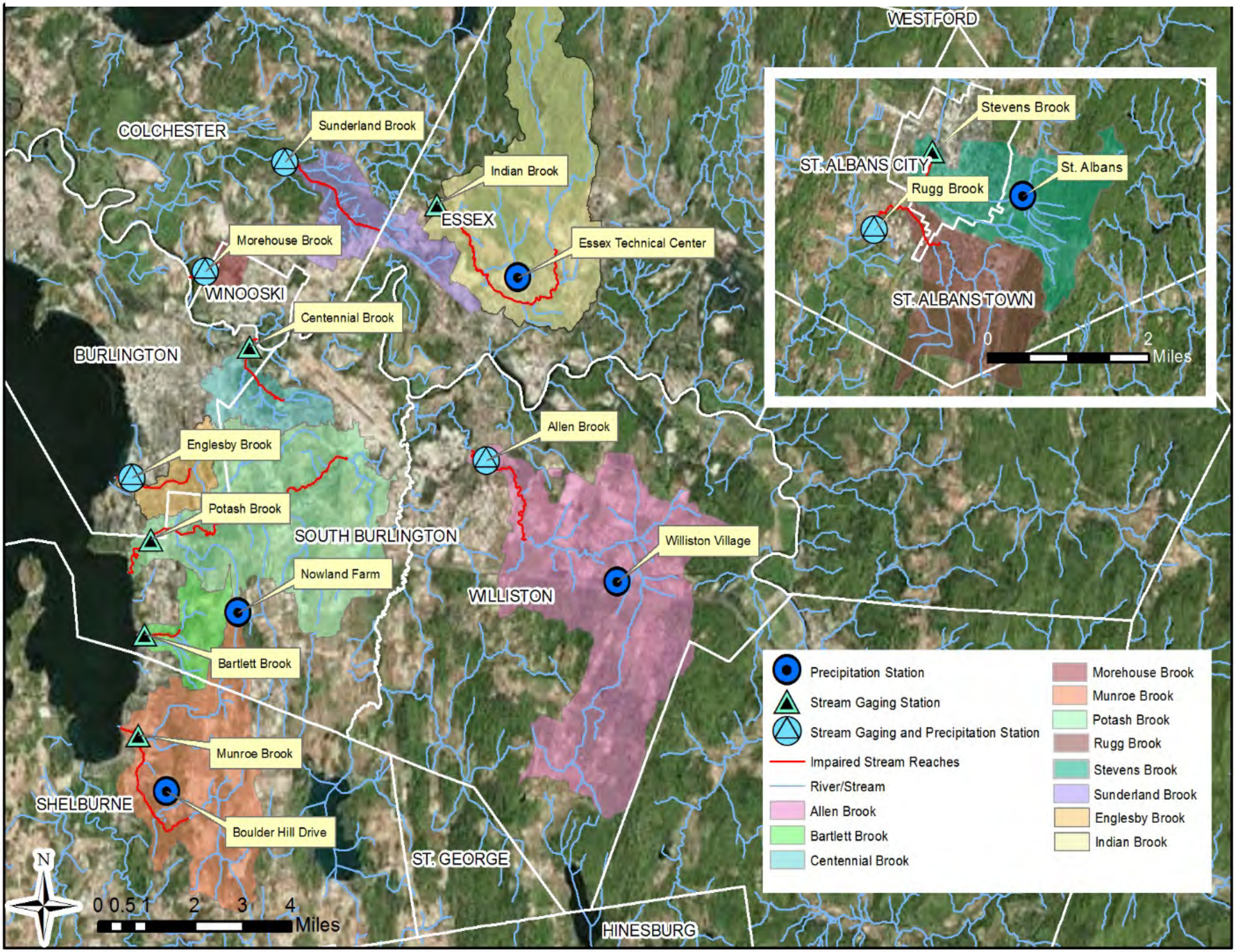
MS4 Flow and Precipitation Monitoring Project

Progress Report

January 7, 2020
Dave Braun and Serena Matt

Stormwater-impaired streams in Chittenden and Franklin Counties. Each has a TMDL to address biological impairment

Stream	Municipality
Allen Brook	Williston
Bartlett Brook	South Burlington, Shelburne
Centennial Brook	South Burlington, Burlington
Englesby Brook	Burlington, South Burlington
Indian Brook	Essex
Morehouse Brook	Winooski, Colchester
Munroe Brook	Shelburne, South Burlington
Potash Brook	South Burlington, Burlington
Rugg Brook	St. Albans Town, St. Albans City
Stevens Brook	St. Albans City, St. Albans Town
Sunderland Brook	Colchester, Essex Junction

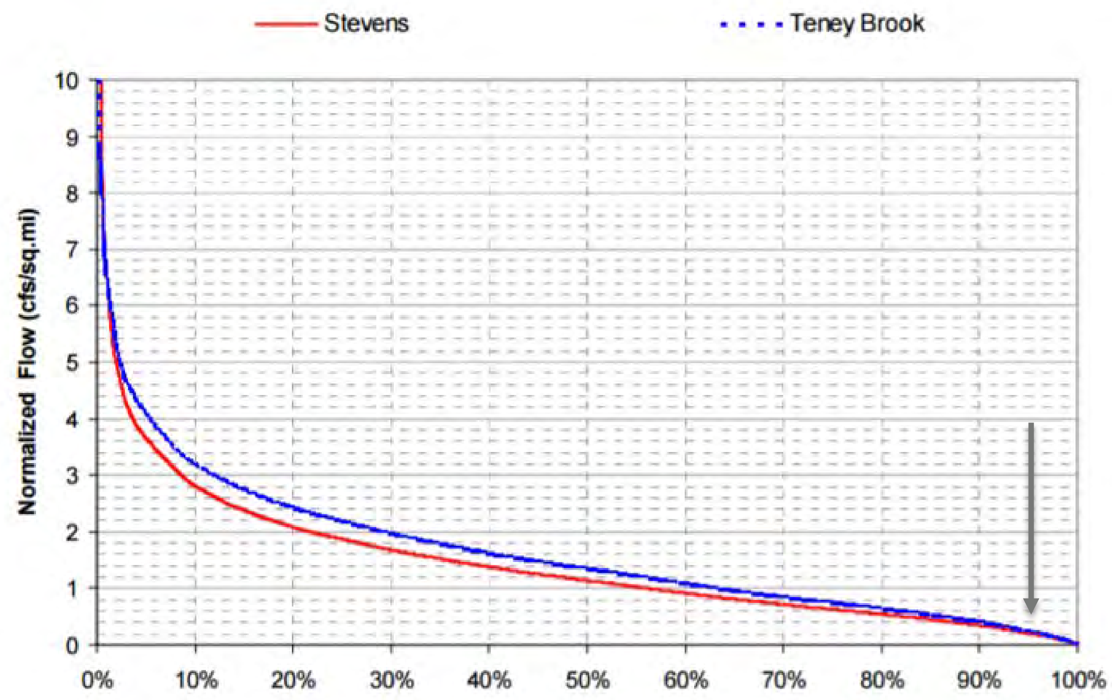


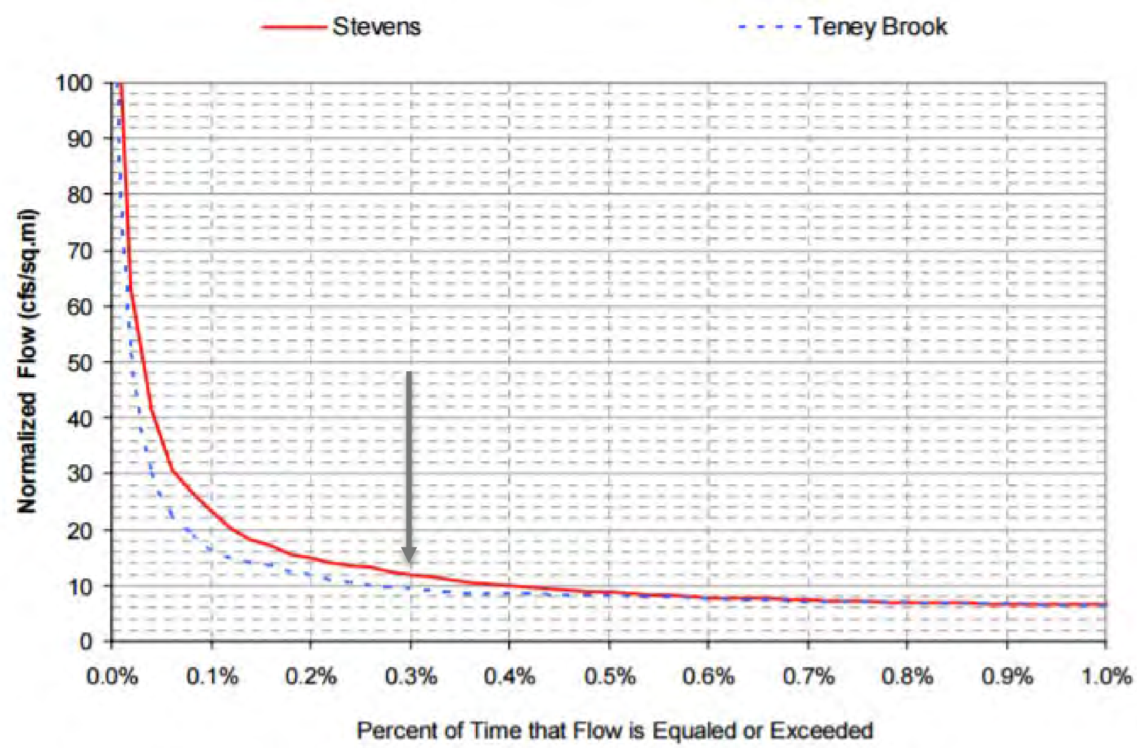
Streamflow and precipitation monitoring stations

TMDL Hydrologic Targets

Flow is a surrogate measure for multiple stressors

> **High flow (0.3% exceedance)**
> **Reductions range from 1 to 54%**
>
> **Low flow (95% exceedance)**
> **Increases range from 0.4 to 27%**



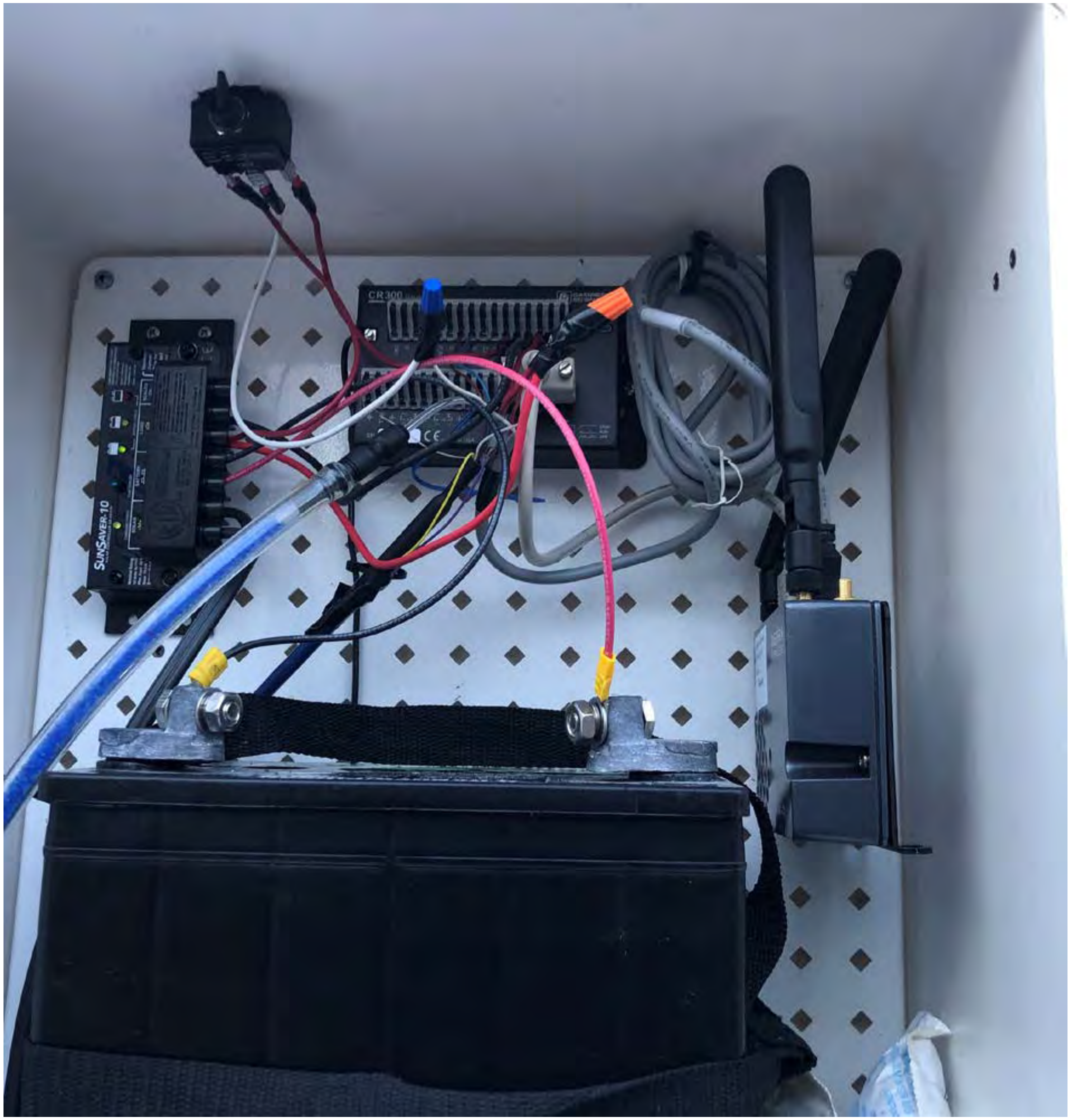


TMDL to Address Biological Impairment in Stevens Brook, Franklin County, Vermont. October 2008. VTDEC

Instrumentation and Equipment

Stream Monitoring Station

- Fiberglass enclosure
- Solar panel (12-20W)
- 12-V deep cycle battery
- Charge controller
- Datalogger (Campbell CR300)
- Pressure transducer (INW)
- Cellular modem
- Staff plate
- Survey benchmarks
- Time-lapse camera



Station Construction Details

Rugged materials required for extended and year-round deployment

- Rigid galvanized conduit
- Anchored to bedrock with ½" SS threaded rod
- Anchored to streambeds with heavy (1 1/8") rebar and 3/8" steel tube brackets

Custom weir plates at 3 sites

- Munroe, Morehouse, and Englesby Brook

Controlled Cross-Section Monitoring Stations

Controlled Cross-Section Monitoring Stations

Open-Channel Monitoring Stations

Precipitation Monitoring Stations

Field Activities Review

- **Discharge measurements**
- **Annual survey of benchmarks and staff gauges**
- **Annual calibration of tipping bucket rain gauges**
- **Routine maintenance (approximately monthly)**
  - Time-lapse camera download and battery replacement
  - Staff gauge cleaning and reading / pressure transducer calibration
  - Desiccant replacement
  - Clear minor debris from channel
  - Flushing pressure transducer conduits to remove sediment
- **Non-routine maintenance (2019)**
  - Data logger replacement at Morehouse Brook and Essex Junction TB
  - Staff gauge replacement /repair at Allen Brook and Indian Brook
  - Debris jams and boulder removal at Munroe, Indian, and Potash Brooks
  - Pressure transducer replacement at several sites
  - Data logger firmware updates

No beaver problems in 2019!

