

Standard Operating Procedure #10:

Flow Measurement

Version 1.0

In Monitoring Protocol for Wadeable Streams of the Great Lakes Network

Prepared by

Suzanne Magdalene¹, Joan E. Elias², Richard Damstra², David D. VanderMeulen^{*2}

¹ St. Croix Watershed Research Station
16910 152nd Street North
Marine-on-St.-Croix, Minnesota 55047

² National Park Service
Great Lakes Inventory and Monitoring Network
2800 Lake Shore Drive East
Ashland, Wisconsin 54806

* Contact author: david_vandermeulen@nps.gov

December 2017

Please cite this publication as:

Magdalene, S., J. E. Elias, R. Damstra, and D. D. VanderMeulen. 2017. Standard operating procedure #10: Flow measurement. *In* D. D. VanderMeulen, J. E. Elias, S. Magdalene, R. Damstra, and J. Glase. 2017. Monitoring protocol for wadeable streams of the Great Lakes Network, version 1.0. Natural Resource Report NPS/GLKN/NRR—2017/1567. National Park Service, Fort Collins, Colorado.

Contents

	Page
Figures	iii
Tables.....	iii
Revision History Log.....	v
Acknowledgements.....	v
10.0 Introduction and Background.....	1
10.1 During Site Establishment	1
10.1.1 Assess Site Viability	1
10.1.2 Install Staff Gage or Benchmark.....	1
10.1.3 Deploy Datalogger	2
10.2 Prior to Field Work	3
10.3 Field Work	3
10.3.1 Record Visual Observations.....	3
10.3.2 Measure and Record Stream Stage	4
10.3.3 Measure and Record Stream Discharge	4
10.4 After Field Work.....	10
10.4.1 Calculate the Total Flow of the Stream Cross-section.....	10
10.4.2 Convert Stage Data to Discharge Data.....	10
10.5 Quality Assurance/Quality Control Procedures	11
10.6 Literature Cited	13
Appendix A. Stream Gaging Field Form	15

Figures

	Page
Figure 1. Features used to identify bankfull discharge (i.e., high bench level). From Woodyer (1968).	4
Figure 2. Division of stream cross-section into partial sections.....	7
Figure 3. Top-setting wading rod, showing an example for measuring flow at 60% of depth.	8

Tables

	Page
Table 1. Stream discharge measurement methods.	5
Table 2. Reporting values for total flow (Q_w), measured in cubic feet per second (cfs).....	10

Revision History Log

The following table lists all edits and amendments to this document since the original publication date. Information entered in the log must be complete and concise. Users of this standard operating procedure will promptly notify the project manager and/or the Great Lakes Network (GLKN) data manager about recommended and required changes. The project manager must review and incorporate all changes, complete the revision history log, and change the date and version number on the title page and in the header of the document file. For complete instructions, please refer to Procedure for Revising the Protocol, SOP #16.

Previous Version #	Revision Date	Author (with title and affiliation)	Location in Document and Concise Description of Revision	Reason for Change	New Version #
Add rows as needed for each change or set of changes tied to an updated version number					

Acknowledgements

Major portion of this standard operating procedure (SOP) are based on flow measurement procedures described in Magdalene (2008). Thanks to L. Kainulainen from Pictured Rocks National Lakeshore for field testing and providing valuable feedback on this SOP.

10.0 Introduction and Background

Long-term monitoring of stream ecology requires an understanding and analysis of stream discharge. Stream ecology is affected by fluctuations in flow; a record of discharge enables the assessment of flow-sensitive wadeable stream variables. For all freshwater flowing waterbodies, Penoyer (2003) recommends the qualitative estimate or quantitative measurement of discharge during each sampling event. No single method for measuring discharge is applicable to all types of stream channels at all flow levels; a range of flow measurement methods could be required, depending on the rate and volume of flow at the time of measurement.

