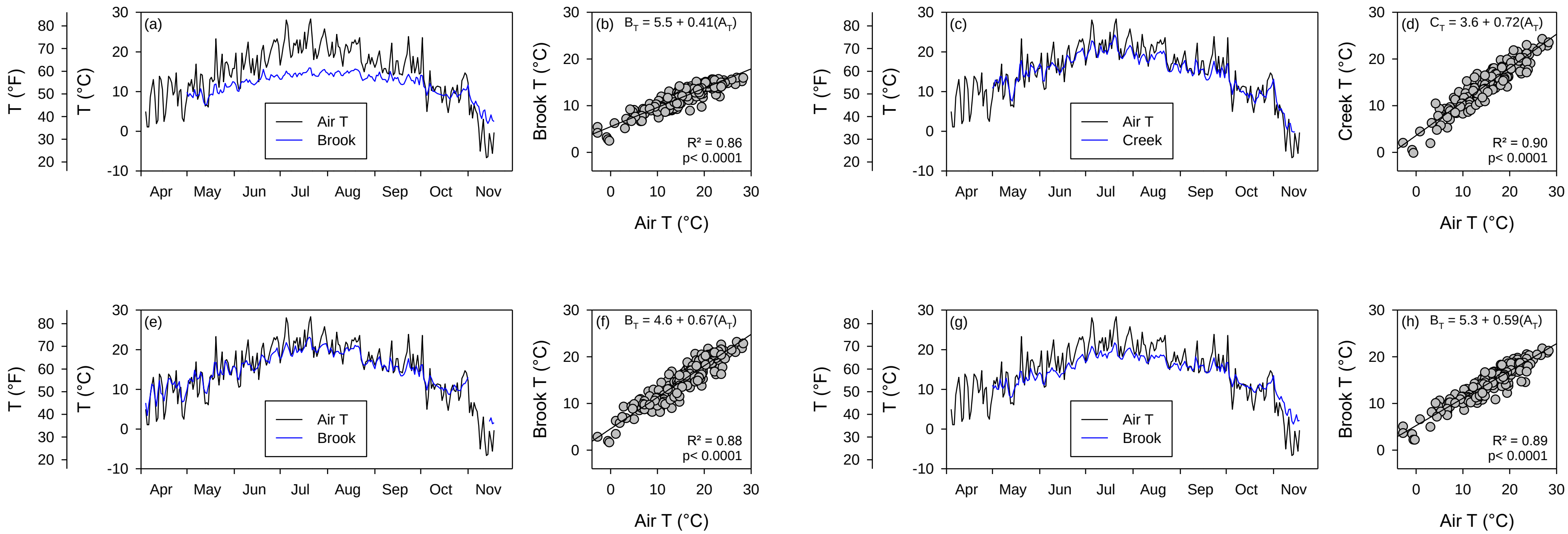

Figure A.2. Relationship between air temperatures (Air T or A_T) and stream temperatures (Brook T or B_T and Creek T or C_T) of four major tributaries to Skaneateles Lake in 2019: (a,b) Grout Brook, (c,d) Bear Swamp Creek, (e,f) Shotwell Brook, (g,h) Harold Brook. The left panel shows a time series of daily average air temperatures (Auburn NWS) and stream temperatures (°C). The right panel shows the linear regression of daily stream and air temperatures with associated statistics.