High Flow Measurements


AA Price current meter


RiverSurveyor S5 ADCP

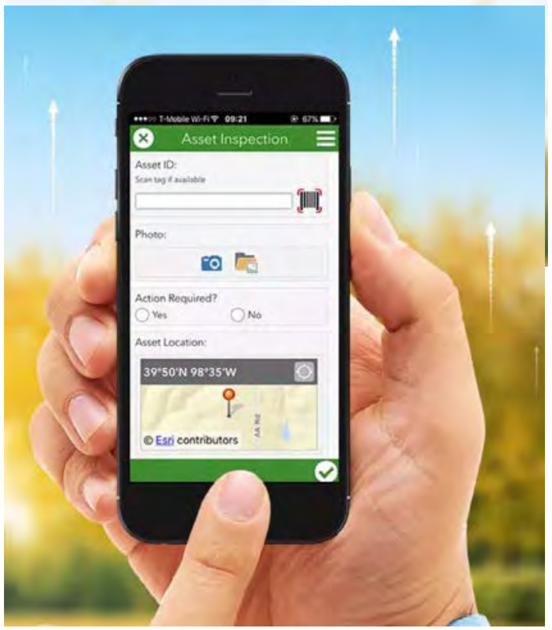
Low Flow Measurements

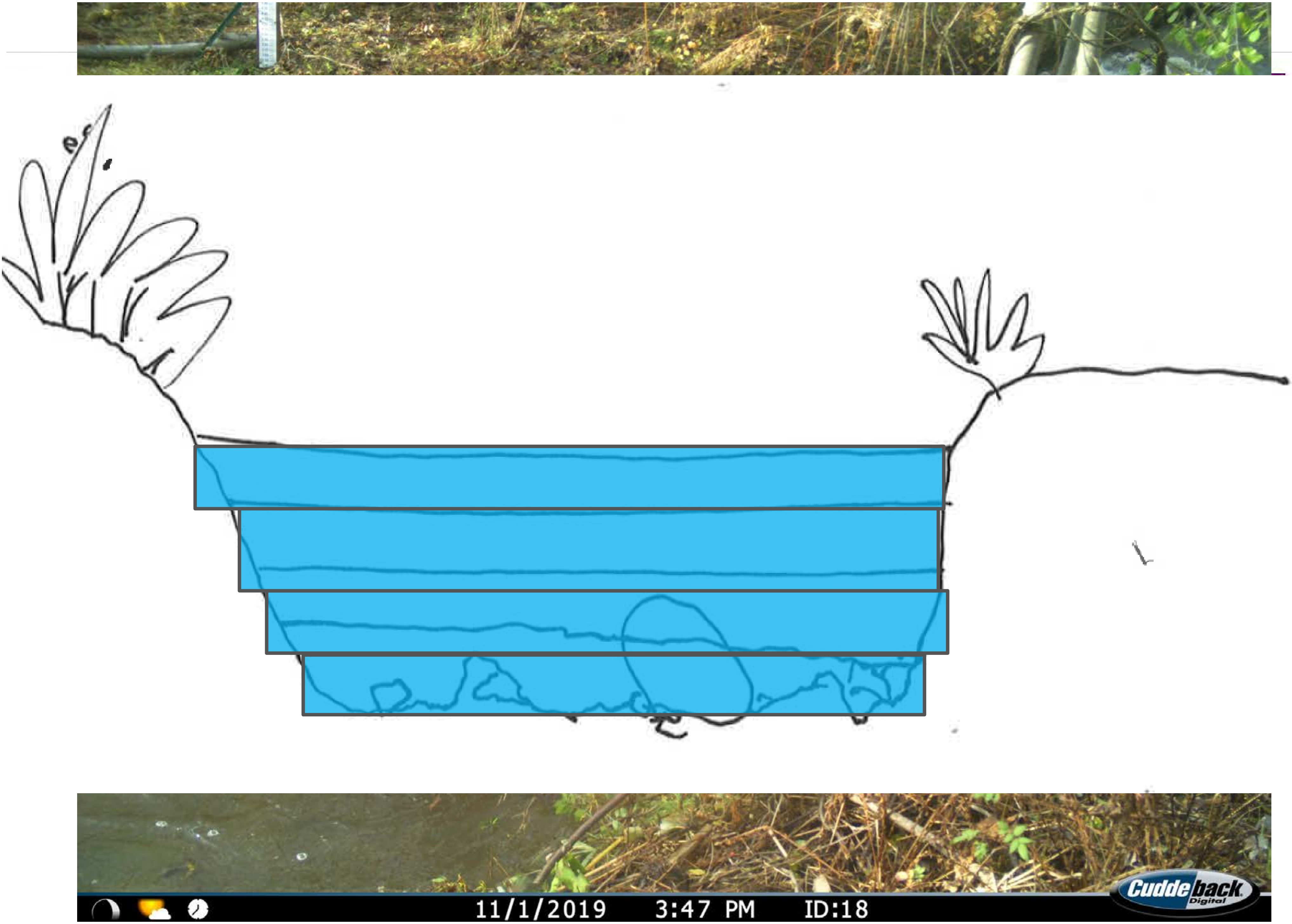

Baski Cutthroat Flume

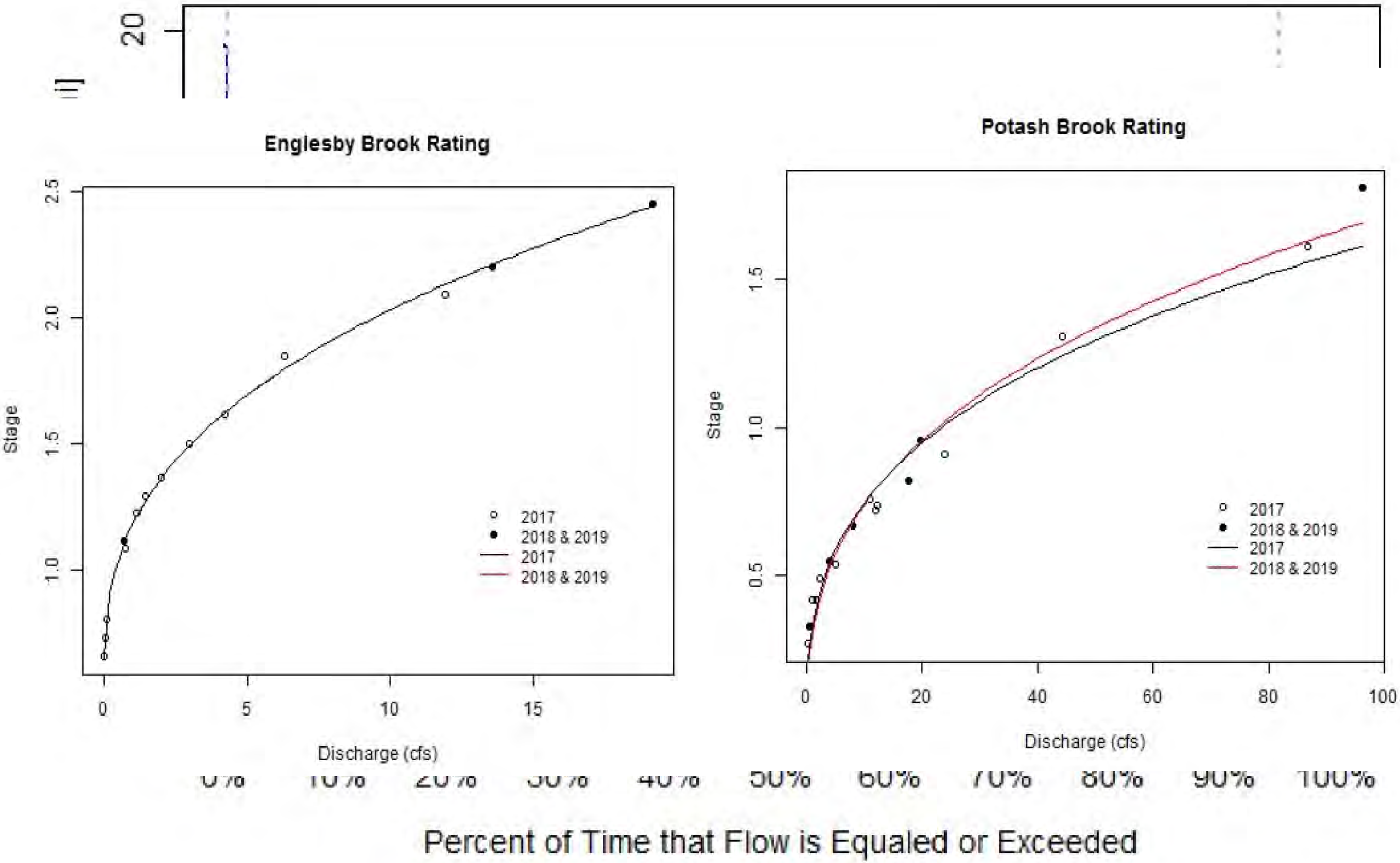
Continuous rate salt addition


Pygmy flowmeter

Field Data Collection




11/1/2019 3:47 PM ID:18
Cuddeback Digital


20
Englesby Brook Rating
Stage
2.5
2.0
1.5
1.0
0
5
10
15
Discharge (cfs)
2017
2018 & 2019
2017
2018 & 2019
Potash Brook Rating
Stage
1.5
1.0
0.5
0
20
40
60
80
100
Discharge (cfs)
2017
2018 & 2019
2017
2018 & 2019
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Percent of Time that Flow is Equaled or Exceeded

Precipitation

Raw 5-minute Tipping Bucket Precipitation

Corrected Total Daily Precipitation

Use of Time-lapse Cameras in Data Processing

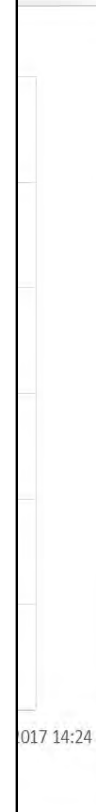
T
st

•R
(e
M
d

•D
(e
a
s
p

•I(
o

•C



http://vt-ms4-flow.stone-env.com/FlowDev/index.html

Allen Brook Streamflow Station

Provisional Data, Subject to Revision

Communication Status Alarm: (Modem powered down 12:00 to 07:00 daily)

Battery voltage (hourly min.): 14.2 volts

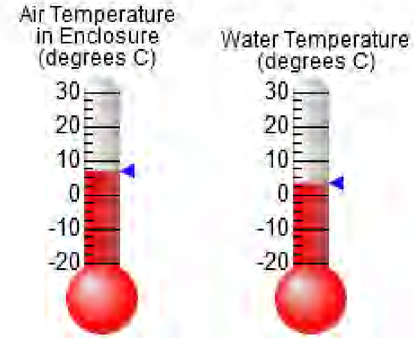
Latest Values (5-Minute Data)

4/17/2018, 2:00:00 PM

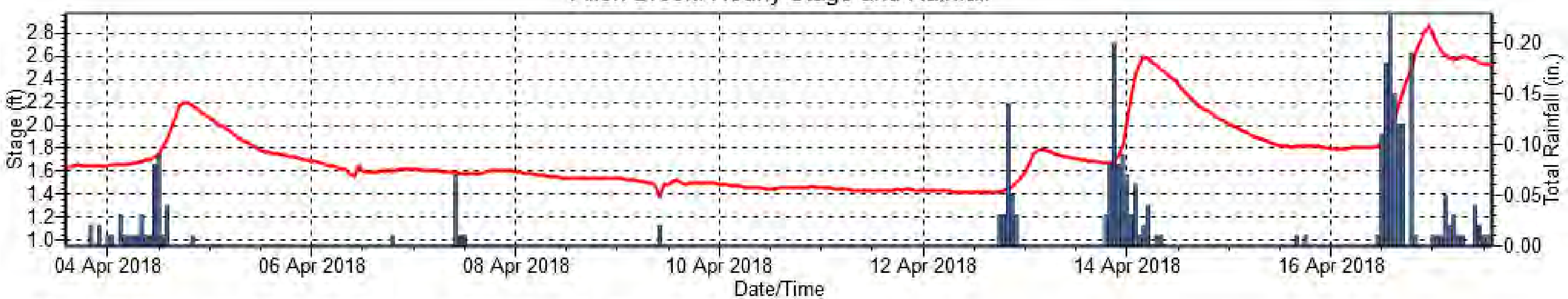
All dates and times reported at this station are Atlantic Time (UTC-4:00), without adjustment for Daylight Savings Time.

Stage (avg): 2.542 feet

Discharge (avg): In development



Allen Brook: Hourly Stage and Rainfall



Allen Brook: Hourly Temperature, Precipitation, and Stage Data

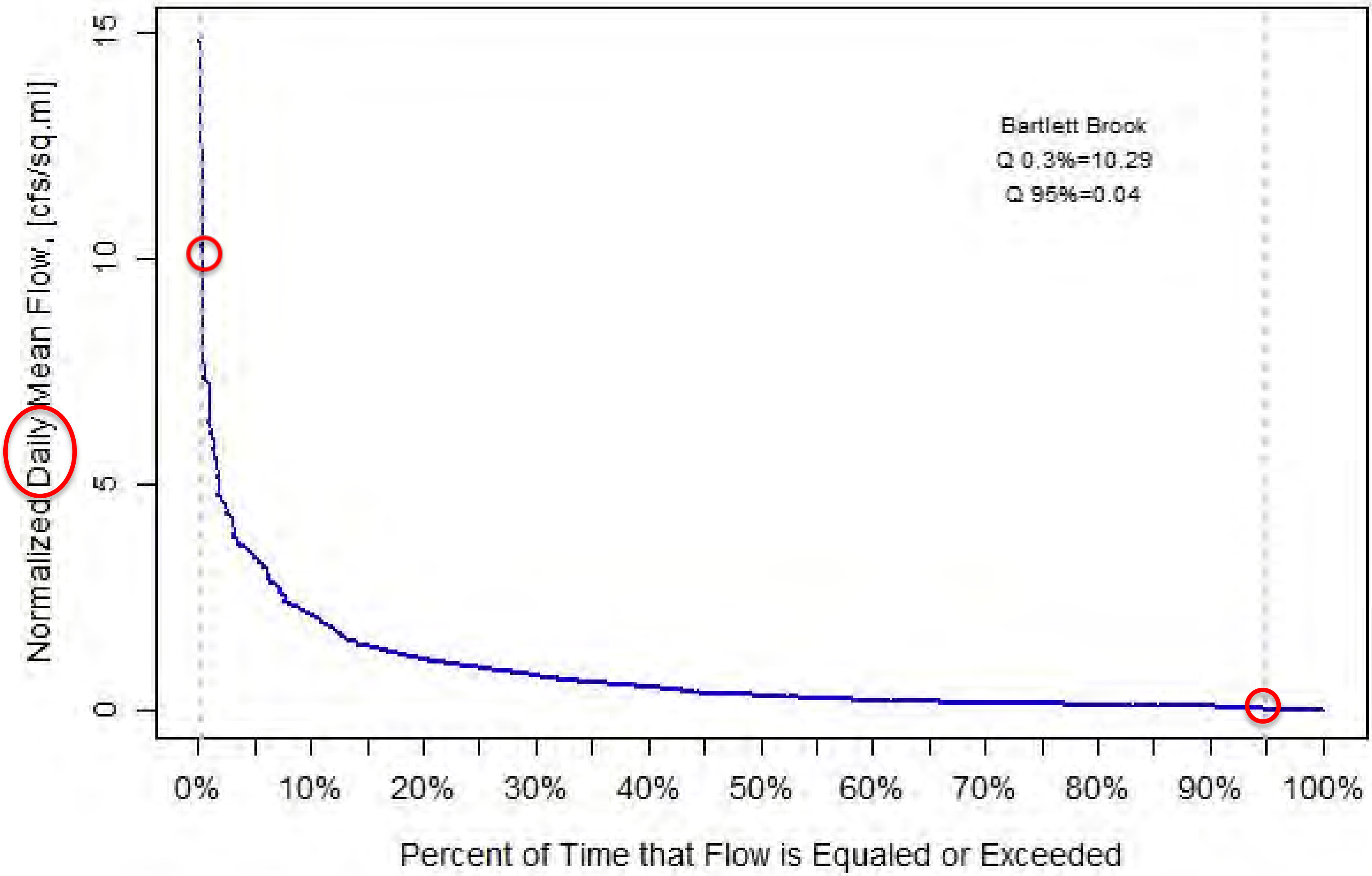
Timestamp	Air Temp. (Enclosure), deg. C	Water Temp., deg. C	Rainfall (total), in.	Stage (avg.), ft.
4/17/2018, 2:00:00 PM	6.88	3.36	0.00	2.54
4/17/2018, 1:00:00 PM	5.87	3.05	0.01	2.53
4/17/2018, 12:00:00 PM	5.22	2.84	0.01	2.54
4/17/2018, 11:00:00 AM	4.50	2.68	0.02	2.55
4/17/2018, 10:00:00 AM	3.95	2.59	0.04	2.56
4/17/2018, 9:00:00 AM	3.49	2.56	0.00	2.58
4/17/2018, 8:00:00 AM	3.16	2.56	0.00	2.60
4/17/2018, 7:00:00 AM	2.88	2.58	0.01	2.59

VERMONT DEPARTMENT OF ENVIRONMENTAL CONSERVATION

STONE ENVIRONMENTAL

Fitzgerald Environmental Associates, LLC. Applied Watershed Science & Ecology

Preliminary FDCs (2017-2018)



STONE ENVIRONMENTAL

Fitzgerald Environmental Associates, LLC

Thank you!

Streamflow and Precipitation Monitoring for MS4s:

2018 Annual Report

PROJECT NO.

15-200

PREPARED FOR:

Blaine Hastings / *Hydrologist*
Vermont DEC
1 National Life Drive, Main 2
Montpelier, VT 05602-3522

SUBMITTED BY:

Serena Matt / *Water Resources Scientist*
Stone Environmental, Inc.
smatt@stone-env.com
917.364.1553

David Braun / *Senior Water Resources Scientist*
Stone Environmental, Inc.
dbraun@stone-env.com
802.272.8819

Streamflow and Precipitation Monitoring for MS4s: 2018 Annual Report

Cover Photo: Making a discharge measurement at Allen Brook, Williston, VT

Contents

Table of Figures

Table of Tables

1. Introduction

Stone Environmental, Inc. (Stone) and Fitzgerald Environmental Associates, LLC. (FEA) are monitoring flow at gauges on 11 streams in Chittenden and Franklin Counties classified as stormwater-impaired. The monitored streams are identified in Table 1, below. We are also monitoring precipitation at a network of 10 gauges across the watersheds of these streams. The purpose of this annual report is to document activities and present results of monitoring at these stations in the 2018 calendar year.

Table 1. Names and locations of monitored streams

Stream	Municipality
Allen Brook	Williston
Bartlett Brook	South Burlington, Shelburne
Centennial Brook	South Burlington, Burlington
Englesby Brook	Burlington, South Burlington
Indian Brook	Essex
Morehouse Brook	Winooski, Colchester
Munroe Brook	Shelburne, South Burlington
Potash Brook	South Burlington, Burlington
Rugg Brook	St Albans Town, St. Albans City
Stevens Brook	St. Albans City, St. Albans Town
Sunderland Brook	Colchester, Essex Junction

Stream gauges were installed between August and December 2016. The gauges provide continuous records of stream stage. Flow data are calculated from stream stage by applying a rating equation specific to each site. When ice in the stream channel precludes use of an open-water rating curve, or when streamflows are affected by beaver or leaf damming, flow data are estimated using data from reference streams. Daily mean flow data are used to develop flow duration curves, which illustrate the percentage of daily mean flow values equaling or exceeding a given value. Finally, daily precipitation totals for each watershed are calculated through interpolation among precipitation gauges.

2. Location of Stream Gauging Stations

Gauging stations were constructed on all 11 streams classified as stormwater-impaired in Chittenden and Franklin Counties, Vermont. The stream and precipitation gauge locations are illustrated in Figure 1, below.