10.1 During Site Establishment

10.1.1 Assess Site Viability

Visit the site to assess whether it is an appropriate flow monitoring location. Select a location within the sample reach that has as many as possible of the following characteristics (Rantz and others 1982):

- straight channel, preferably 300 feet in both upstream and downstream directions from flow monitoring site
- flow should be confined at all stream stages to one channel
- stream discharge should be free-flowing and tranquil, not stagnant, but not overly aerated or churned
- preferably, the stream is confined between high bedrock or clay banks, not low banks or levees prone to overbank flow
- if possible, avoid meander bends, sand bottoms, backwater areas, heavily vegetated banks, logs or other large obstructions on the shore, areas of especially high erosion, and areas of considerable sediment accumulation
- far enough upstream from the confluence with another stream or large lake to avoid any variable influence the other stream or lake may have on the stage.

10.1.2 Install Staff Gage or Benchmark

A permanently-installed staff gage or benchmark can be used either as a stand-alone measurement device or in conjunction with an electronic depth logger. A staff gage is an enameled ruler (note that a staff gauge could also be any hard object against which stage can be measured) installed within the streamflow, while a benchmark is a metal marker that could be installed anywhere near the stream, and from which vertical distances are measured manually (e.g., tape measure or meter stick). In both cases, its fixed installation serves as an important source of data continuity and reduces measurement errors between field visits.

1. Obtain permission from the park to install one staff gage or benchmark on each stream monitored. Locate the gage at or in the vicinity of the site.
2. Select a stable location: a bridge structure, a sturdy fence post driven into the streambed that will not be damaged by debris carried in high flows, or an underwater benchmark.
3. Install the staff gage at an elevation that will measure the full range of stream stage expected for the site. A constricted channel will have a larger range between low and high flows than a wide channel unconstrained by stable banks.
4. Attach the staff gage or benchmark to its structure with weather-resistant metal (i.e. stainless steel) hardware so that it will not shift with time.

10.1.3 Deploy Datalogger

Stream depth will be monitored with a continuous electronic datalogger on each stream. Some models of datalogger, such as the Onset Hobo U-20 depth logger, require correction for changes in barometric pressure (BP). To get BP data, either deploy a second depth (pressure) datalogger in the air on site or acquire data from nearby third party weather stations (<5 miles). Care must be taken to correct BP data for elevation, if different from the sample sites. Vented dataloggers do not require reference BP measurements.

1. Program the datalogger. Digital storage limitations (the number of megabytes of storage) and expected download frequency (frequency of field visits) will determine the frequency with which data are averaged and stored. Hourly or half-hourly data will allow assessment of diurnal fluctuations in stream flow. Select an averaging period that allows field personnel to return and download the data, before it overwrites itself; include a safety margin to allow for minor changes in the field work schedule.
2. Deploy one depth datalogger per stream, at or near the monitoring site. Deploy second data logger in the air if the nearest weather station is >5mi away. It should be noted that the core water quality monitoring site and the flow monitoring site for a given monitoring station do not need to be at the exactly same location, but they should represent the same flow conditions (no tributaries or impoundments between the two sites).
3. Locate the datalogger in the stream as near to the staff gage as possible so that readings from the two devices can be correlated. Attach the depth datalogger securely to a permanent structure or other object that is difficult to move (e.g., a tree) with rust resistant cable and a cable clamp to prevent theft or accidental loss in high water. If possible, it is desirable that the logger should be installed in a case or a stilling well (Lundquist et al. 2008).

10.2 Prior to Field Work

1. Maintain equipment in clean and working condition.
2. Inspect equipment for needed maintenance or repair. Store according to manufacturer's specifications.
3. Calibrate current meters according to the manufacturer's operations manuals. Photocopies of the operations manuals should be taken to the field.
4. Replace batteries on handheld flow calculator or digital recorder.
5. Keep a maintenance and calibration log for relevant equipment.

10.3 Field Work

10.3.1 Record Visual Observations

1. Visually inspect the stream from bank to bank and longitudinally, observing velocity, width and depth distribution, and apparent distribution of sediment and aquatic biota.
2. Record observations on field form (Appendix A).
3. Note and document the location of stagnant water, eddies, backwater, reverse flows, areas of faster than normal flow, and piers or other features.
4. At a minimum, a qualitative estimate of flow will be made based on visual estimation of relative % of bankfull (see Figure 1) conditions at the time of sampling, as follows (Penoyer 2003):
 - Dry: no water or isolated, stagnant pools
 - Low: $\leq 25\%$ of bankfull
 - Intermediate: 25–75% of bankfull
 - High: $\geq 75\%$ of bankfull
 - Flood: $> 100\%$ of bankfull conditions.