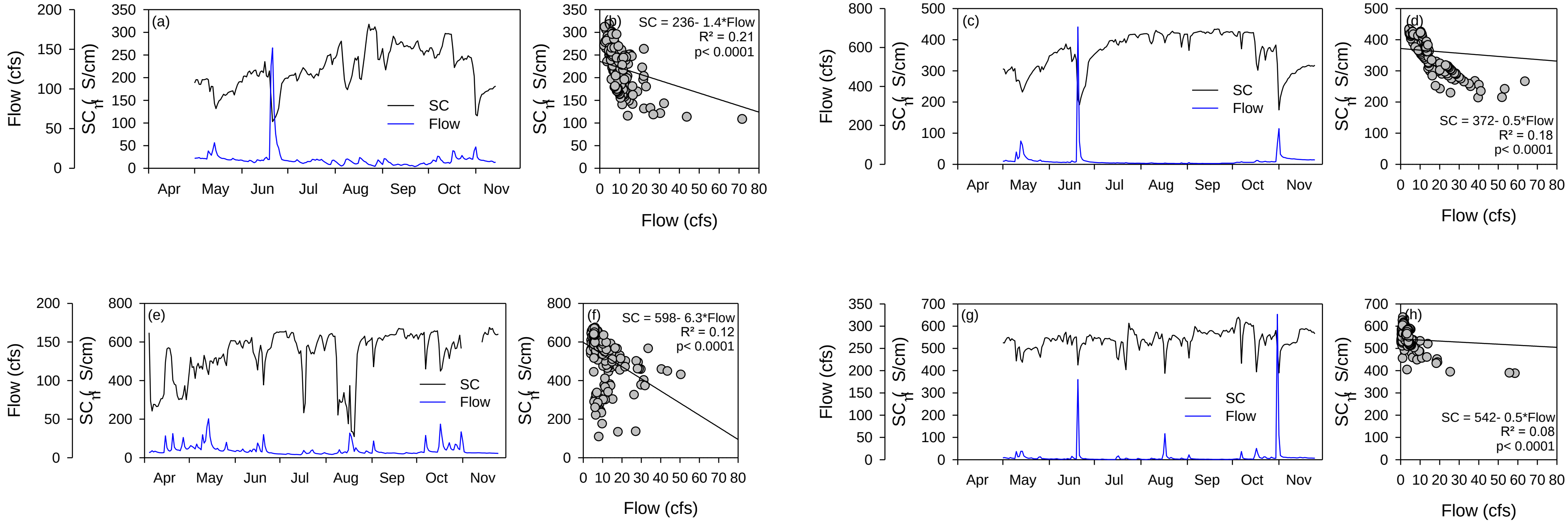

Figure A.3. Relationship specific conductance (SC) and streamflow (Flow) of four major tributaries to Skaneateles Lake in 2019: (a,b) Grout Brook, (c,d) Bear Swamp Creek, (e,f) Shotwell Brook, (g,h) Harold Brook. The left panel shows a time series of daily average specific conductance values and stream flow. The right panel shows the linear regression of daily average SC and flow with associated statistics.