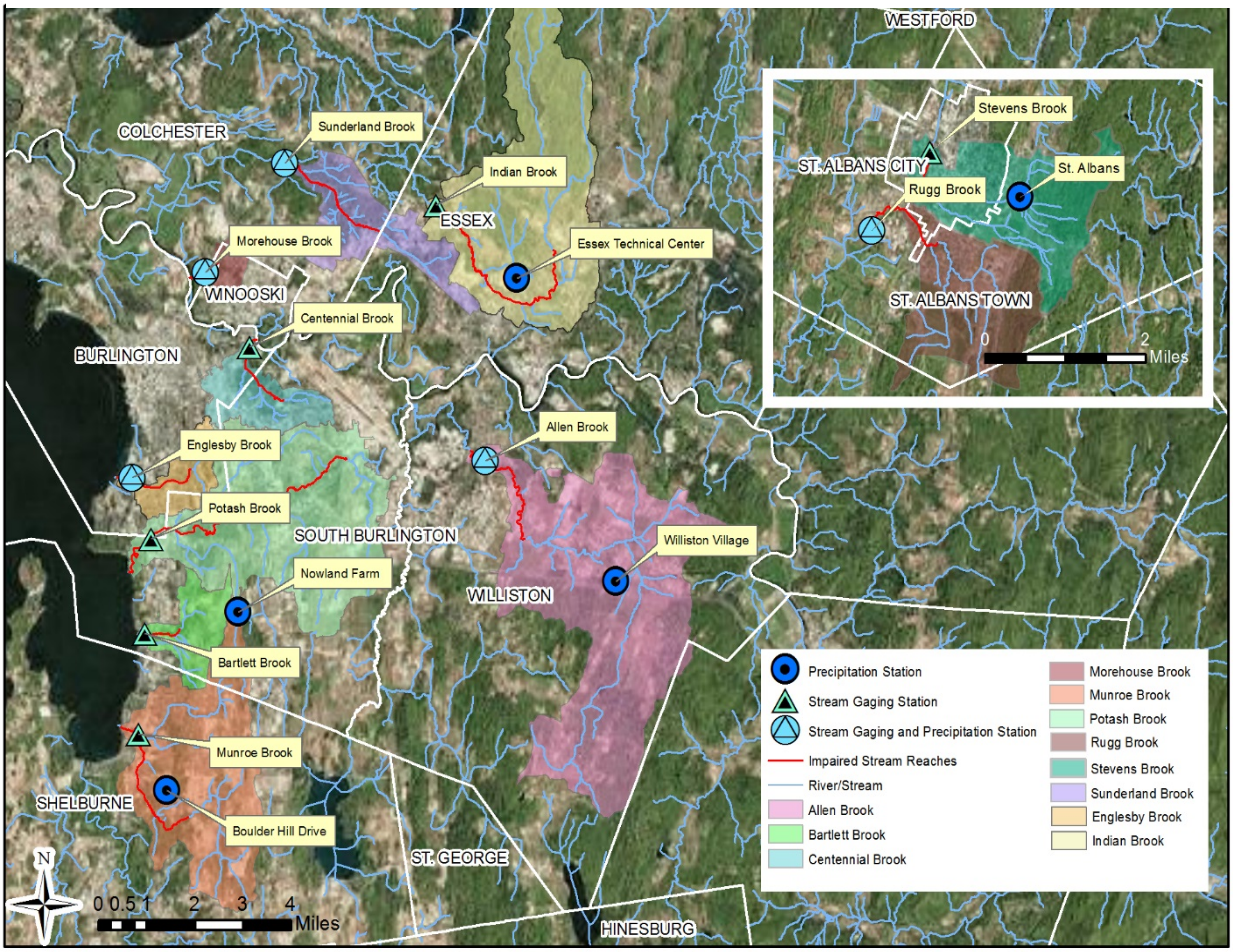


Figure 1. Streamflow and precipitation monitoring stations

In all 11 study watersheds, the location selected for the gauging station is quite close to the downstream end of the stormwater impaired reach (Figure 1). Sites for installation of streamflow gauges were selected with the intent of achieving, to the greatest degree possible, ideal hydraulic conditions. There are no significant inflows between the selected station location and the compliance point on each stream.

Five of the selected sites—Allen, Centennial, Munroe, Potash, and Sunderland Brooks—are located on town-owned or state-owned property, which should ensure long-term, unimpeded access. The six remaining sites are located on privately owned parcels. We have secured written access agreements from all the private property owners. Permissions were granted by the Towns of Colchester and Shelburne for culvert modifications at the Morehouse Brook and Munroe Brook gauging stations, respectively. The State of Vermont Department of Forest, Parks, and Recreation issued Stone Environmental a special use permit for operation of the gauge on Sunderland Brook on land managed by the Department west of Route 7.

USGS formerly monitored locations on Allen Brook, Englesby Brook, Munroe Brook, Potash Brook, and Stevens Brook. The former location of a temporary USGS gauge on Stevens Brook in St. Albans (04292770 Stevens Brook at Lemnah Drive) was determined to be too far upstream from the stormwater compliance point (Pearl Street) to be used for this project. The former USGS sites on the remaining four streams are being reused for this project, with minor adjustments.

3. Stream Gauging Methods

3.1. Stream Monitoring Instrumentation

The primary recording gauge installed at each station is a vented (gauge) pressure transducer. Pressure transducers are deployed in 2-inch diameter electrical conduit installed from the optimum measuring point in the stream up the streambank to the instrument enclosure. The model of pressure transducer used is an INW PT12. At Potash Brook, pressure transducers and staff gauges are deployed in two locations. The downstream gauge was originally considered the primary gauge as it was the location previously monitored by USGS; however, due to instability in the downstream hydraulic control (see Section 3.6.4), the upstream gauge is now the primary gauge.

At each station, water level, stage, and temperature data measured by the pressure transducer are continuously logged using a Campbell Scientific CR300 datalogger. These data are transmitted hourly using a Sierra Wireless RV50 cellular modem to a computer server located at Stone Environmental's offices. Each modem is assigned a unique static IP address. The stations are solar powered. The datalogger and modem, as well as a deep cycle battery and charge controller, are housed in a fiberglass instrument enclosure mounted on a tripod or steel pipe. The system is grounded using a copper grounding rod and cable.

Three reference benchmarks were identified or established at each site, with at least two of these benchmarks not located on a bridge or other structure that could be damaged during a flood event. Existing USGS benchmarks were used at Allen Brook, Englesby Brook, and Potash Brook. New benchmarks include stainless steel rods anchored into bedrock (wherever possible), stainless steel 5/8-inch lag screws set into large trees, and #9 rebar driven below the anticipated frost depth. All benchmarks are located within 400-feet of the stream gauge. Benchmarks were painted or flagged in the field and their locations were described in detail.

3.2. Station Maintenance and Pressure Transducer Calibration

Routine maintenance is performed at all stations approximately monthly. Time-lapse photographs are downloaded, and the camera's site path is cleared of vegetation. Solar panels are cleared of vegetation. The pressure transducer's desiccant is checked and replaced if needed. Pressure transducer conduits are flushed to remove any sediment or debris trapped inside and any significant deposition over the conduit is removed. The stage at the staff gauge is compared to concurrent live pressure transducer readings and the pressure transducer is calibrated on site if the readings differ by more than +/-0.02 ft. The reach is inspected for damming or any obvious changes in stream morphology. If damming is observed or suspected to cause backwater conditions at the gauge the dam is removed to the best of the technician's ability. All activities and observations are recorded using the ArcGIS Survery123 software application for mobile phones and uploaded to an online database for review and record keeping.

At each station, benchmark and staff gauge elevations are surveyed annually to confirm that the staff gauge has not moved. All benchmark survey data are expressed as elevations relative to the level on the staff gauge. No significant changes in staff gauge elevations were measured in 2018. On January 12, 2018 a large snow melt event demolished the lower staff gauge at Allen Brook. The deployed pressure transducer was checked against nearby surveyed reference points until the staff gauge was re-installed on June 22, 2018. The elevation of the new staff gauge was within a hundredth of a foot of the original gauge and thus required no offset adjustment.

3.3. Discharge Measurement

Discharge measurement locations and methods are determined at each site according to the flow conditions present at the time of the measurement. Low flow measurements obtained using a pygmy current meter are best suited for cross-sections with a narrow channel and relatively smooth bottom. High flow measurements using an AA Price current meter (Figure 2) are best made at cross-sections with laminar flow and minimal flow disturbance from large rocks or other channel features. Typically, these cross-sections are deeper and slower. Extreme low flow measurements are made using one of three methods: collapsible (Baski) cutthroat flume, volumetric (Figure 3), or continuous rate salt addition (Figure 4). Extreme high flows are measured using an AA Price current meter in smaller streams and with a River Surveyor S5 acoustic doppler sensor mounted to a hydroboard under non-wadeable conditions (Figure 5).

Figure 2. High flow discharge measurement using an AA Price velocity meter, Potash Brook

Figure 3. A temporary dam used to concentrate flow for volumetric measurement, Munroe Brook

Figure 4. Performing a continuous rate salt addition, Centennial Brook

Figure 5. High flow discharge measurement using a S5 acoustic doppler instrument, Allen Brook

3.4. Determination of Gauge Height of Zero Flow

The gauge height of zero flow (GZF), also commonly referred to as the point of zero flow (PZF), is a necessary correction variable required for rating development. Use of the term in rating computations is detailed in Section 3.6.1. GZF is measured on an annual basis as conditions allow to ascertain if low flow controls have shifted due to changes in channel geometry and bedload distribution. Comparison of the GZF over time can offer the most insight into changes to the section control as it undergoes scouring or filling and is often the only way to explain rating shifts. GZF is defined as the stage at which the flow of the stream is effectively zero. It was calculated by identifying the low-flow tailwater control cross-section at each site, measuring the depth of the water along that cross section at its deepest point, and then subtracting that value from the gauge height at the time of the measurement.

Tailwater controls can be natural or manmade. Low-flow natural channel controls can be thought of as riffles or slightly elevated portions of the streambed immediately downstream of the gauge which, at low flow, control whether that portion of the stream is flowing or still. Natural controls are present at Allen, Bartlett, Centennial, Indian, Potash, Rugg, Stevens, and Sunderland Brooks. Tailwater controls can also be artificial structures such as weirs, which are present at Englesby, Morehouse, and Munroe Brooks. At these sites, the GZF is the stage corresponding to the weir notch. This point is stable over time and easily measured.

3.5. Correction of 5-Minute Stage Record

The 5-minute stage record is posted on the public website (http://vt-ms4-flow.stone-env.com/FlowDev/index.html#); it contains raw stage, corrected stage, and flags and comments describing any corrections made to the data. Most stage corrections were made using R version 3.6.1.

3.5.1. Record Gaps

In general, data gaps ranged in length from five minutes to a few hours. These gaps were filled using linear interpolation. For longer gaps caused by power outages or other equipment malfunctions we recreated the record using hourly time-lapse photographs of staff gauges. We then used the tsSmooth base package in R to interpolate values at the 5-minute level. All interpolated data were flagged accordingly in the record.

In 2018 datalogger program losses resulted in longer data gaps at Bartlett Brook, Centennial Brook, Englesby Brook, Morehouse Brook, Munroe Brook, and Stevens Brook. Recreating the stage record from time-lapse photographs worked well to fill these gaps in all cases except a 4-day gap at Morehouse Brook, when the photographs were unusable due to burial and obstruction of the staff plate. Instead the missing stage data were estimated at the daily mean discharge level using data from Bartlett Brook. Log-transformed daily mean flows at Morehouse Brook were significantly correlated with log-transformed daily mean flows at Bartlett Brook (adjusted $R^2=0.94$) in the twenty days bracketing the gap, therefore we estimated missing Morehouse flows based on this relationship with Bartlett Brook. Note that updating datalogger firmware in the spring of 2019 has since resolved the recurring program loss bug.

3.5.2. Sensor Drift and Calibration Offsets

In addition to monthly field checks described in Section 3.2, we compared time-lapse photographs of staff gauges to concurrent pressure transducer readings during event and non-event periods to check for sensor deviation or drift. Differences of less than a tenth of a foot were generally not accurately discernible using the photographs. We paired our record of field checks and pressure transducer calibrations with photographic comparisons to determine if back-corrections were appropriate. Additionally, we manually corrected for calibration offset losses caused by occasional program setting glitches in the field calibration procedure.

The pressure transducer at Centennial Brook began drifting intermittently on October 8, 2018. It took some time to determine the source of the sensor's deviation. Initially we assumed the discrepancies between the sensor and the staff plate photographs were caused by sediment accumulation around the pressure transducer or they resulted from misreading of the photographs due to waves against the staff plate. A series of field maintenance visits and checks confirmed the deviation to be real, however, and a carefully reconstructed stage record from photographs exposed first a linear drift, and then more erratic drifts later in the month. The pressure transducer was replaced on November 16, 2018, which resolved the problem. The stage record was corrected during this period using both photographic reconstruction and a linear drift correction package in R (Shaughnessy et al. 2018). The data in this period were flagged accordingly.

Sediment accumulation over the pressure transducer was a recurrent problem at Englesby Brook in 2017 and spring 2018. Sediment burial resulted in muted sensor response, requiring laborious correction of muted hydrograph peaks using the staff plate photographs. In late May and early June 2018, a few hydrograph peaks muted by sediment accumulation could not be corrected using the photographic record due obstruction of the staff plate. These data were flagged accordingly. After a large flow event on June 18, 2018 completely buried the pressure transducer, it became unresponsive to stage changes. Because continuing to drain and dig out the weir pool after large flow event is impractical in the long term, we chose to relocate the pressure transducer. On July 12, 2018 the pressure transducer was installed more centrally within the channel, which has largely resolved the issue.

3.5.3. Graphical Review

We visually reviewed the stage record using interactive plots generated by plotly (Sievert et al., 2017) and dygraphs (Vanderkam et al., 2017) in R. We compared hydrographs of similar streams and overlapped hydrographs with precipitation and temperature data to identify atypical behavior warranting closer scrutiny of the field or photographic record. We used the visual review in conjunction with our field record to identify and remove noise generated by site maintenance activities such as digging out the weir pool.

3.5.4. Identification of Ice-impacted Data

We assumed any ice present in the channel was hydraulically impacting stream flow at the gauge and we flagged all data associated with periods of channel and bank ice as provisional and in need of correction. Ice-in and ice-out periods were initially identified by the presence of channel and bank ice in time-lapse photographs. When photographs were unavailable or unclear, we used photographs from nearby sites. If these were unavailable, we inferred the presence of ice from nearby USGS station data marked as estimated due to ice. We visually compared the hydrographs of similar streams to further refine these designations. The method used to infer ice presence is indicated in the Comments column of the 5-minute stage record. Ice corrections are applied to daily mean flow data only; the procedures are further described in Section 3.7.1.

3.5.5. Identification of Dam-impacted Data

As with ice, damming creates a dynamic obstacle in the stream. Damming in a stream can result in backwater conditions at the gauging station, precluding application of established rating curves to calculate flow. Stage data impacted by damming were identified and flagged using field maintenance records, visual inspection of hydrographs, and time-lapse photographs. Stage data impacted by damming were only corrected if we determined the damming was significant enough to affect the calculation of daily mean discharge. Short periods of leaf and debris damming with negligible impacts on calculated daily mean discharges were ignored.

In 2018, damming significantly impacted stream stage only at Sunderland Brook. Beaver damming at Sunderland Brook from June 25, 2018 through August 3, 2018 and October 19, 2018 through October 27, 2018 resulted in elevated stage readings. Dams were removed approximately weekly through July and early August. Stage recorded before and after the dams were removed, as well as relative flow responses at nearby streams, were used to estimate stage during these periods. Stage data impacted by, or corrected for, damming were flagged accordingly in the record.

In late October 2018 beaver dam construction at Sunderland Brook outpaced our ability to remove dam debris. Because the debris was blocking both the upstream and downstream ends of a culvert under Route 7, we informed the Vermont Agency of Transportation. The Agency removed three beavers from the stream and demolished the dams on October 27, 2018. For a period of several weeks following the dam removal on October 27, 2018 the gauged reach appeared to be equilibrating hydraulically. Elevated stream stages caused by damming have not been observed since.

3.6. Rating Curve Development

The determination of the stage–discharge relation and development of the rating is one of the fundamental tasks in computing a flow record. The rating is usually the relation between gauge height and flow rate (simple rating).

Procedures for the development, modification, and application of ratings are described in Kennedy (1984). Additional guidelines pertaining to rating and records computation are presented in Rantz and others (1982, chap. 10–14 and p. 549) and in Kennedy (1983, p. 14). Measurements taken between 2017 and spring 2019 were used to construct the 2018 stage–discharge ratings; these measurements are presented in Table 2.