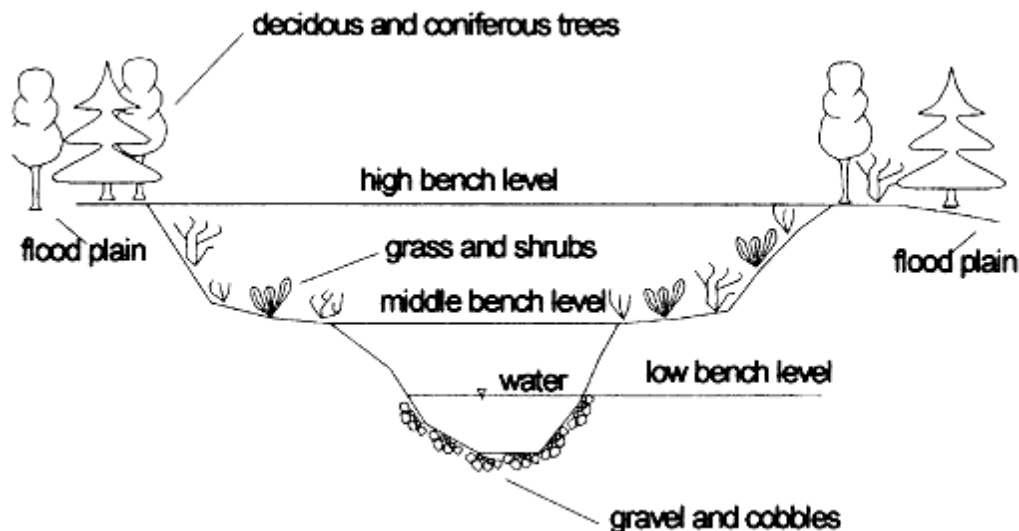


Figure 1. Features used to identify bankfull discharge (i.e., high bench level). From Woodyer (1968).

10.3.2 Measure and Record Stream Stage

1. Take staff gage readings as often as field visits are possible.
2. Record the water level or stream stage from staff gage. Record the following information on the field form:
 - Date and time
 - Recent weather, especially precipitation or lack of it
 - Name of person taking reading
 - Water level reading from staff gage
3. Download the stage readings from the datalogger according to the instruction manual.

10.3.3 Measure and Record Stream Discharge

1. Conduct long-term stream monitoring at or near a permanently-installed continuous flow gaging station. If no gaging station is available, stream discharge should be measured by field personnel. Conducting a series of stream discharge measurements will enable the development of a stage-discharge rating relationship so that in the future stream discharge can be calculated from subsequent stage readings or datalogger readings.
2. Select a method of stream discharge measurement (Table 1) based on the following considerations:
 - Safety: wading is not recommended when the product of the flow velocity and flow depth exceed 10 ft²/s; for example, a velocity of 5 ft/s and a depth of 2 ft.

- Equipment: depending on watershed drainage area, the depth of high flows may exceed the standard wading rod, requiring the use of a sounding weight suspended from a bridge or boat, if feasible.
- Flow depths: for very low flows or very high flows (less than 0.3 ft or greater than safety limits), a neutrally-buoyant object, or float, is recommended.

The measurement methods listed in Table 1 are described below.

Table 1. Stream discharge measurement methods.

Depth (ft)	Recommended Meter	Measurement Method	Access Method
0–0.3	too shallow	Float or weir	wading
0.3–1.5	Pygmy	One-point	wading
1.0–2.5	Type AA	One -point	use safety guidelines
2.5 and above	Type AA	Two-point	boat or bridge

3. Measurement method: Float

- Select a subreach for the float test, and measure its length.
- Select a neutrally-buoyant object (a ball or an orange).
- Place or toss the object into the stream, allowing it to reach full velocity before it passes the upstream end of the subreach.
- Time the float until it reaches the downstream end of the subreach.
- Retrieve the object, using a net if necessary. Run the float test at least three times, and calculate the average of the object's velocity.
- Depending on its weight and immersion, the object's velocity should be multiplied by about 0.85 to obtain the average stream velocity for that location.
- Multiply the average stream velocity by the average cross-sectional area of streamflow in the subreach used for the float test, giving an estimate of stream discharge $\pm 25\%$ (Buchanan and Somers 1969).
- Ideally, a float test is run for each partial section (see instructions below regarding partial sections) of the total stream width, obtaining volumetric discharges for each partial section that can be averaged, giving an estimate of stream discharge $\pm 10\%$ (Buchanan and Somers 1969).