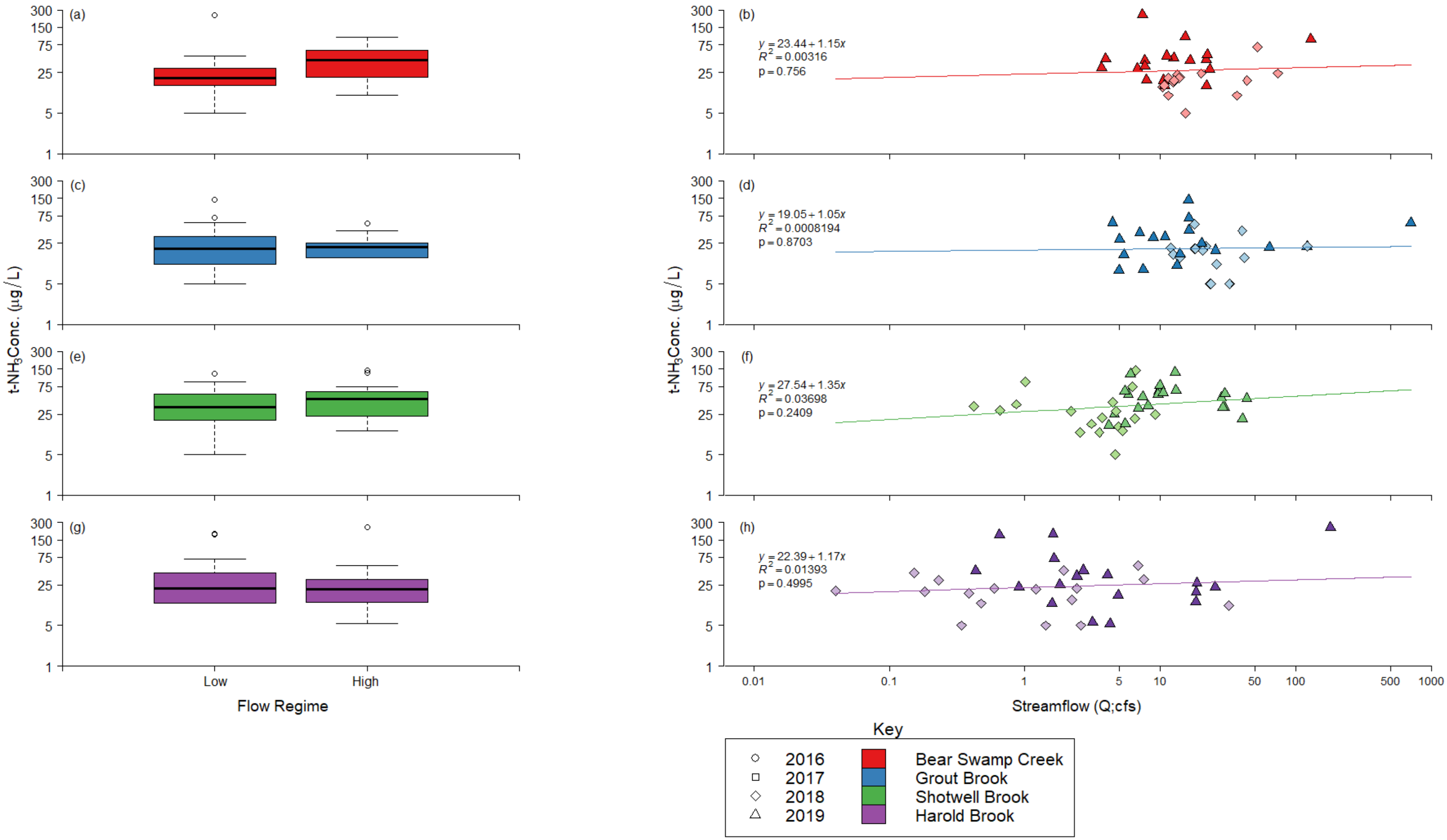

Figure A.4. Comparison of t-NH_3 concentration measured during high and low flow regimes (a,c,e,g) and relationship between t-NH_3 and flow (b,d,f,h) in (a,b) Bear Swamp Creek (2018-2019), (c,d) Grout Brook (2018-2019), (e,f) Shotwell Brook (2016-2019), and (g,h) Harold Brook (2018-2019). Statistically significant differences between concentrations within each tributary is denoted with * and **. Linear relationship equation and statistical significance shown within plot.