Table 2. Stage and discharge measurements used in 2018 rating computations

Stream	Date	Stage (ft)	Discharge (cfs)	Discharge Method
Allen	8/12/2016	0.65	0.04	CRA
Allen	9/28/2016	0.725	0.15	CRA
Allen	10/3/2017	0.84	0.22	Pygmy
Allen	10/31/2016	0.96	1.01	Pygmy
Allen	11/4/2016	1.105	2.37	Pygmy
Allen	11/1/2017	1.3	5.54	AA
Allen	10/31/2017	1.44	8.59	AA
Allen	10/31/2017	1.54	14.28	AA
Allen	5/8/2019	1.58	16.23	AA
Allen	1/4/2017	1.63	17.67	AA
Allen	5/23/2018	1.73	24.91	AA
Allen	10/30/2017	1.9	34.99	AA
Allen	4/18/2018	2.2	50.81	AA
Allen	2/26/2017	2.32	80.99	AA
Allen	4/7/2017	2.72	114.88	S5
Allen	6/30/2017	3.6	320.31	S5
Bartlett	7/16/2018	0.08	0.014	Baski
Bartlett	9/17/2018	0.12	0.036	Baski
Bartlett	9/26/2016	0.165	0.06	CRA
Bartlett	10/31/2016	0.2	0.07	Pygmy
Bartlett	8/10/2017	0.21	0.25	Pygmy
Bartlett	9/8/2017	0.295	0.7	Pygmy
Bartlett	10/27/2017	0.31	0.71	Pygmy
Bartlett	11/4/2016	0.35	0.51	Pygmy
Bartlett	12/1/2016	0.43	0.96	Pygmy
Bartlett	10/26/2017	0.48	1.37	Pygmy
Bartlett	3/29/2018	0.6	1.76	Pygmy
Bartlett	5/3/2019	0.68	2.71	Pygmy
Bartlett	3/30/2018	0.83	5.49	Pygmy
Bartlett	2/23/2017	0.96	7.46	Pygmy
Bartlett	10/9/2017	1	9.1	Pygmy
Bartlett	5/10/2019	1.12	13.16	AA
Bartlett	3/15/2019	1.29	17.95	AA
Centennial	9/26/2016	0.41	0.23	CRA
Centennial	10/24/2016	0.47	0.56	Pygmy
Centennial	8/9/2017	0.49	0.65	Pygmy
Centennial	9/8/2017	0.55	1.22	Pygmy
Centennial	10/28/2016	0.58	2.1	Pygmy
Centennial	5/8/2019	0.59	1.42	Pygmy
Centennial	4/15/2019	0.68	3.29	Pygmy
Centennial	4/3/2017	0.68	3.66	Pygmy
Centennial	4/30/2018	0.79	5.75	Pygmy
Centennial	6/23/2017	0.85	6.99	Pygmy
Centennial	6/6/2017	1.08	15.29	AA
Centennial	5/10/2019	1.19	24.58	AA
Centennial	1/12/2018	1.32	29.16	AA
Englesby	11/11/2016	0.66	0.0035	Vol
Englesby	11/1/2016	0.735	0.04	Baski
Englesby	8/9/2017	0.81	0.11	Pygmy

Stream	Date	Stage (ft)	Discharge (cfs)	Discharge Method
Englesby	12/19/2016	1.09	0.73	Pygmy
Englesby	5/8/2019	1.12	0.72	Pygmy
Englesby	12/1/2016	1.23	1.14	Pygmy
Englesby	1/26/2017	1.295	1.45	Pygmy
Englesby	2/22/2017	1.37	1.99	Pygmy
Englesby	2/21/2018	1.5	2.98	Pygmy
Englesby	2/26/2017	1.62	4.24	Pygmy
Englesby	6/6/2017	1.85	6.32	Pygmy
Englesby	6/30/2017	2.09	11.92	AA
Englesby	3/15/2019	2.2	13.54	AA
Englesby	6/21/2019	2.45	19.16	AA
Indian	9/5/2018	0.27	0.65	Pygmy
Indian	8/15/2017	0.35	1.12	Pygmy
Indian	10/31/2016	0.45	1.29	Pygmy
Indian	12/7/2016	0.53	2.27	Pygmy
Indian	11/30/2016	0.64	3.64	AA
Indian	9/6/2017	0.79	6.59	AA
Indian	12/6/2017	0.82	8	AA
Indian	5/6/2019	0.95	9.45	Pygmy
Indian	12/1/2016	0.98	12.67	AA
Indian	5/24/2018	1.07	16.38	AA
Indian	5/2/2019	1.12	17.65	AA
Indian	4/16/2018	1.28	27.46	AA
Indian	4/4/2018	1.35	29.56	AA
Indian	3/2/2017	1.45	32.61	AA
Indian	4/5/2017	1.8	56.5	S5
Indian	4/30/2018	1.95	64.12	S5
Indian	4/7/2017	2.31	89.47	S5
Morehouse	10/17/2016	0.57	0.007	Vol
Morehouse	10/4/2016	0.595	0.012	Vol
Morehouse	12/7/2016	0.65	0.052	Vol
Morehouse	2/28/2017	0.8	0.21	Pygmy
Morehouse	2/26/2017	0.94	0.45	Pygmy
Morehouse	2/23/2017	1.06	1.11	Pygmy
Morehouse	5/22/2017	1.15	1.63	Pygmy
Morehouse	6/19/2017	1.25	2.45	Pygmy
Morehouse	10/11/2018	1.38	3.76	Pygmy
Morehouse	10/11/2018	1.5	5.13	Pygmy
MunroeI	10/7/2016	0.63	0.017	Vol
MunroeI	9/17/2018	0.66	0.062	Vol
MunroeI	8/10/2017	0.73	0.22	Pygmy
MunroeI	12/7/2016	0.88	0.52	Pygmy
MunroeI	11/4/2016	0.99	0.85	Pygmy
MunroeI	12/1/2016	1.26	2.08	Pygmy
MunroeI	1/4/2017	1.47	3.72	Pygmy
MunroeI	5/8/2019	1.65	5.51	Pygmy
MunroeI	2/28/2017	1.77	6.47	Pygmy
MunroeI	2/27/2017	2	12.7	Pygmy
MunroeII	4/18/2018	2.2	21.63	AA
MunroeII	2/26/2017	2.78	54.48	AA

Stream	Date	Stage (ft)	Discharge (cfs)	Discharge Method
Munroell	3/30/2018	2.86	44.97	AA
Munroell	4/17/2018	3.12	68.18	AA
Munroell	3/28/2017	3.44	98.93	AA
Munroell	5/10/2019	3.9	135.7	AA
Munroell	6/30/2017	4.55	183.99	S5
Potash US	7/16/2018	0.27	0.36	Pygmy
Potash US	9/17/2018	0.33	0.61	Pygmy
Potash US	8/11/2017	0.42	1.1	Pygmy
Potash US	5/31/2018	0.42	1.75	Pygmy
Potash US	11/30/2016	0.49	2.43	Pygmy
Potash US	11/4/2016	0.54	5.11	Pygmy
PotashUS	10/4/2018	0.55	4.07	Pygmy
PotashUS	5/1/2019	0.67	8.16	Pygmy
Potash US	4/20/2018	0.72	12.12	Pygmy
Potash US	10/26/2017	0.76	11.02	Pygmy
Potash US	12/1/2016	0.74	12.3	AA
PotashUS	9/11/2018	0.82	17.72	AA
Potash US	10/30/2017	0.91	24.01	AA
PotashUS	5/3/2019	0.96	19.81	Pygmy
Potash US	4/30/2018	1.31	44.21	Pressure
Potash US	6/6/2017	1.61	86.77	AA
PotashUS	11/3/2018	1.81	96.19	AA
Rugg	9/20/2018	-0.03	0.034	CRA
Rugg	8/16/2017	0.06	0.09	Pygmy
Rugg	8/7/2017	0.1	0.14	Pygmy
Rugg	10/9/2017	0.37	0.8	Pygmy
Rugg	6/28/2017	0.5	2.31	Pygmy
Rugg	4/19/2019	0.68	4.29	Pygmy
Rugg	12/6/2017	0.71	4.42	Pygmy
Rugg	6/6/2017	0.81	7.11	Pygmy
Rugg	5/2/2019	0.88	7.89	Pygmy
Rugg	3/2/2017	1.02	11.98	AA
Rugg	5/2/2017	1.17	20.64	AA
Rugg	11/3/2017	1.53	28.16	AA
Rugg	3/30/2018	1.95	58.83	AA
Rugg	5/10/2019	2.875	137.76	AA
Stevens	8/16/2017	0.24	0.02	Baski
Stevens	8/10/2017	0.27	0.034	Baski
Stevens	9/11/2018	0.44	0.23	Pygmy
Stevens	10/27/2016	0.52	1.04	Pygmy
Stevens	12/1/2016	0.67	2.06	Pygmy
Stevens	12/6/2017	0.78	3.46	Pygmy
Stevens	11/29/2017	0.84	3.52	Pygmy
Stevens	4/19/2019	0.86	3.61	Pygmy
Stevens	10/9/2017	0.94	4.31	Pygmy
Stevens	5/2/2019	1.005	5.76	Pygmy
Stevens	3/29/2017	1.12	8.14	Pygmy
Stevens	3/2/2017	1.19	10.72	AA
Stevens	5/2/2017	1.35	14.6	AA
Stevens	5/10/2019	1.5	19.57	AA

Stream	Date	Stage (ft)	Discharge (cfs)	Discharge Method
Stevens	3/30/2018	1.81	36.54	AA
Sunderland	8/29/2017	0.48	0.46	Pygmy
Sunderland	9/16/2016	0.46	0.28	Pygmy
Sunderland	10/21/2016	0.54	0.78	Pygmy
Sunderland	8/9/2017	0.6	1.5	Pygmy
Sunderland	11/4/2016	0.67	1.59	Pygmy
Sunderland	12/1/2016	0.8	2.69	Pygmy
Sunderland	5/2/2019	0.88	3.36	Pygmy
Sunderland	2/26/2017	1.02	4.06	Pygmy
Sunderland	4/15/2019	1.06	4.76	Pygmy
Sunderland	4/30/2018	1.15	7.36	Pygmy
Sunderland	6/19/2017	1.47	18.82	AA
Sunderland	1/12/2018	1.83	33.17	AA

3.6.1. Defining Stage-Discharge Relationships with a Power Function

A simple rating, following a power curve of the form given below, was appropriate for use at all the sites.

$Q=C(h\text{-}a)^n$, where:

Q is discharge in cubic feet per second;
h is stage in feet;
a is the gauge height of zero flow in feet;
C is a unitless coefficient equal to the discharge at which (*h-a*) is equal to 1; and
n is a unitless coefficient equal to the slope of the best-fit line on log-transformed stage and discharge.

Typically, *a* can be measured, or at least checked for a reasonable physical basis in the field, while *C* and *n* are estimated based on the line of best fit. Note that although discharge is solved for in this form of the equation, it is convention to plot discharge as the abscissa and to rearrange the equation accordingly.

3.6.2. Fitting the Data with a Curve

The nonlinear least squares regression function (nls) in R (Baty et al., 2017) was used to fit a power curve to paired stage and discharge data. This function makes nonlinear least squares estimates of coefficients *C* and *n* to generate a curve that best fits the data. More typically, the relationship between stage and discharge is linearized by log-transforming both variables, and the slope and intercept of the line are used to calculate the coefficients of the power formula. We compared coefficients calculated by both methods and found them to be similar. However, the nls-generated curve fit the data more closely and did not require that the data be transformed, therefore we elected to use this method. The coefficients calculated using the nls regression method are presented in Table 3. Note that Table 3 displays coefficients used in both the 2017 and 2018 ratings.

Table 3. Coefficients used in the 2017 and 2018 ratings

Stream	2017 Rating Coefficients			2018 Rating Coefficients		
	a	C	n	a	C	n
Allen	0.510	12.148	2.923	0.510	12.265	2.913
Bartlett	-0.060	7.536	2.854	-0.060	7.620	2.915
Centennial	0.230	23.708	2.520	0.230	24.905	2.596
Englesby	0.590	3.873	2.596	0.590	3.869	2.597
Indian	-0.205	7.068	2.923	-0.205	7.039	2.932
Morehouse	0.470	4.897	2.868	0.470	4.824	2.846
Munroe I	0.595	5.502	2.116	0.595	5.414	2.092
Munroe II	1.508	34.142	1.524	1.508	34.223	1.536
Potash US	-0.050	20.161	3.067	-0.050	19.664	2.860
Rugg	-0.207	6.110	3.009	-0.207	6.312	2.804
Stevens	0.180	10.392	2.496	0.180	10.175	2.509
Sunderland	0.100	7.056	2.843	0.100	6.856	2.877

3.6.3. Rating Revisions

Rating curves fitted to paired stage and discharge data changed with the addition of new 2018 and 2019 measurements (Table 3). None of these changes are indicative of rating shifts; rather these new measurements extend the curves across a greater range of flow conditions, thus improving and refining our representations of relationships between stage and discharge. While changes to rating curve coefficients C and n can be seen in Table 3, coefficient a remains unchanged at all streams, as the term represents a field measurement of the gauge height of zero flow taken in the summer of 2018 and used in both the 2017 and 2018 ratings.

To evaluate the impact of rating changes for each stream we calculated 2018 daily mean discharges using both the 2017 rating equation and the 2018 rating equation. We then compared these two derivations of daily mean discharge and counted the number of days in the year for which the difference in discharge equaled or exceeded 5 and 10 percent (Table 4). At Allen, Englesby, Indian, and Morehouse Brooks differences between 2017- and 2018-derived mean daily discharges were less than 5% for every day of the year, demonstrating that the addition of 2018 discharge measurements did not appreciably change the ratings of these streams. The rating change at Englesby Brook, for example, is almost imperceptible despite the addition of two discharge measurements 13% and 60% greater than the previous highest measurement (Figure 6). At Centennial, Munroe, Stevens, and Sunderland

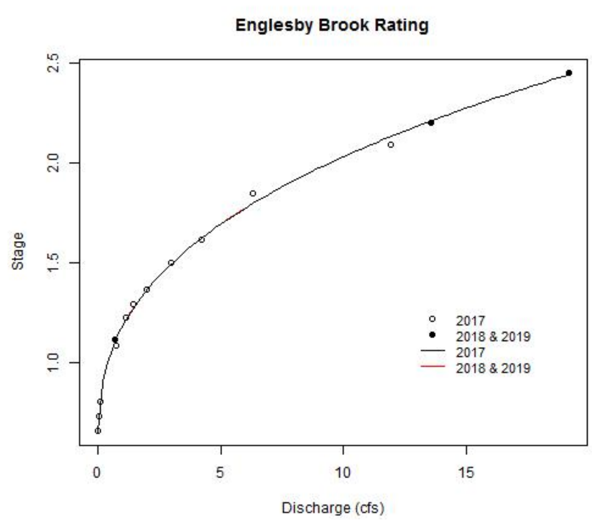


Figure 6. Comparison between 2017 and 2018 rating curves at Englesby Brook

Brooks, discharge differences fell between 5% and 10% for a significant portion of the year due to the addition of new mid- to high-flow measurements. Bartlett, Rugg, and Potash Brooks showed the largest changes. At Rugg Brook and Potash Brook, new high discharge measurements were added to the 2018 ratings, which caused departures in the rating curves (Figure 7). At Rugg Brook, for example, the new highest discharge measurement exceeded the previous highest measurements by 134%. The resulting differences in calculated mean daily discharge were greater than 15% on 147 days for Rugg Brook and 58 days for Potash Brook.

Table 4. Comparison of 2018 mean daily discharges calculated using the 2017 and improved 2018 ratings

	Number of Days with Substantially Different Computed Discharge	
Stream	**≥ 5% difference**	**≥ 10% difference**
Allen	0	0
Bartlett	115	26
Centennial	115	0
Englesby	0	0
Indian	0	0
Morehouse	0	0
Munroe	55	0
Potash US	199	119
Rugg	218	176
Stevens	30	0
Sunderland	79	0

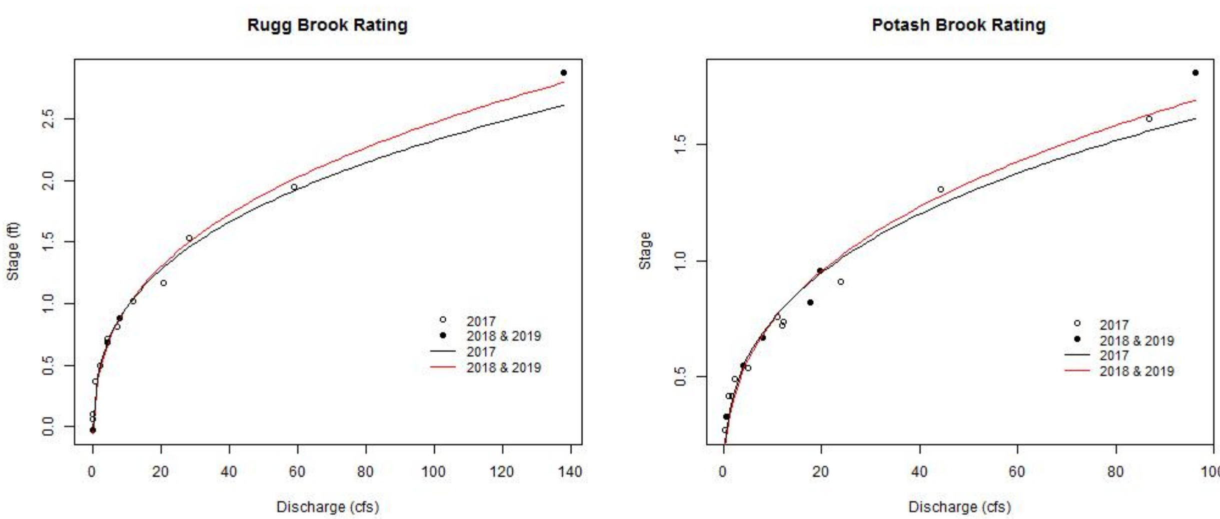


Figure 7. Comparison between 2017 and 2018 rating curves at Rugg Brook and Potash Brook

3.6.4. Special Circumstances

The Munroe Brook gauging station is located at the upstream end of a large concrete box culvert. At low and moderate flows, the hydraulic control is a pair of weir plates spanning the culvert opening. The stream's hydraulic control changes dramatically at a stage of 2.1 ft: the weir plates become submerged and the stream becomes confined by the wall of the box culvert. As a result, there is a distinct change in the slope of the rating at approximately this stage. We fit the data below and above this 2.1 ft threshold separately with two different rating curves and made sure that the intersection of the two curves corresponded to the stage at which the channel control changes. Table 3 provides the coefficients for the lower (Munroe I) and upper (Munroe II) portions of this two-part rating.

Two gauging locations were established at Potash Brook. The downstream location was originally considered the primary gauge. A rating shift occurred in 2018 as a result of scouring, braiding, and deposition during snowmelt. Because we anticipated continued channel instability at the downstream control, and because the channel at the upstream location is more hydraulically stable due to its bedrock streambed, we decided to discard the downstream rating and treat the upstream gauging location as our primary gauge.