4. Measurement method: Weir

- Use the volumetric method. Select a location where all streamflow can be constricted into a small cross-section and allowed to freefall, such as a nearby falls or drop-off, or at a weir plate placed across the streamflow. Measure the amount of time that it takes to fill a container of known volume.
- Use the stage method. Permanently install a weir plate across the stream flow such that none of the water flows around the weir but all water flows through the weir opening. Measure the height of water as it passes over the notch in the weir opening. Calibrate this height to a pressure transducer that has been installed in the pool behind the weir. Based on the geometry of the weir opening (45°, 60°, and 90° v-notches are common), depth measurements are easily converted to flow volumes.
- Install a Parshall flume. Find a straight area of the stream and install the flume so that the “floor” section of flume is level. All flow in the stream should be going through the flume. Discharge of the stream can be determined by reading the stage at the prescribed location within the flume, and performing the proper calculations as provide by the flume’s manufacturer. There are many variations on the Parshall flume, including portable versions (Johnson 1963).

5. Measurement method: For all current meters

- Most handheld flow calculators do not allow you to switch current meters in the middle of the measurement of a cross-section as you work your way across a stream. Therefore, select a current meter that will suffice for all flow depths.
- Choose the number of partial sections (Figure 2) or measurement interval, according to the following rule of thumb:
 - If the stream width is less than 5 ft, partial sections are 0.5 ft wide.
 - If the stream width is greater than 5 ft but less than 10 ft, the minimum number of partial sections is 10.
 - If the stream width is greater than 10 ft, the preferred number of partial sections is 20 to 30.

Though not required, it may be most convenient to select a uniform width for all the partial sections. For example: a 7-ft wide stream consisting of 14 × 0.5-ft partial sections, a 26-ft wide stream consisting of 26 × 1.0-ft partial sections. To minimize measurement errors, the most important criterion of measurement intervals is that **no single partial section should contain greater than 10 percent of the total flow.**

- Be prepared to track your lateral position. As you work your way across the river, the midpoint of the next partial section is measured one partial section width from the

previous midpoint. When wading, a tagline (nylon cord that will not stretch when wet), knotted at the distance of one partial section width, can be used to measure the intervals, or you can stretch a tape measure along the tagline to keep track of the cumulative width as you work across.

- After locating the midpoint of a partial section, measure the total depth and record it on the field form. Record your lateral position on the field form.
- Based on the water depth, determine whether the one-point or two-point method is required (Table 1). The top-setting wading rod is designed to allow the user to easily set the current meter at 20-, 60-, or 80-percent of the total depth (Figure 3), for either the one-point or two-point method.
 - 20% of total depth: Multiply the total depth by 2. If the total depth is 3.1 feet, the rod is set at 6.2 feet. Line up the foot scale on the sliding rod with the tenth scale, located on top of the depth gauge rod. Line up the 6 on the sliding rod with the 2 on the tenth scale.
 - 60% of total depth: If the total depth is 3.1 feet, then line up the 3 on the foot scale with the 1 on the tenth scale.
 - 80% of total depth: To set the sensor at 80% of the depth, divide the total depth by two. For example, the total depth is 3.1 feet and the rod is set at 1.55 feet. Line up the 1 on the sliding rod between the 5 and 6 on the tenth scale.