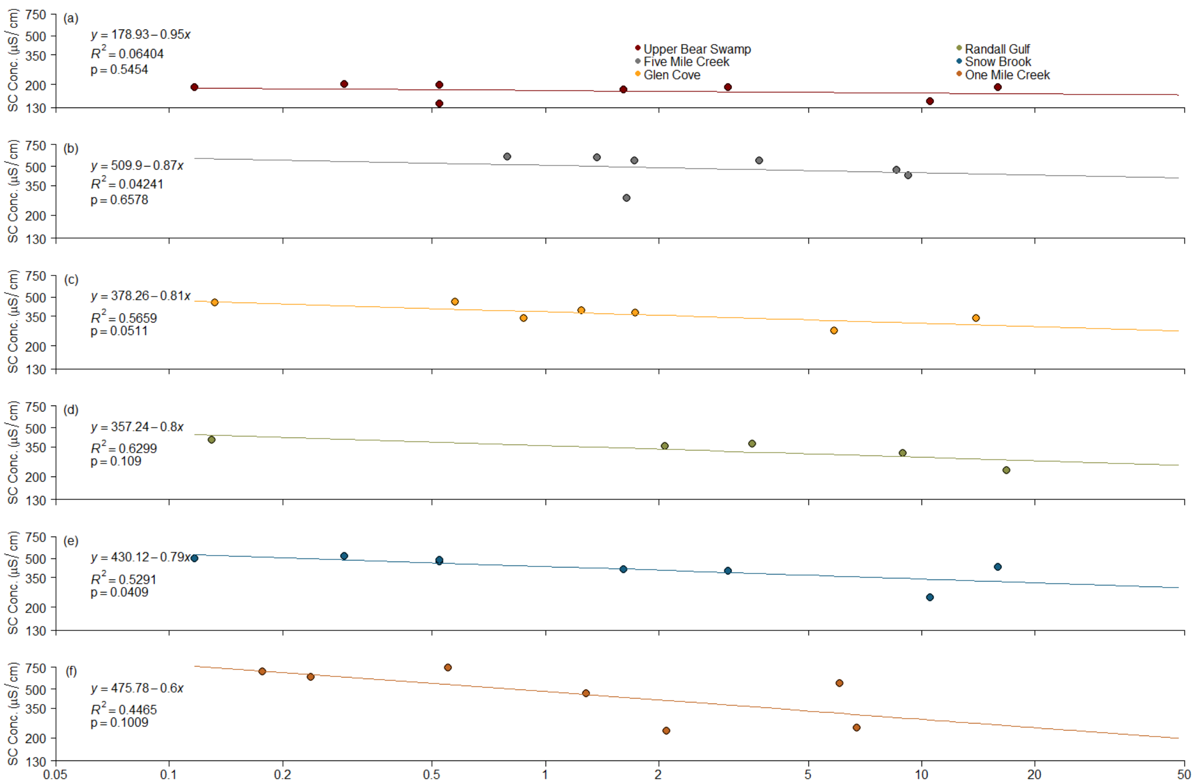

Figure A.5. Linear relationship between specific conductance (SC) and streamflow (cfs) of minor tributaries: (a) Upper Bear Swamp, (b) Five Mile Creek, (c) Glen Cove, (d) Randall Gulf, (e) Snow Brook, and (f) One Mile Creek. Summary statistics shown.

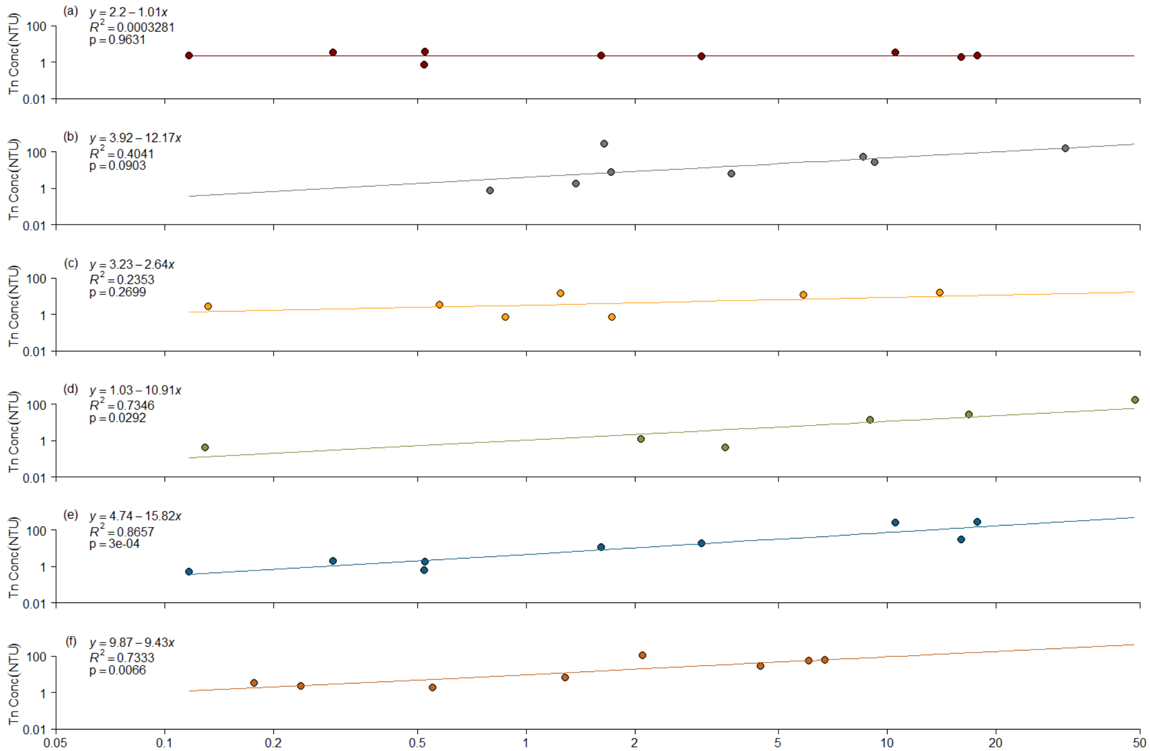

Figure A.6. Linear relationship between turbidity (Tn) and streamflow (cfs) of minor tributaries: (a) Upper Bear Swamp, (b) Five Mile Creek, (c) Glen Cove, (d) Randall Gulf, (e) Snow Brook, and (f) One Mile Creek. Summary statistics shown.