Since the upstream gauge on Potash Brook was originally treated as a secondary gauge, staff plate readings were not always made during discharge measurements in 2017. Notably, we are missing the upstream staff gauge reading associated with the second highest discharge measurement on record, which was taken on April 30, 2017. Because it was necessary to include this point in our rating, we used the 5-minute stage recorded by the pressure transducer at the time of the discharge measurement rather than a staff plate reading, assuming that this stage measurement was accurate. Before including this value in the rating, we verified that the sensor had been recently serviced and checked and was stable during the period in which the discharge measurement was made.

3.7. Calculation and Estimation of 2018 Daily Mean Flows

We applied finalized 2018 stage-discharge rating equations (Table 3) to the corrected 5-minute stage record at each site to derive 5-minute flow data for 2018. We then calculated daily mean flow (DMQ). Flags in the 5-minute stage record were preserved in the daily mean flow record and were used to identify daily mean flow values that required estimation due to ice (Figure 8).

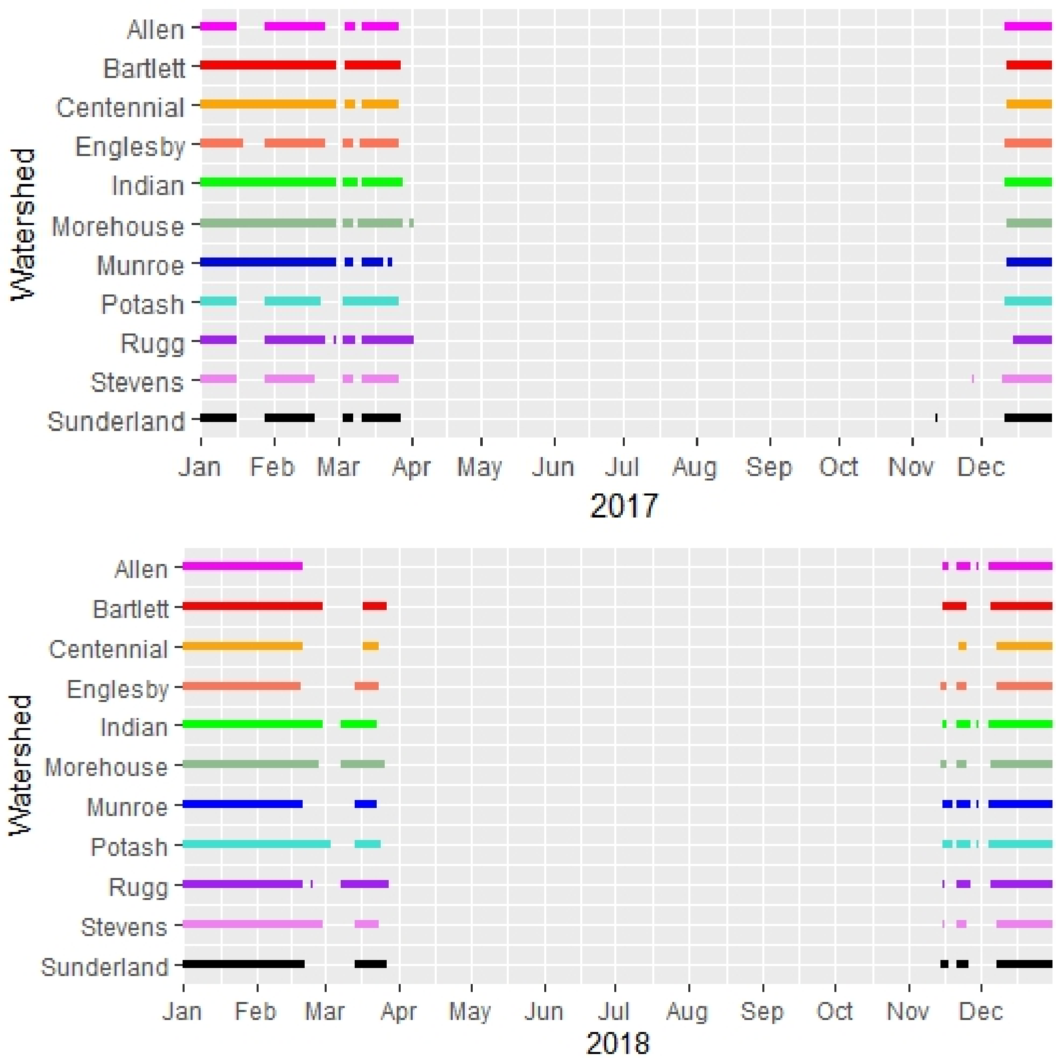


Figure 8. Periods of ice-impacted flow in 2017 and 2018

3.7.1. Flow Estimation During Ice-Impacted Conditions

Simple linear regressions with USGS-gauged streams were used to estimate corrected values for flows that were impacted, or entirely missing, due to ice (Sauer 2002). We examined all USGS-gauged streams with similar basin areas within 150 miles of our stream gauges and determined that the LaPlatte River and Mill River gauges were the most appropriate reference gauges. Table 5 identifies which reference gauge is used in deriving flow estimates for each stream gauged in this program. While the LaPlatte River and Mill River watersheds, at these USGS gauges, are between 5 to 120 times larger than our sites (Table 6), they are proximate and similar in elevation.

Log-transformed DMQs at every site were significantly explained by the log-transformed DMQs at either the Mill River or the LaPlatte River USGS gauges (Table 5). Normalizing DMQ by basin area did not improve regression results. Note that Table 5 displays regression statistics calculated in both 2017 and 2018 and that the 2018 regression statistics are derived from combined 2017 and 2018 data, the selection of which is described in more detail below. DMQ data estimated using these regression equations were flagged accordingly.

In 2017, DMQ values between January 1, 2017 and May 15, 2017 and between November 15, 2017 and December 31, 2017 were selected for regression analyses, as we wanted to restrict the analysis to date ranges most similar to the periods being estimated. At the time, certain reference gauge data were marked provisional by the USGS. In 2018, these values were updated to reflect all final 2017 data and combined with 2018 DMQ values selected using similar criteria. These aggregated datasets encompassed a greater variety of conditions while allowing us to shorten the selected date ranges to make them even closer to the periods being estimated. Notably, we shortened the first range, ending it on approximately April 25th in 2018 and April 15th in 2017, and selected 2018 DMQ values between October 28th and November 8th due to ice forming in streams much earlier than the prior year. We also excluded 2018 dates for which the USGS reference stream data were flagged as provisional. For sites referenced against the LaPlatte River, this resulted in the exclusion of all 2018 fall and winter data. For now, this season is represented by 2017 data. Like last year, we excluded all flow data already flagged for ice or damming. Although we used the Mill River as the reference stream for Sunderland Brook, there was excessive damming at Sunderland Brook in the fall (see Section 3.5.5) and, as a result, all 2018 fall and winter data is excluded from the Sunderland Brook /Mill River regression as well.

When 2018 provisional reference gauge data are approved by the USGS we will integrate any newly approved data which meet the criteria described above into next year's regressions. Additionally, we tentatively plan to incorporate one more years' worth of data (2019) into these regressions.

All DMQ data used in the regression models were log transformed to meet parametric statistical assumptions. Additionally, the discharge data were found to be autocorrelated, violating the assumption of independence between observed variables. This is a common characteristic of time series data because variables are ordered sequentially, and what happens one moment is often related to what happened moments prior. To address this violation, we developed subsets of the data by every 2nd, 3rd, or 4th day until the autocorrelation function (ACF) and Durbin-Watson test no longer indicated significant autocorrelation (see "Subset by nth value" in Table 5). That is why sample sizes for combined 2017 and 2018 regression data are less than in the 2017 regression data (Table 5).

The USGS corrects winter flow data for the LaPlatte and Mill Rivers using climactic records, periodic winter discharge measurements, gauge-height records, and nearby station behavior. USGS flow data are currently marked as provisional (meaning USGS has not completed corrections) from October 25, 2018 onwards at the LaPlatte River gauge and from November 09, 2018 onwards at the Mill River gauge. During these periods, DMQ data that we estimated using provisional reference gauge flow data were flagged; these data will be reexamined after USGS finalizes the provisional LaPlatte River and Mill River data. Additionally, no LaPlatte River flow data are currently available from November 14, 2018 to November 24, 2018 and December 02, 2018 onwards. Ice affected flows which require estimation using LaPlatte River gauge data, and fall during these periods, have not been corrected; these data are flagged accordingly. There are no Morehouse Brook and Bartlett Brook flow data from December 05, 2018 onwards because we had removed the pressure transducers to avoid ice damage. Flow estimates will be completed for these streams when USGS finalizes data for the LaPlatte River and Mill River reference gauges.

Table 5. Regression coefficients used for flow estimation during ice-impacted conditions in 2017 and 2018

Stream	USGS Reference Gauge	2017 Equation				2018 Equation				
		R^2	Intercept	Slope	n	R^2	Intercept	Slope	n	Subset by n^{th} value
Allen	LaPlatte	0.94	-0.42*	0.86*	95	0.92	-0.31*	0.81*	40	3
Bartlett	LaPlatte	0.89	-2.23*	1.16*	74	0.84	-2.09*	1.11*	29	3
Centennial	LaPlatte	0.75	-0.69*	0.43*	54	0.80	-0.79*	0.50*	49	2
Englesby	LaPlatte	0.92	-2.76*	1.34*	89	0.91	-2.60*	1.24*	56	2
Indian	LaPlatte	0.95	-0.62*	0.92*	70	0.95	-0.49*	0.84*	39	2
Morehouse	LaPlatte	0.85	-2.36*	0.93*	69	0.88	-2.21*	0.79*	25	3
Munroe	LaPlatte	0.95	-1.88*	1.38*	79	0.91	-1.70*	1.28*	26	4
Potash US	LaPlatte	0.87	-0.57*	0.75*	93	0.86	-0.42*	0.69*	34	3
Rugg	Mill	0.95	-0.80*	0.96*	99	0.94	-0.58*	0.82*	43	3
Stevens	Mill	0.93	-0.93*	0.98*	81	0.92	-0.95*	0.98*	58	2
Sunderland	Mill	0.83	-0.66*	0.55*	65	0.90	-0.61*	0.54	25	3

***P-value<0.001**

Table 6. Watershed area for each stream

Stream	Watershed Area (mi^2)
Allen Brook	9.77
Bartlett Brook	1.12
Centennial Brook	1.38
Englesby Brook	0.95
Indian Brook	7.19
Morehouse Brook	0.37
Munroe Brook	5.53
Potash Brook	7.06
Rugg Brook	2.58
Stevens Brook	2.87
Sunderland Brook	2.24
LaPlatte River*	45
Mill River*	22

USGS-gauged stream used as reference in flow estimation

3.8. Re-estimation of 2017 Free Flowing Daily Mean Discharge Record

Since no rating shifts have been observed (discounting the shift at the Potash Brook downstream gauge), we applied the improved 2018 ratings (described in Section 3.6.3) to recalculate the 2017 daily mean discharge record at all streams during free-flowing conditions. We did not modify discharge data that were estimated by other means or corrected for ice. The recalculated 2017 discharge data are now available on the project website.

We expect to make further refinements to the ratings in 2020 as additional discharge measurements expand the range of captured flow conditions for a given stream. In 2020 we expect to back-apply improved ratings to recalculate the 2017 and 2018 discharge record. We are hopeful that beyond 2020 the annual discharge data submittals will be essentially final as produced; that is, rating refinements will be subtle enough as to have negligible impact on previously computed discharge data.

4. Precipitation Monitoring Methods

A network of precipitation monitoring stations was installed to provide representative and unique precipitation data for each of the 11 stormwater-impaired watersheds in Chittenden and Franklin Counties. The precipitation monitoring network includes 10 gauges installed and operated by Stone and FEA. The approximate locations of these precipitation gauges are shown in Figure 1. These locations and the instruments installed are described in Table 7.

Table 7. Locations of precipitation gauges and types of instruments installed

Watershed	Town	Location	Precipitation Gauge Installed
Allen Brook	Williston	In field adjacent to Allen Brook stream gauge	Rickly Model 3510
Allen Brook	Williston	In field south of Williston town offices	Rickly Model 3510
Englesby Brook	Burlington	In yard adjacent to Englesby Brook stream gauge	Rickly Model 3510
Indian Brook	Essex Junction	Near orchard at Essex Technical Center	Rickly Model 3510
Morehouse Brook	Colchester/ Winooski	At Morehouse Brook stream gauge	ISCO 674
Munroe Brook (near Bartlett Brook watershed boundary)	S. Burlington	In field south of Nowland Farm Drive	Hydrological Services TB3
Munroe Brook	Shelburne	Bordering stormwater pond at the end of Hawley Road	Rickly Model 3510
Rugg Brook	St. Albans Town	In field adjacent to Rugg Brook stream gauge	Rickly Model 3510
Stevens Brook	St. Albans City	128 Fisher Pond Road, in field border on property of Northern Valley Eye Care	Rickly Model 3510
Sunderland Brook	Colchester	At Sunderland Brook stream gauge	Rickly Model 3510

Precipitation monitoring sites were selected with the intent of achieving, to the greatest degree possible, ideal precipitation monitoring conditions. Criteria which describe the ideal site include level ground with an unobstructed view of the sky (minimum distance from a tree or building equal to the height of the tree or building) and no overhanging wires. Locations somewhat sheltered from prevailing winds were also given preference. Considering all the above factors, we believe the selected sites best meet the monitoring objectives.

For Bartlett Brook, Centennial Brook, and Potash Brook, no precipitation gauge was installed within the watershed. Precipitation totals from multiple gauges outside these watersheds are used to calculate unique daily precipitation values for each watershed.

The majority of the precipitation monitoring sites have tall meadow vegetation. Precipitation gauges were installed such that the rim of the tipping bucket funnel is approximately one foot above the height of the tallest nearby vegetation. Mounting tipping buckets as low as possible but above the height of surrounding vegetation and potential snow level is recommended to capture the most representative measurement of precipitation possible, while minimizing the problem of debris routinely clogging the gauge.

The precipitation gauges installed are Rickly Hydrological Company model 3510 (Figure 7) and ISCO model 674 tipping buckets with NOAA standard 8-inch diameter funnels. These tipping buckets record one tip per 0.01-inch of rainfall but are not designed to accurately record the water equivalent in snow and sleet.

Figure 9. Precipitation monitoring station in Williston Village, Allen Brook watershed

At each station, precipitation data are continuously logged using a Campbell Scientific CR300 datalogger. These data are transmitted hourly using a Sierra Wireless RV50 cellular modem to a computer server located at Stone Environmental's offices. Each modem has a unique static IP address. The stations are solar powered. The datalogger and modem, as well as a deep cycle battery and charge controller, are housed in a fiberglass instrument enclosure mounted on a tripod or steel pipe. The system is grounded using a copper grounding rod and cable.

4.1. Tipping Bucket Gauge Maintenance and Calibration

The precipitation gauge's funnel and siphon are inspected monthly and any debris is removed. Gauges are additionally visited when live data suggest atypical measurements, such as too little or too much rainfall relative to neighboring stations. Calibration of the precipitation gauges is performed annually. If a precipitation gauge is out of calibration (the measurement error exceeds 5 percent), the tipping mechanism is adjusted and the gauge is retested until it is within the calibration limits (5 percent of the test volume, as recommended by Office of Surface Water Technical Memorandum 2006.01).

4.2. Raw Data Review

Erroneous tips in the raw, 5-minute precipitation record resulting from tipping bucket calibration and cleaning were zeroed out. Any gaps in the raw precipitation record were identified. In general, gaps ranged in length from five minutes to a few hours; these were corrected by interpolating based on bounding values or by extrapolating from precipitation amounts at the two or three closest stations. Often it was clear that no precipitation fell during a given data gap. In 2018 malfunctions at three stations resulted in data gaps longer than one day. The malfunctions were caused by power losses, datalogger program glitches, or clogs in some part of the tipping bucket. The longest gap occurred at the Morehouse Brook gauge from October 13, 2018 to October 26, 2018 due to clogging. For longer gaps, we relied on daily precipitation estimates generated by the PRISM model, which is discussed in more detail in Section 4.3.

In addition to addressing the known data gaps, we compared precipitation amounts among neighboring rain gauges at 5-minute, daily, and monthly intervals to identify any divergent patterns. No definite problems were identified through this review, although one consistent pattern we observed is that monthly precipitation totals at the Morehouse Brook gauge tend to be low relative to the other gauges. We believe this is a function of siting, since the gauge itself operates properly. We are now considering moving the gauge further from the tree line.

Data from January through March and November through December were automatically flagged as potentially impacted by winter conditions. Temperature data, time-lapse camera photographs, field visits, and data from nearby COCORAHS and NWS weather stations were reviewed to further refine these winter condition designations. In 2018, several days in April were additionally determined to be impacted by winter conditions and the data were flagged accordingly.

4.3. Incorporating Data into PRISM

The PRISM Climate Group at Oregon State University uses the Parameter-Elevation Regressions on Independent Slopes Model (PRISM) to produce spatial estimates of monthly and daily climate variables as 800-meter raster datasets covering the conterminous United States (PRISM Climate Group 2004). PRISM aggregates daily precipitation values from NWS, COOP, and CoCoRaHS weather stations and uses these data to construct simple linear regressions between climate and elevation. The inclusion of each station into the model is weighted by other spatial, climactic, and topographic variables such as distance of any given station to the point being estimated, coastal proximity, and orographic effects (Daly et al. 2008).

To obtain daily, watershed average precipitation estimates for the stormwater-impaired watersheds, it is necessary to spatially interpolate among our point (gauge) precipitation data. Since we do not have an adequate number of gauges to use geostatistical interpolation methods and wanted to avoid the abrupt boundaries generated by non-geostatistical interpolation methods such as the Nearest-Neighbor and the Triangular Irregular Network (Li and Heap 2011), we approached the PRISM Climate Group about incorporating data from our precipitation gauge network into their model and providing us with the model output. Beginning in April 2017, the PRISM Climate Group ingests corrected precipitation data from our 10 gauges into their model. PRISM completes a series of scheduled revisions and provides Stone with a national 800-m raster data set for each day of the calendar year. Typically, PRISM delivers the annual dataset to Sone in August of the following calendar year.