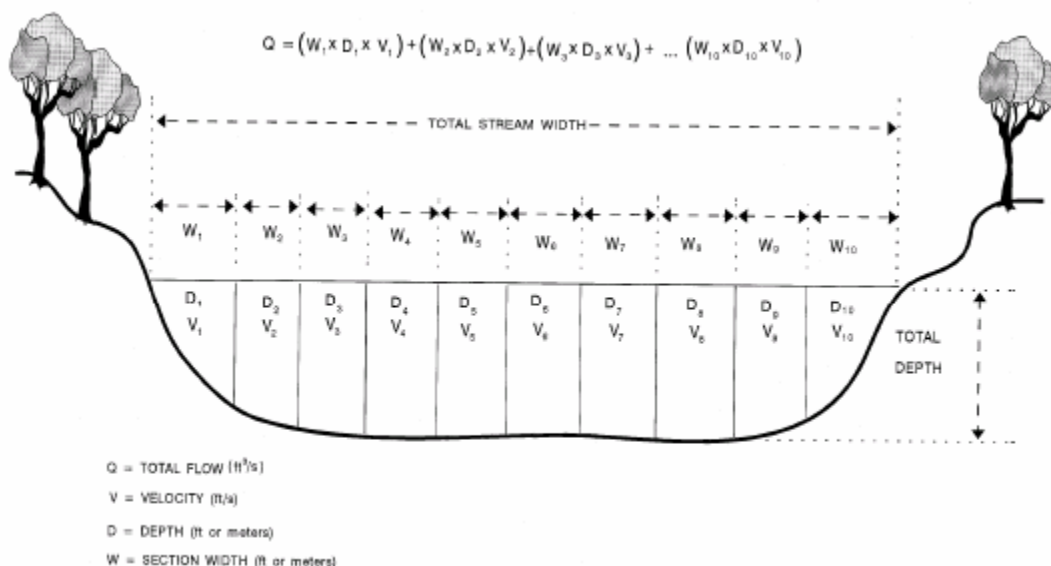


Figure 2. Division of stream cross-section into partial sections.

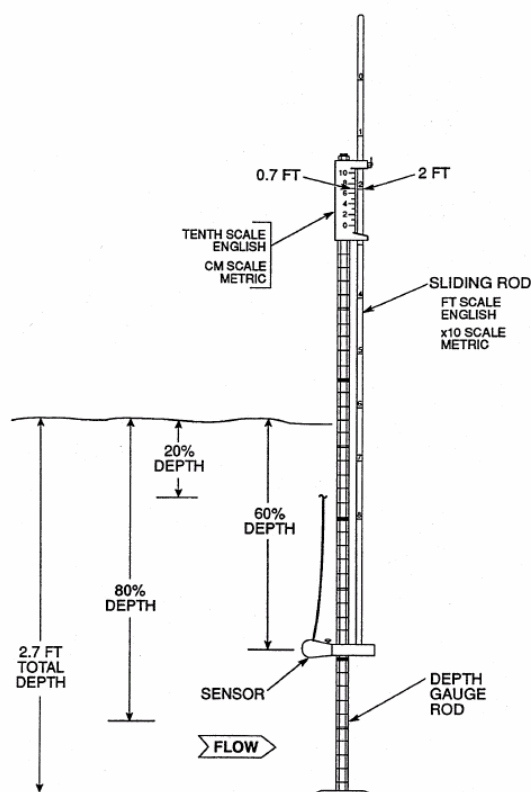


Figure 3. Top-setting wading rod, showing an example for measuring flow at 60% of depth.

6. Measurement method: Current meter and one-point method

- Position the meter on the rod at the correct depth (60% of total depth), and lower it into the water.
- When wading, stand a minimum of 1.5 feet downstream and off to the side of the flow meter to minimize the effect of your presence on the velocity of water passing the current meter.
- Keep the wading rod vertical, and keep the long axis of the flow meter perpendicular to the flow.
- Permit the meter to equilibrate to the current for a few seconds. Measure the velocity for a minimum of 40 seconds.
- Record the flow velocity on the field form in the correct column.