To prepare datasets for PRISM, 5-minute precipitation data for each station are summed by the "PRISM day", defined as the 24 hours ending at 7:05 AM Eastern Standard Time. For example, the daily precipitation for April 10th is the total precipitation that has fallen between April 9th at 7:05 AM EST and April 10th 7:00 AM EST. Because our 5-minute precipitation data is reported year-round in Eastern Daylight Time (EDT), for this example, we would total all precipitation that has fallen between April 9th at 8:05 AM EDT and April 10th 8:00 AM EDT. The definition of the PRISM day should be taken into consideration when viewing or applying our daily, watershed average precipitation results.

Table 8 lists all the weather stations that were used in the PRISM model in our study area throughout the year, as well as the number of days out of the 2018 calendar year that an individual station was included. The table also lists the years a given station was included in the PRISM model, as station operation and performance can change from year to year, especially among the COCORAHS stations maintained by volunteers.

PRISM has certain standards that determine which precipitation data will be ingested into its model. With respect to Stone's network of gauges, there are two acceptance criteria that were important in 2018. First, since the gauges in our network are not designed to measure solid precipitation, daily precipitation totals impacted by freezing conditions and flagged accordingly from November through March were excluded from PRISM. In April 2018, individual daily precipitation totals were additionally flagged as occurring in winter conditions. Although half of April precipitation was unimpacted by winter conditions, the entire month was excluded from the PRISM model because more than four daily records were flagged.

The second acceptance criterion concerns gauge location relative to other reporting gauges. When two gauges close to one another both report data, one of the stations will generally be excluded in the PRISM model, because co-located stations can produce unstable model conditions. The Stone gauge in Williston is within a 0.15-mile radius of COCORAHS station VT-CH-38. In 2018, the Williston gauge ("STEN-10") data were often excluded by PRISM de-clustering due to its proximity to station VT-CH-38 (Table 8).

Table 8. Summary of weather stations used in the 2018 PRISM model

PRISM Code	Location	Weather Station Type	Days Used in 2018	Years Used	Station Data Used in Winter?
431320	Charlotte	COOP	179	2017, 2018	N
432769	Enosburg Falls	COOP	NA	2017	N
432773	Enosburg Falls	COOP	210	2017, 2018	Y
437607	South Hero	COOP	241	2017, 2018	Y
438597	Vergennes	COOP	323	2017, 2018	Y
VT-CH-3	Charlotte	COCORAHS	31	2018	N
VT-CH-4	Underhill	COCORAHS	363	2017, 2018	Y
VT-CH-7	Huntington	COCORAHS	31	2017, 2018	N
VT-CH-11	Underhill	COCORAHS	330	2017, 2018	Y
VT-CH-13	Richmond	COCORAHS	361	2017, 2018	Y
VT-CH-15	Huntington	COCORAHS	361	2017, 2018	N
VT-CH-19	Jericho	COCORAHS	212	2017, 2018	Y
VT-CH-37	Jericho	COCORAHS	56	2018	Y
VT-CH-38	Williston	COCORAHS	251	2017, 2018	Y
VT-CH-40	Essex Junction	COCORAHS	119	2017, 2018	Y
VT-GI-3	Alburgh	COCORAHS	149	2017, 2018	Y
VT-FR-12	St. Albans	COCORAHS	NA	2017	Y
VT-FR-19	Swanton	COCORAHS	321	2017, 2018	Y
STEN-01	Williston	Stone	184	2017, 2018	N
STEN-02	Shelburne	Stone	184	2017, 2018	N
STEN-03	Burlington	Stone	154	2017, 2018	N
STEN-04	Essex Junction	Stone	184	2017, 2018	N

STEN-05	Colchester	Stone	123	2017, 2018	N
STEN-06	S. Burlington	Stone	184	2017, 2018	N
STEN-07	St. Albans	Stone	154	2017, 2018	N
STEN-08	St. Albans	Stone	184	2017, 2018	N
STEN-09	Colchester	Stone	184	2017, 2018	N
STEN-10	Williston	Stone	86	2017, 2018	N

4.4. Computation of Watershed Average Precipitation Totals

A script was run in ArcMap 10.5.1 to calculate daily watershed average precipitation totals from the 800-m PRISM raster datasets. The script clips the dataset to our watershed boundaries, as delineated in the ANR Impaired Watershed dataset. It then resamples the raster to a finer pixel size so that truncation and subsequent exclusion of grid cells by the watershed boundary line is minimized. Next, the script runs zonal statistics to generate the minimum, maximum, and mean of the raster grid precipitation values within each watershed. Lastly, it queries PRISM metadata to determine which weather stations, within a defined area extending beyond our gauge network, were used to calculate the raster grid on any given PRISM day. The defined area encompasses all stations north of Vergennes, south of the Canadian border, west of the Green Mountains, and east of the Champlain Islands. The list of weather stations considered in the PRISM models in 2017 and 2018 is the basis for Table 8.

PRISM precipitation estimates during winter months rely on snow water equivalent (SWE) measurements, which we do not measure at our precipitation monitoring stations. Though we continue to provide the 5-minute precipitation data from our stations to PRISM during winter months, the data are flagged and are not incorporated into their estimates at this time. As a result, daily mean precipitation during winter months is an interpolation based solely on stations that provide SWE measurements (Table 8). PRISM hopes to eventually develop methods of automatically correcting, or selectively incorporating, precipitation data from our stations during winter months, but does not yet have the capability to do so.

To check PRISM model outputs, we compared the estimated mean daily precipitation of each watershed to the mean daily precipitation of the two closest Stone tipping bucket gauges and flagged the watershed estimates that were greater than two times or less than half the gauge measurements. We discounted differences for days falling during flagged winter months when our gauge data are provisional and excluded from the PRISM model. In 2018, substantial differences were flagged only for 5 dates. In reviewing these dates, we concluded that the differences occurred due to locally intense rain falling irregularly across the watershed. In addition to this numeric comparison, we visually compared differences by comprehensively plotting the mean daily precipitation of each watershed and the mean daily precipitation of each Stone tipping bucket for every day of the year using an interactive scatterplot tool in R (Plotly). Overall, both methods of comparison showed strong agreement between PRISM watershed estimates and the tipping bucket rain gauge measurements in Stone's network.

4.5. Precipitation Type Designation

We used hourly observations of weather type at the Burlington ASOS weather station to characterize daily watershed average precipitation totals as solid, mixed, or wet. Weather type is reported at the ASOS station by automated weather sensors and manually by human observation. Burlington ASOS is the only weather station proximate to our sites that records precipitation type at this frequency. Because daily estimates of precipitation in our watersheds are totaled using the "PRISM day" method described in Section 4.3, hourly observations of weather type allowed us to better match our periods of measurement. Furthermore, though multiple

CoCoRaHS stations log daily precipitation type, the periods of record for these stations are incomplete, missing data for weeks at a time.

Precipitation type recorded by the Burlington ASOS station included many tens of categories (https://www1.ncdc.noaa.gov/pub/data/cdo/documentation/LCD_documentation.pdf) which we then reclassified as either solid, mixed, or wet. Either a weather type designation fell into only one of these categories at the daily interval (for example, all hourly precipitation in a day was observed as snow (SN:70) and was reclassified as solid) or solid, wet, and mixed types were observed in separate hours but on the same day and thus reclassified as mixed at the daily interval.

5. Results

5.1. Rating Curves

The number of stream discharge measurements used to develop the 2018 stage-discharge ratings ranged from a low of 10 for Morehouse Brook to a high of 18 for Munroe Brook (Figures 10-20). The three highest discharges measured at Indian Brook indicate a noticeable change in slope and suggest that high flows may require a separate rating (two-part rating). We do not have enough high flow measurements currently to establish a second rating but are prioritizing additional high flow measurements at Indian Brook, as field conditions allow. The channel geometries at Englesby Brook and Potash Brook suggest that new high measurements at these sites also likely represent transitions to high flow controls, thus requiring two-part ratings. A concerted effort will be made to capture high flow measurements at these streams.

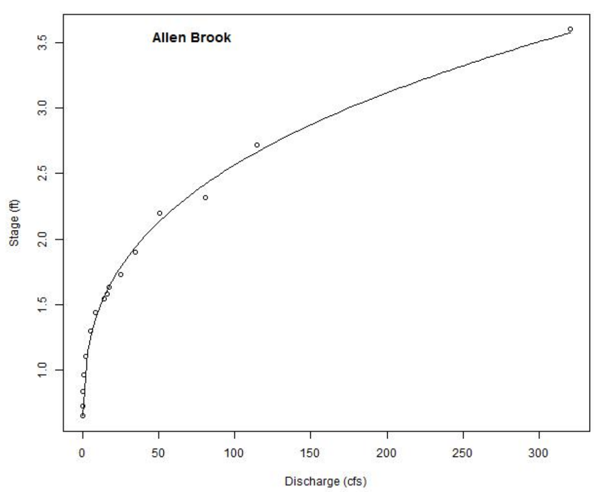


Figure 10. Stage-discharge relation for Allen Brook

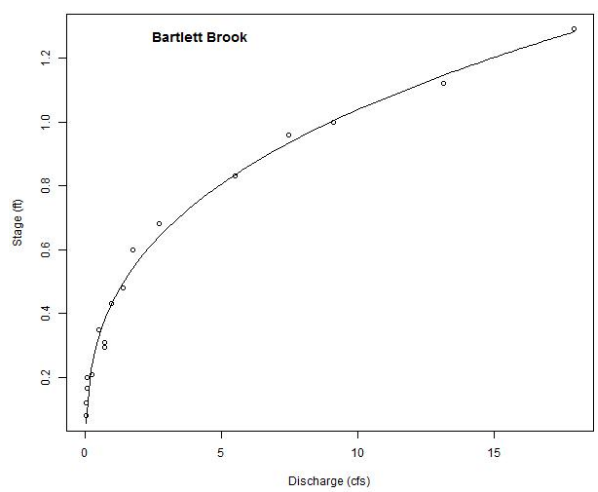


Figure 11. Stage-discharge relation for Bartlett Brook

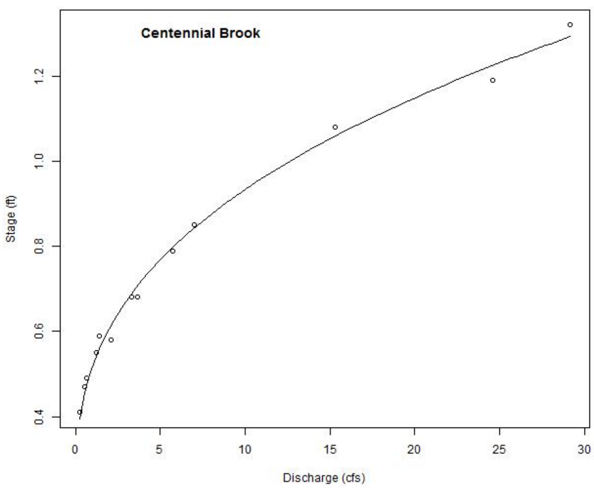


Figure 12. Stage-discharge relation for Centennial Brook

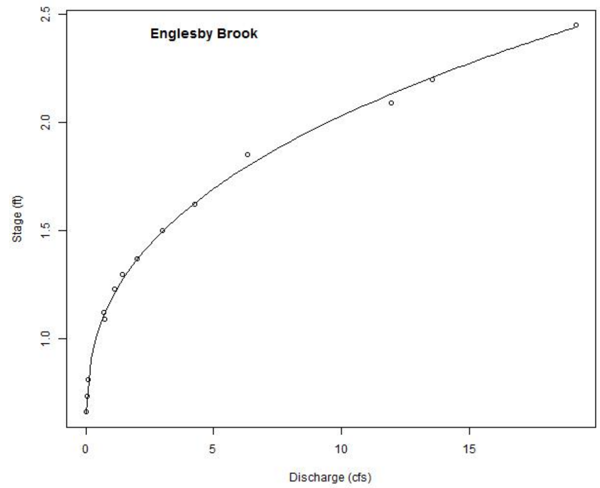


Figure 13. Stage-discharge relation for Englesby Brook

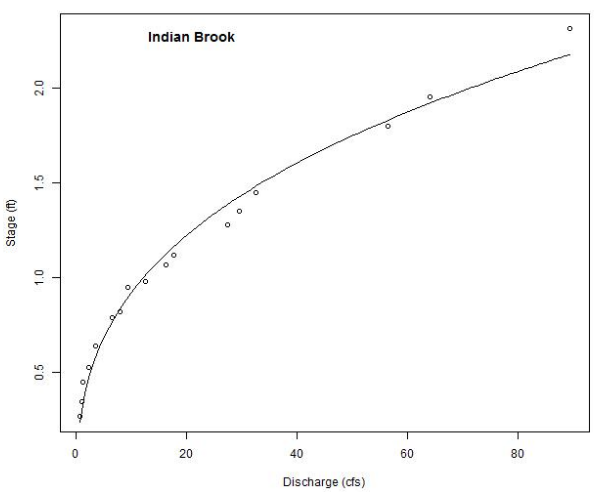


Figure 14. Stage-discharge relation for Indian Brook

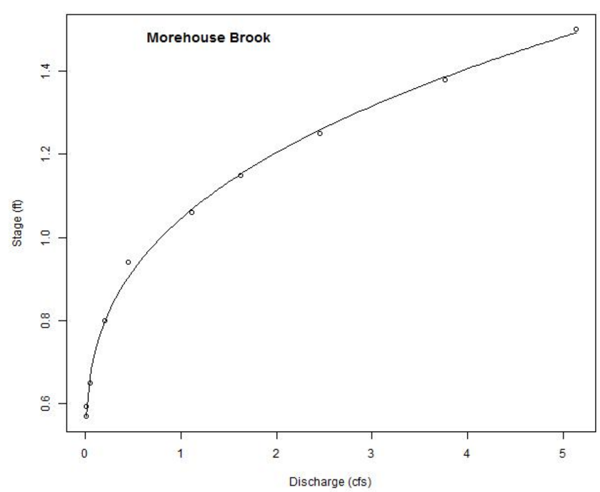


Figure 15. Stage-discharge relation for Morehouse Brook

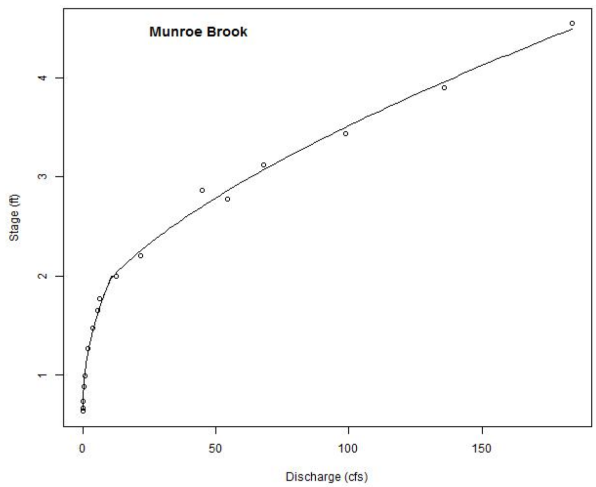


Figure 16. Stage-discharge relation for Munroe Brook

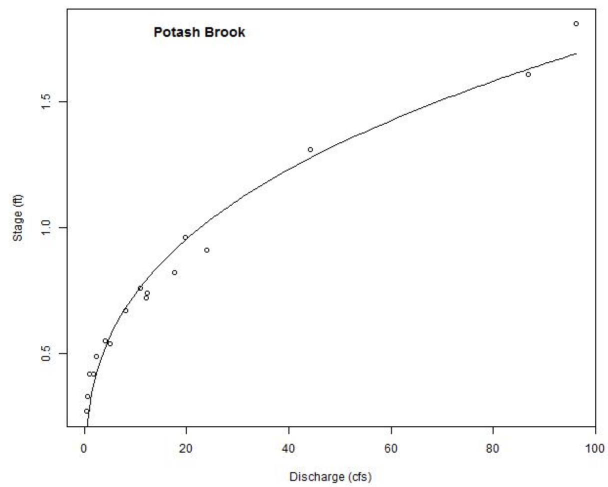


Figure 17. Stage-discharge relation for Potash Brook

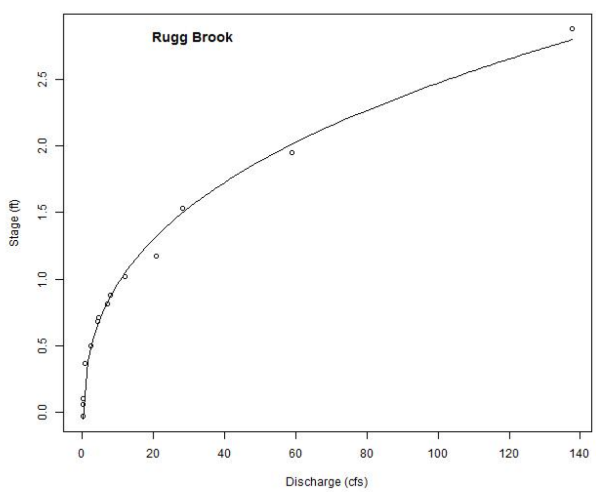


Figure 18. Stage-discharge relation for Rugg Brook

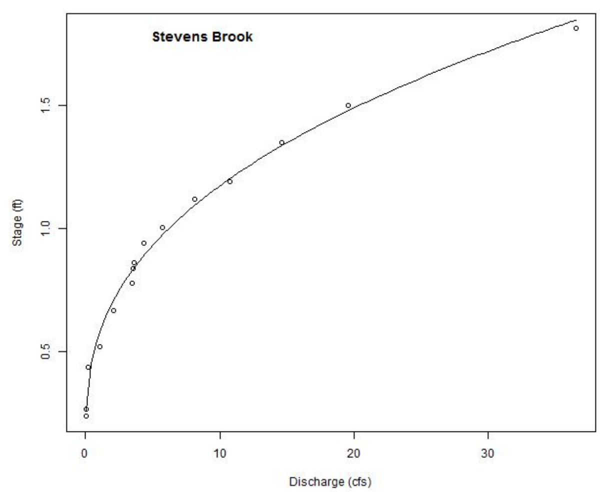


Figure 19. Stage-discharge relation for Stevens Brook

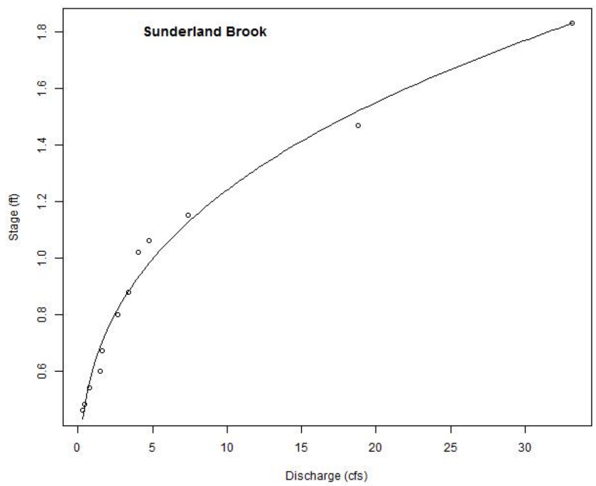


Figure 20. Stage-discharge relation for Sunderland Brook

5.2. Daily Mean Discharge Results

Corrected daily mean discharge values for 2018 are posted on the project website (http://vt-ms4-flow.stone-env.com/FlowDev/index.html#).