7. Measurement method: Current meter and two-point method

- Position the meter on the rod at the correct setting for 20% of total depth, and lower it into the water. Permit the meter to equilibrate to the current for a few seconds. Measure the velocity for a minimum of 40 seconds. Record the flow velocity on the field form in the correct column.
8. Position the meter on the rod at the correct setting for 80% of total depth, and lower it into the water. Permit the meter to equilibrate to the current for a few seconds. Measure the velocity for a minimum of 40 seconds. Record the flow velocity on the field form in the correct column.
9. Complete the field form. At a minimum, the following information should be recorded on a flow measurement field form (an example is appended below):
- Measurement date, station ID and location, and names of field personnel;
 - Visual observations of flow conditions, note any known precipitation in the last 48 hours;
 - At start, gage height reading (if available) and time (in military units);
 - Total stream width (water's edge to water's edge);
 - Preliminary velocity measurement and choice of instrumentation/method;
 - For each partial section:
 - Distance from partial section midpoint to the water's edge or to laser target,
 - Water depth and flow velocity measurement(s) at the midpoint,
 - If necessary, angle between flow and perpendicular to tagline (avoid this condition, if possible),
 - Unusual flow conditions (turbulence, back eddies, or flow blockages; avoid such conditions, if possible),
 - Distance measurements for the partial section endpoints (optional),
 - Calculated average flow velocity (from two-points) (optional),
 - Calculated flow discharge for partial section (optional);
 - Cumulative discharge, from the first bank to each partial section (optional) and calculated total discharge for the stream cross-section;
 - Readout from flow calculator of total discharge for the stream cross-section;

- Distance from permanent marker (if present) to flow centroid (location of 50-percentile of cumulative discharge (optional);
- At finish, gage height reading (if available) and time (in military units), to check for rising or falling stage.

10.4 After Field Work

10.4.1 Calculate the Total Flow of the Stream Cross-section

1. Calculate flow at each partial section (Q_i , cfs or ft^3/sec) by multiplying the width (W_i , ft.) by the depth (D_i , ft) and velocity (V_i , ft/s) measured at the midpoint, or $Q_i = W_i \times D_i \times V_i$.
2. When recording flow for each partial section, do not round flow values. Rounding each value on the worksheet could introduce an error in the final value. Only the final value is rounded.
3. **Do not** treat partial sections with negative flow values as zero. Negative values obtained from areas with back eddies should be subtracted from the total flow.
4. When flow is calculated for each partial section, add them together for the total flow, or $Q_w = [(W_1 \times D_1 \times V_1) + (W_2 \times D_2 \times V_2) + \dots + (W_n \times D_n \times V_n)]$, for n sections.
5. Depending on the final value of total flow, round it to a reporting value based on the guidelines in Table 2.

Table 2. Reporting values for total flow (Q_w), measured in cubic feet per second (cfs).

Measured value (cfs)	Reporting value (cfs)	Example
$Q_w < 0.01$	<0.01	0.003 reported as <0.01
$0.01 < Q_w < 0.1$	Not rounded	0.07 reported as 0.07
$0.1 < Q_w < 10$	Rounded to nearest 0.1	9.35 reported as 9.4
$Q_w > 10$	Rounded to nearest 1	20.62 reported as 21

10.4.2 Convert Stage Data to Discharge Data

1. If stream monitoring station is located at or near a permanently installed gaging station, correlate the stage readings and/or datalogger readings to the discharge record from the gaging station.
2. If a nearby gaging station is not available, then calculate a stage-discharge relationship for the stream site by using computer software (e.g., Aquatic Informatics Aquarius software) or manually, as follows:

- a. Collect a series of paired stream stage and stream discharge readings.
- b. Plot the points of stage (measured in feet) versus discharge (measured in cubic feet per second) and draw a smooth curve through the points. The more points, the more precise the rating curve is likely to be. For increased precision, the rating curve should be developed from a minimum of 10 data points, covering a range from low to high flows.
- c. After the rating curve is developed, stream discharge can be read from the rating curve using a new stream stage reading, or calculated from the mathematical rating relationship.
- d. However, the rating curve may shift over time, such as when changes occur in the stream channel, in the equipment used, or in personnel, and periodic measurements are necessary after the initial rating to either confirm the permanence of the rating or to follow changes/shifts in the rating. Given this added work required to develop, check, and update a rating relationship, it is most cost-effective to use rating curves for sites that will have a multitude of stage readings each year, as with a dedicated datalogger.
- e. Refer to Magdalene (2008) for a comprehensive description of the rating curve development process applied in a Great Lakes Network park.

10.5 Quality Assurance/Quality Control Procedures

1. Maintain equipment in clean and working condition, per manufacturer instructions
2. Be prepared for the unexpected. Carry the necessary tools, replacement parts, and batteries in the field.
3. During installation, secure the staff gage to its structure so that it will not shift with time.
4. During the measurement of stream discharge, ensure that no more than 10% of the flow is contained within any one partial section. The more partial section readings that can be made, the more accurate the calculated stream discharge will be. Rantz and others (1982) estimate that typical discharge measurement errors are within 10%.
5. When calculating a stage-discharge rating relationship for the stream monitoring site, use a minimum of 10 measurements. More than 10 may be needed to cover the full range of measured stream stages, and to develop greater detail for some portions of the rating curve.
6. If qualitative estimates of flow will be made based on visual estimation of relative % of bankfull, conduct multiple comparisons between crew members and an expert to train the crew member's eye and minimize bias.

7. When changes in flow meters (or personnel) occur, conduct at least seven side-by-side measurements with the new and old equipment (or the new and experience crew members) if possible. Such comparisons will minimize bias (or at least document its occurrence).
8. At least once a year, calculate Alternate Measurement Sensitivity (AMS+) by conducting seven consecutive measurements of flow in a stream cross section. AMS+ is a two-sided estimation based on the 99% confidence interval for sample size 7. Of interest is the size of the difference between two individual values that can be considered to actually be a true difference. This calculation differs from the minimum detection limit (MDL), which is a one-sided true difference from zero. The standard deviation will then be calculated and used in the estimation of AMS+ ($3.708 \times SD$). Documentation (Appendix A and SOP #15) will be kept in the project files.

10.6 Literature Cited

- Buchanan, T. J., and W. P. Somers. 1969. Discharge measurements at gaging stations. Chapter A8 in U.S. Geological Survey. Techniques in Water Resources Investigations Book 3. Available at: <http://pubs.usgs.gov/twri/twri3a8/>.
- Johnson, A. I. 1963. Modified Parshall Flume. Open-File Report. U.S. Geological Survey, Denver, Colorado. Available at: <https://pubs.usgs.gov/of/1963/0063/report.pdf>.
- Lundquist, J., B. Huggett, and H. Roop. 2008. Electronic supplement to: Strategic use of stream stage recorders as proxy rain gauges in complex terrain. Available at: http://depts.washington.edu/mtnhydr/publications/Lundquist_stillingtubesupplement_new.pdf.
- Magdalene, S. 2008. Site establishment for large rivers water quality monitoring: Stage-discharge relationships at selected sites within the St. Croix National Scenic Riverway. National Park Service, Great Lakes Inventory and Monitoring Network Report GLKN/2008/02. Available at: <http://science.nature.nps.gov/im/units/GLKN/monitorreportpubs.cfm>.
- Penoyer, P. 2003. Vital signs long-term aquatic monitoring projects: Part C, draft guidance on WRD required and other field parameter measurements, general monitoring methods and some design considerations in preparation of a detailed study plan. Draft. Available at: <http://science.nature.nps.gov/im/monitor/protocols/wqPartC.doc>.
- Rantz, S. E., and others. 1982. Measurement and computation of streamflow, Volume 1: Measurement of stage and discharge. Water Supply Paper 2175. U. S. Geological Survey, Reston, Virginia. Available at: <http://water.usgs.gov/pubs/wsp/wsp2175/>.
- Woodyer, K. D. 1968. Bankfull frequency in rivers. Journal of Hydrology 6:114–142.

Appendix A. Stream Gaging Field Form

Date _____ Start Time _____ End Time _____

Name of Stream/River _____

Location (GPS coordinates) _____

NAD _____

Personnel _____

Gage height start _____

Gage height end _____

**Record measurement depth for cable suspension only

		60% or 80% depth				20% depth (ft)			
		Distance from L / R bank (circle one)	Total depth (ft)	1-pt meas ✓	2-pt meas ✓	Meas depth (ft)	Flow velocity (fps)	Meas depth (ft)	Flow velocity (fps)
LB / RB facing upstream -----circle which bank at start and which bank at finish-----			0.00				0.00		0.00
	LB / RB facing upstream			0.00				0.00	

Method (circle one for each)

Type AA meter or Pygmy meter

Rod suspension or cable suspension

Wading, boat, or bridge access

Total flow

Flow: _____ cfs

Velocity: _____ fps