5.2.1. Flow Exceedances

Across all 11 gauged streams, only a small fraction (0-2%) of 2018 total annual free-flow exceeded 2.5 times our highest measured discharge (Table 9). A series of short summer storms accounted for the flow exceedances at Morehouse Brook, while a single summer storm on the night of July 25, 2018 accounted for the exceedances at both Centennial Brook and Englesby Brook. At Englesby Brook, the June 25th event resulted in its highest ever recorded stage (3.88 ft). Though the event peak lasted less than an hour, it caused 2% of the stream's total annual flow to exceed 2.5 times our highest measured discharge.

Flow occurring below 0.25 times our lowest measured discharge is better examined as a percent of time rather than of annual flow. The occurrence of these extremely low flows was negligible at all sites except Englesby Brook, Stevens Brook, and Munroe Brook. (Table 9). Additional low flow discharge measurements at these sites will be obtained as field conditions allow.

Stevens Brook ran dry for approximately 14% of the free-flowing year. These dry periods occurred intermittently between July 4 and September 25, 2018. Frequent field visits during these periods allowed us to precisely measure the stage at which the gauged reach became dry, providing the rare opportunity for a near real-time determination of the gauge height of zero flow (see Section 3.4).

Table 9. High and low flow exceedances as a percentage of free-flowing annual flow and time

Stream	High Flow Exceedance		Low Flow Exceedance	
	Percentage of Annual Flow	Percentage of Time	Percentage of Annual Flow	Percentage of Time
Allen	0.0	0.0	0.0	0.0
Bartlett	0.0	0.0	0.0	0.0
Centennial	0.80	<0.01	0.0	0.0
Englesby	2.39	0.02	<0.01	0.81
Indian	0.0	0.0	0.0	0.0
Morehouse	1.56	0.02	0.0	0.0
Munroe	0.0	0.0	<0.01	14.02
Potash	0.0	0.0	0.0	0.0
Rugg	0.0	0.0	0.0	0.0
Stevens	0.0	0.0	<0.01	5.85
Sunderland	0.0	0.0	0.0	0.0

5.3. Flow Duration Curves

Flow duration curves for each gauged stream were generated from combined 2017 and 2018 daily mean flows using the hydroTSM package in R (Zambrano-Bigiarini 2017) (Figures 21-31). The 0.3% and 95% daily mean flow exceedance values are shown in Table 10. Note that the flow exceedance values in Table 10 are not directly comparable with the modeled and attainment values in the corresponding Total Maximum Daily Load (TMDL) for these stormwater-impaired streams; these 2017-2018 values are based on daily mean flow data whereas the TMDL values are based on hourly data. As with the rating curves (see Section 3.6.3), we expect additional years of data to change the flow duration curves as a greater range of hydrologic conditions is represented. The flow duration curves provided in the 2019 Annual Report will be based on 2017–2019 daily mean flow data and will reflect rating curve updates as well as any updates of 2018 provisional LaPlatte and Mill River reference site data, as summarized in Section 3.7.1.

Table 10. 0.3% and 95% exceedance values for 2017-2018 daily mean flows

Stream	2017/2018 Q 0.3% (cfs/mi²)	2017/2018 Q 95% (cfs/mi²)
Allen	14.40	0.02
Bartlett	10.29	0.04
Centennial	6.92	0.33
Englesby	8.42	0.01
Indian	14.36	0.14
Morehouse	4.86	0.09
Munroe	15.72	0.00
Potash	10.32	0.17
Rugg	22.35	0.03
Stevens	15.12	0.00
Sunderland	7.16	0.22

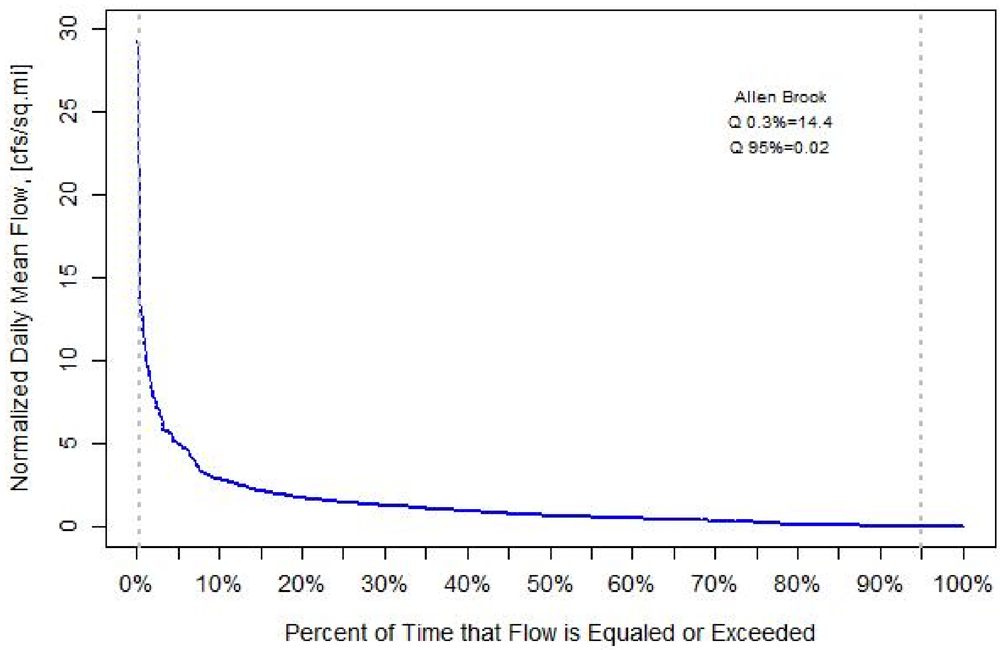


Figure 21. Flow duration curve for Allen Brook

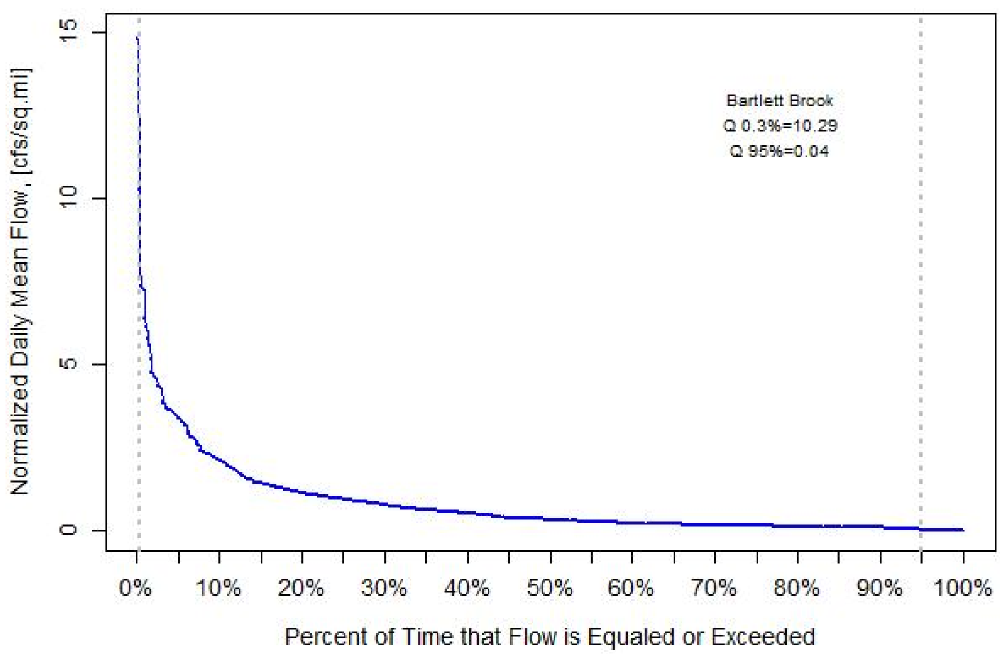


Figure 22. Flow duration curve for Bartlett Brook

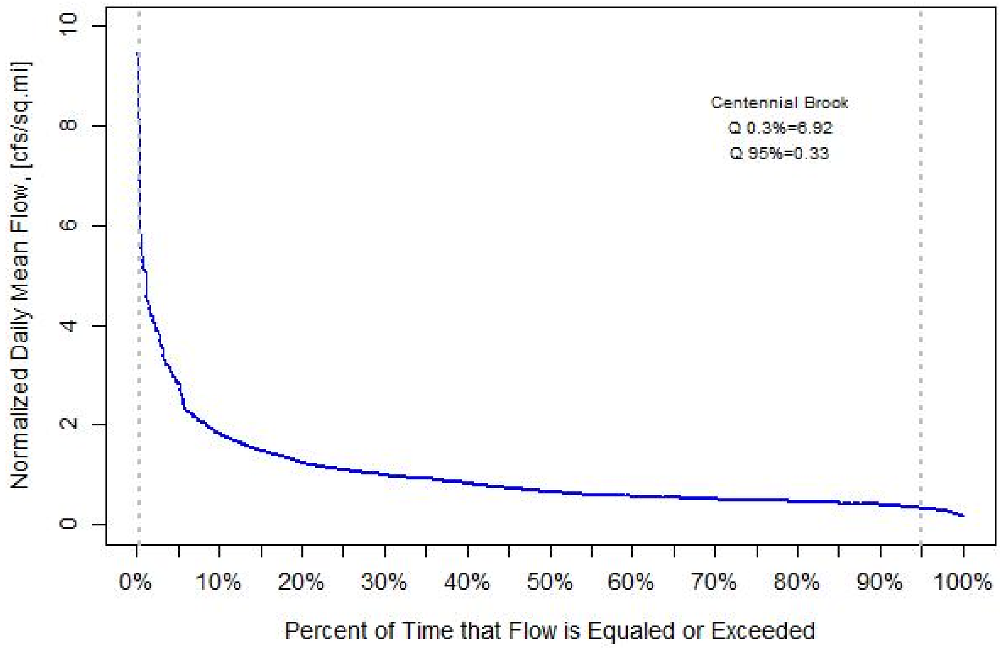


Figure 23. Flow duration curve for Centennial Brook

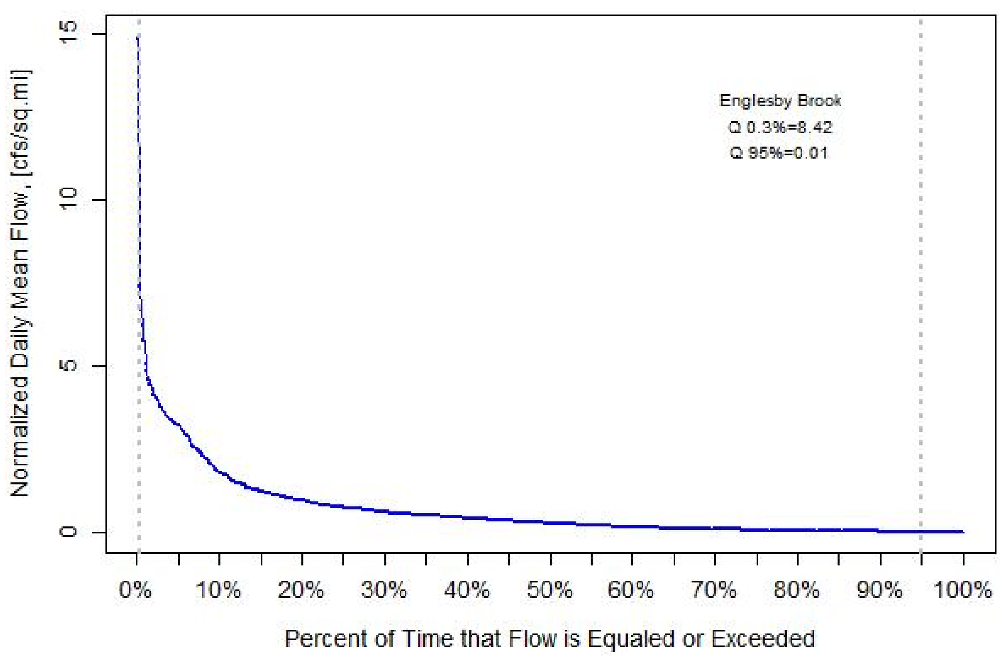


Figure 24. Flow duration curve for Englesby Brook

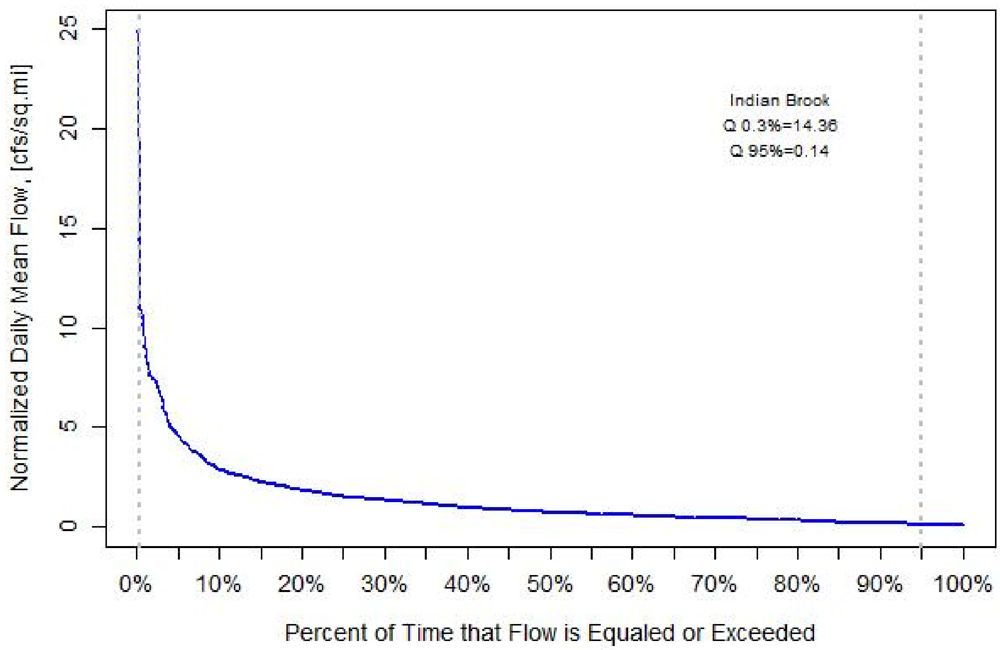


Figure 25. Flow duration curve for Indian Brook

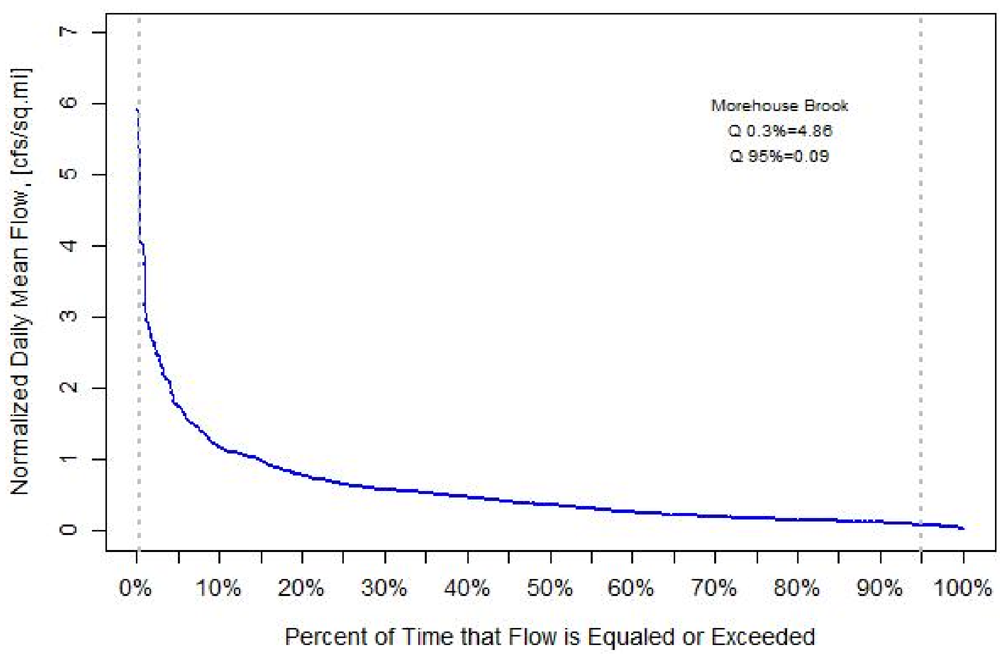


Figure 26. Flow duration curve for Morehouse Brook

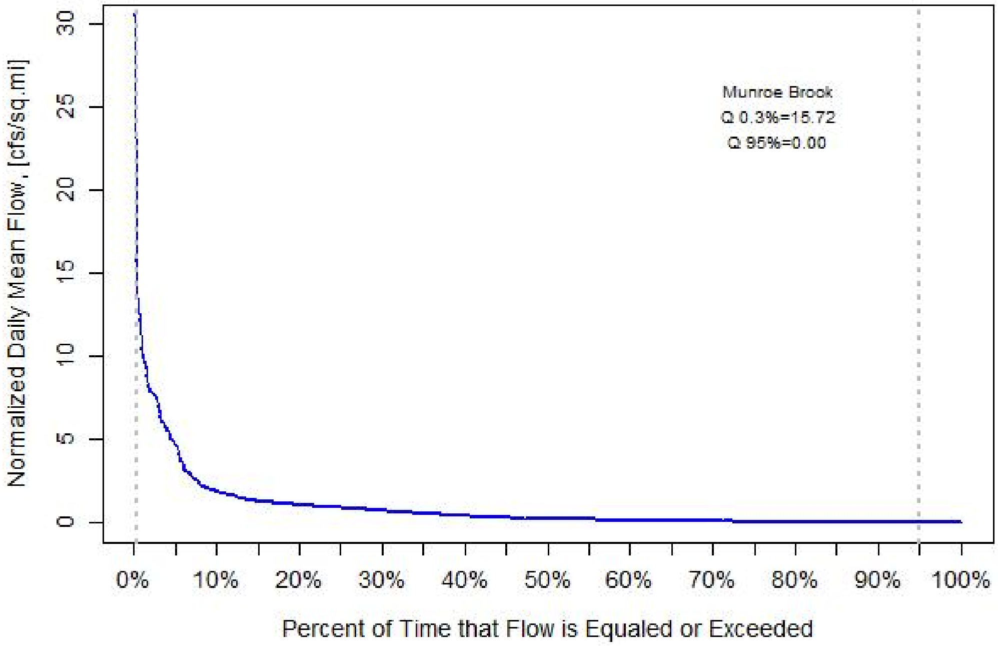


Figure 27. Flow duration curve for Munroe Brook

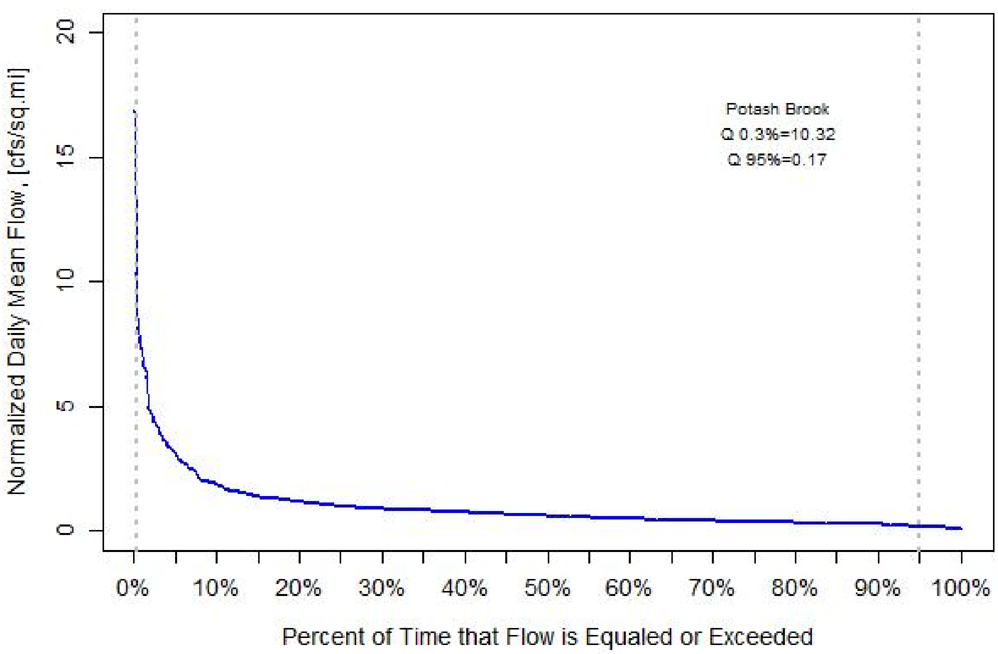


Figure 28. Flow duration curve for Potash Brook

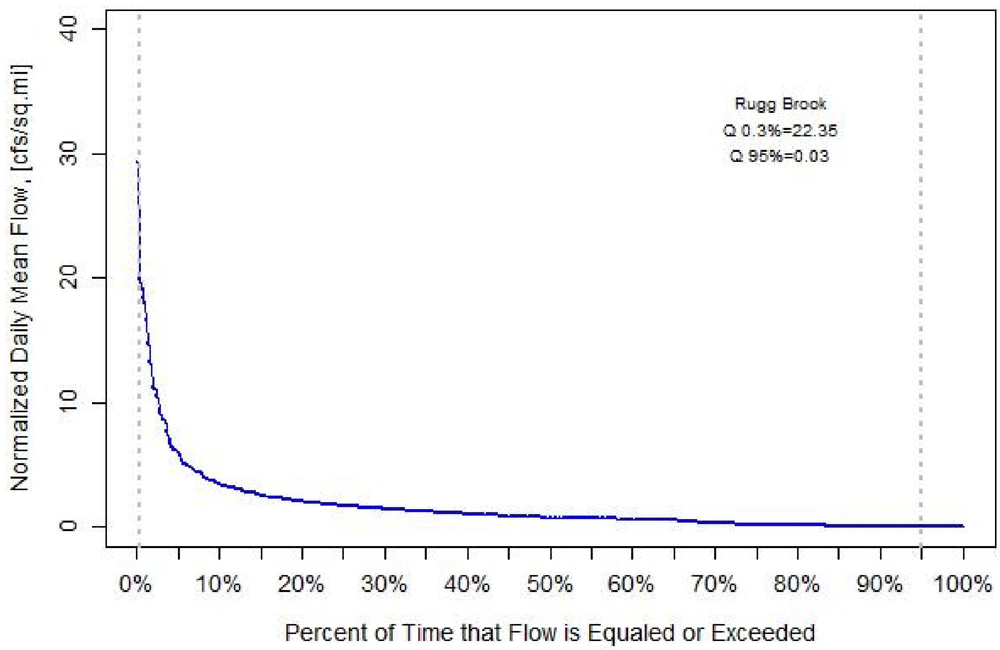


Figure 29. Flow duration curve for Rugg Brook

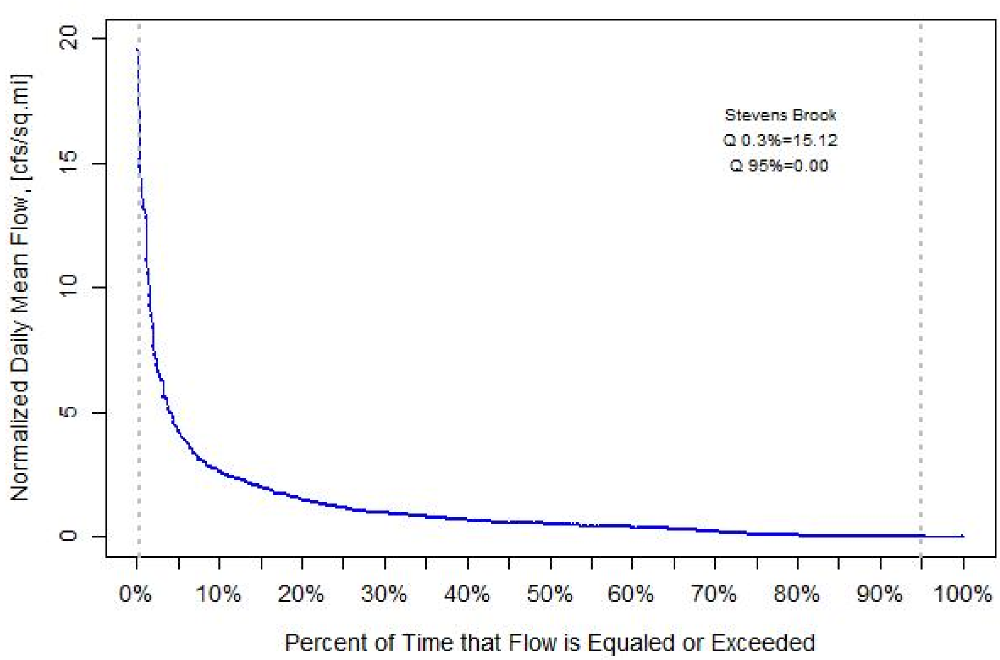


Figure 30. Flow duration curve for Stevens Brook

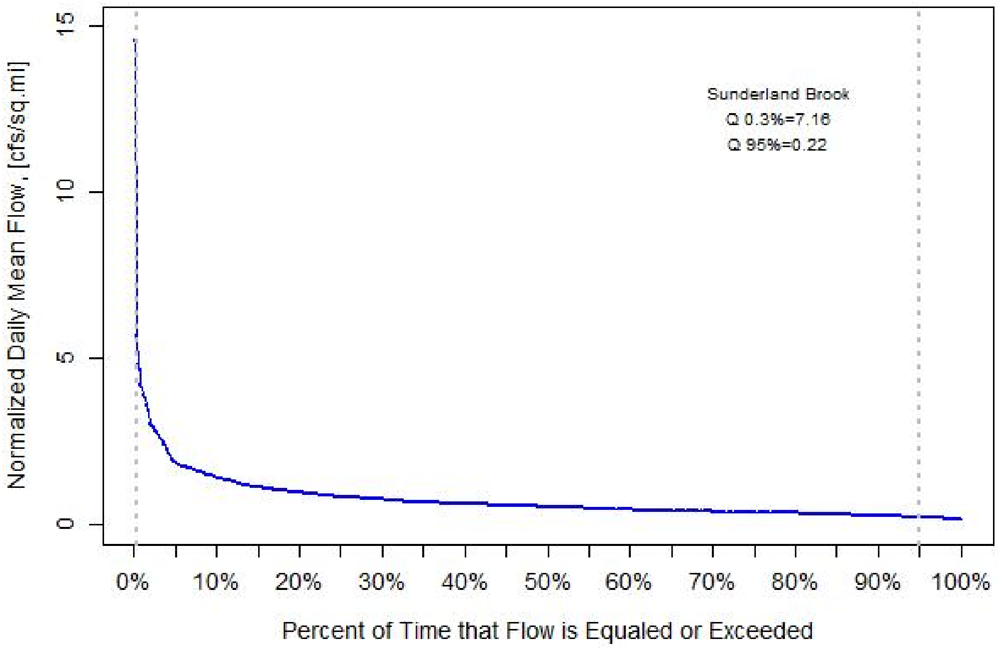


Figure 31. Flow duration curve for Sunderland Brook

5.4. Precipitation Monitoring Results

The daily (PRISM day) precipitation minimum, maximum, and mean totals by watershed are posted on the project website (http://vt-ms4-flow.stone-env.com/FlowDev/index.html#). It is possible to get a sense of the spatial variability of rainfall in each watershed by comparing the daily minimum and maximum precipitation amounts across each watershed. Tables 11 and 12 provides monthly totals of watershed average precipitation in 2017 and 2018.

Table 11. Total monthly precipitation (inches) by watershed in 2017

Watershed	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Allen	2.15	3.02	3.60	4.33	5.29	8.98	4.07	4.34	3.31	4.09	2.17	2.50	47.84
Bartlett	2.08	3.21	3.14	3.77	4.52	8.61	3.66	3.00	2.84	3.85	1.47	2.51	42.66
Centennial	2.10	3.07	3.19	3.97	5.00	8.81	4.11	2.33	2.90	3.62	1.50	2.25	42.85
Englesby	2.08	3.17	3.19	3.84	4.69	8.72	3.97	2.49	2.92	3.74	1.48	2.24	42.53
Indian	2.04	2.81	3.63	4.10	5.21	8.60	3.35	2.83	3.18	3.65	1.85	2.27	43.53
Morehouse	2.05	3.02	3.14	3.99	5.13	9.06	3.93	2.10	2.73	3.41	1.35	2.21	42.11
Munroe	2.10	3.26	3.08	3.96	4.80	9.63	3.27	3.25	3.17	4.25	1.53	2.70	45.02
Potash	2.13	3.17	3.28	4.00	4.79	8.52	4.04	2.99	2.93	3.79	1.62	2.35	43.60
Rugg	2.13	3.07	3.59	4.44	4.29	6.54	4.31	2.31	2.74	4.49	3.28	2.21	43.40
Stevens	2.18	3.00	3.62	4.40	4.35	6.54	4.36	2.38	2.72	4.58	3.32	2.22	43.67
Sunderland	2.08	2.91	3.29	4.41	5.12	9.09	4.02	2.47	3.11	3.71	1.67	2.21	44.09

Table 12. Total monthly precipitation (inches) by watershed in 2018

Watershed	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Allen	3.61	1.88	3.44	5.33	3.39	4.51	1.96	2.80	4.50	4.52	6.56	2.83	45.33
Bartlett	3.21	1.46	2.97	4.81	2.35	3.33	2.05	2.59	3.44	3.90	6.13	2.48	38.71
Centennial	3.24	1.45	2.89	4.81	2.13	4.46	3.26	3.02	4.48	4.49	6.18	2.50	42.91
Englesby	3.12	1.45	2.83	4.73	2.09	3.90	3.06	2.65	4.15	4.16	6.23	2.42	40.79
Indian	3.58	1.59	3.13	4.95	2.43	4.38	2.68	3.01	4.68	4.84	6.31	2.66	44.23
Morehouse	3.17	1.50	2.76	4.78	2.02	4.54	2.99	2.91	4.66	4.78	6.23	2.38	42.73
Munroe	3.22	1.41	3.01	4.82	3.04	3.07	1.76	2.40	3.34	3.80	6.04	2.55	38.45
Potash	3.31	1.59	3.08	4.97	2.34	4.02	2.60	2.77	3.97	4.20	6.18	2.53	41.56
Rugg	3.27	2.56	3.16	5.48	2.24	2.90	2.74	2.19	3.37	4.41	6.57	3.02	41.90
Stevens	3.29	2.61	3.21	5.46	2.29	2.72	2.96	2.18	3.43	4.37	6.53	3.03	42.07
Sunderland	3.43	1.48	2.89	4.82	2.36	4.66	3.12	3.38	4.70	4.95	6.20	2.51	44.52

6. References

Baty, F., C. Ritz, S. Charles, M. Brutsche, J. Flandrois, and M. Delignette-Muller. 2015. A toolbox for nonlinear regression in R: The package nlstools. *Journal of Statistical Software*, 66(5): 1-21. URL http://www.jstatsoft.org/v66/i05/.

Daly, C., M. Halbleib, J.I. Smith, W.P. Gibson, M.K. Doggett, G.H. Taylor, J. Curtis, and P.P. Pasteris. 2008. Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. *International Journal of Climatology: A Journal of the Royal Meteorological Society,* 28.15: 2031-2064.

Kennedy, E.J. 1984. Discharge ratings at gaging stations: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3, Chapter A10, 59 p.

Kennedy, E.J. 1983. Computation of continuous records of streamflow: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3, Chapter A13, 53 p.

Li, J. and A.D. Heap. 2011. A review of comparative studies of spatial interpolation methods in environmental sciences: Performance and impact factors. *Ecological Informatics,* 6.3-4: 228-241.

Local Climatological Data (LCD) Dataset Documentation, URL: https://www1.ncdc.noaa.gov/pub/data/cdo/documentation/LCD_documentation.pdf

PRISM Climate Group, Oregon State University. URL: http://prism.oregonstate.edu, created 4 Feb 2004.

R Core Team. 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL: http://www.R-project.org/.

Rantz, S.E.. 1982. Measurements and computation of streamflow, Volumes 1 and 2: U.S. Geological Survey Water-Supply Paper 2175, 631 p.

Sauer, V.B. 2002. Standards for the analysis and processing of surface-water data and information using electronic methods, U.S. Geological Survey Water Resources Investigations Report No. 2001-4044.

Shaughnessy, A., C. Prener, and E. Hasenmuelle, 2018. DriftR: Drift Correcting Water Quality Data. R package version 1.1.0. URL: https://CRAN.R-project.org/package=driftR.

Sievert, C., C. Parmer, T. Hocking, S. Chamberlain, K. Ram, M. Corvellec, and P. Despouy. 2017. plotly: Create Interactive Web Graphics via 'plotly.js'. R package version 4.7.1. URL: https://CRAN.R-project.org/package=plotly.

Vanderkam, D., J.J. Allaire, J. Owen, D. Gromer, P. Shevtsov, and B. Thieurmel. 2017. dygraphs: Interface to 'Dygraphs' Interactive Time Series Charting Library. R package version 1.1.1.4. URL: https://CRAN.R-project.org/package=dygraphs.

Zambrano-Bigiarini, M. 2017. hydroTSM: Time Series Management, Analysis and Interpolation for Hydrological Modelling R package version 0.5-1. URL: https://github.com/hzambran/hydroTSM.

Memoranda Cited

The following memoranda were cited in this report. Copies of the memoranda are available to the public at the following Web site: http://water.usgs.gov/osw/pubs/techmemos.html.

Office of Surface Water memorandum 87.05

Office of Surface Water memorandum 92.10

Office of Surface Water memorandum 93.07

Office of Surface Water memorandum 2006.01

Office of Surface Water memorandum 2010.07

Office of Surface Water memorandum 2011.05

Office of Surface Water memorandum 2011.08