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USDA LTAR Common Experiment measurement: Channelized surface flow discharge

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Abstract

Measurement of surface flow rate (discharge) is often needed for agroecological studies, whether to understand the movement of water itself or to estimate what flowing water carries (e.g., nutrients or sediments exported from cropland or grazing land). Water may flow over land in non-channelized ways (the subject of a different protocol) or be confined to discrete channels. The present protocol addresses channelized flow within the context of the LTAR Common Experiment (i.e., from fields or plots), recognizing that such flow occurs as a continuum from rivulets to open drainage channels and small streams; hence, the optimal discharge measurement method depends on channel size and other considerations. Since the US Geological Survey measures discharge from large drainage areas, this protocol is geared toward discharge measurements in headwater streams and ditches. Because the situations in which channelized discharge may need to be measured vary considerably across the LTAR network, we are not recommending a specific protocol but instead offering considerations for selecting measurement methods and published references with more information on various options.

Protocol steps

1 Instantaneous discharge measurements pose challenges in headwater and ephemeral stream channels because discharge often changes considerably during and shortly after rain or snowmelt events, resulting in a “flashy” hydrograph, and much or most of the movement of water and materials may occur during high discharge periods.

- Therefore, automated, continuous measurement systems are required to estimate total water and material export over a season or year.
- Automated discharge measurement usually relies on a water level (stage) measurement.

2 Commercially available devices for measuring the water level and logging the data are often based on hydrostatic pressure (pressure transducers, see the protocol on water table measurement) or capacitance, and the latter device can be the best for shallow depths.

3 Stage is most easily monitored using a flume or weir but can also be monitored using another natural or engineered structure, such as a box culvert under a road that confines the channel such that changes in water level correlate well with changes in discharge.

- These structures (flume, weir, or box culvert) provide a well-defined rating curve relating discharge to water level.
- The exact measurement point of the water level depends on the type of structure used.
- In some cases, a “stilling well,” a type of vertical pipe hydraulically connected to the channel, is a good option for monitoring water levels because it produces a calm water surface and protects against damage from floating debris.

4 The stage at a particular time is converted into discharge using a stage–discharge relationship called a rating curve.

- Extrapolating beyond the measurement range must heed the possibility of non-linearity, particularly at the upper end of the relationship where streams may overflow onto their banks or floodplains or become backed up by downstream channel features.

5 Water level monitoring, whether by visually reading a gauge or by installing a sensor, must have a location carefully chosen to serve the entire expected range of water levels, responsive to changes in discharge, where channel features are stable over time, and resistant to damage by large flow events.

6 Flumes and weirs may have known water level-to-discharge relationships, but lacking these relationships, or when water levels rise beyond the known relationship, one must measure discharge across the range of water levels to estimate discharge under all observed conditions.

7 Constructing the rating curve may necessitate spot measurements.

- Measure discharge in open channels deeper than approximately 5–10 cm using flow (velocity) meters, ideally electromagnetic ones for shallow waters.
- Measure velocities at multiple points and depths across the channel cross section because the cross-sectional velocity profile under laminar or slow flows varies with depth and channel obstructions. It is important to select a reach with the most uniform channel morphology. Compute discharge from the sum of velocity multiplied by the cross-sectional area of each subsection.

8 Alternative methods are often required when velocity profiles are difficult to measure because streams are very shallow, flow very slowly, flow over very irregular terrain, or contain vegetation or other obstructions.

- If the water flows over a small waterfall or pipe outflow, simply measuring the time needed to fill a container can provide an accurate estimate of discharge.

9 Adding conservative solute tracers such as salts or dyes can provide estimates of discharge in channels unconducive to flow meter use (Baker and Webster 2017).

10 Perform tracer addition as a pulse or steadily over a longer period to reach stable concentrations, the latter option using a pump or drip.

- If the discharge is small and/or the water is low in dissolved ions, add table salt (NaCl), monitoring its passage downstream with a conductance meter once the salt/conductance relationship is known for a particular water chemistry.
- If this approach is infeasible, measure individual ions (e.g., Cl-) using ion-specific electrodes or lab instrumentation (e.g., ion chromatography). As a conservative ion tracer, bromide (Br-) is often preferred over Cl- because of its low background concentration.
- At higher discharges, adding salts becomes impractical, and the dye Rhodamine-WT is often used. Rhodamine-WT is measurable fluorometrically in the field or the lab over wide-ranging concentrations.

11 In all cases, tracer measurements are necessary after the tracer becomes well mixed in the channel (including with any lateral inputs of water), which should be verified with cross-sectional measurements because the distance for full mixing is often surprisingly long. In low-gradient channels, placing baffles or other obstructions can encourage mixing.

12 Longitudinal measurements of a continuously added tracer can provide estimates of new water inputs to the channel as the tracer becomes diluted downstream as long as cross-channel mixing receives attention.

- One must avoid adding tracers to levels that could be toxic (or, in the case of dyes, visible to the public), and government permits (usually from state environmental agencies) may be required for any chemical addition to surface waters, thus requiring advanced planning for tracer additions.

Equipment

13 The selection of a flume or a weir and its size depends on several considerations, including the drainage area, the expected range of flows, and the topography at the point of measurement.

- Often, several structures are appropriate, and the selection criterion becomes cost.
- We refer the reader to **https://instrumentationtools.com/weirs-and-flumes/** for information about each type of flume or weir, including photos.
- A stilling well is encouraged for any location where the water surface is not flat.

14 Similarly, multiple devices can measure and record water levels, including a float and weight with either a chart recorder, a shaft encoder or bubblers connected to a non-contact pressure transducer, submerged pressure transducers, and non-contact radars or ultrasonic devices.

- Unless a submerged pressure transducer vents, compensating for barometric pressure, a separate logger is needed to measure barometric pressure to correct the underwater measurements (see the water table measurement protocol).
- In addition, synchronized measurements can readily help automatically correct the data using software that comes with the sensor system.
- Pressure transducers, flow bubblers, and radars connect to a data logger, which records, stores, and transmits the data.
- Alternatively, manually download the data at regular intervals.

15 For best-quality data when financially feasible, duplicate the measurements to increase the likelihood of the availability of one measurement in case of malfunction.

- Three independent measurements allow for determining the correct value when sizable deviations exist between two sensors.
- Otherwise, literature provides data collection accuracy based on current and past uses (Harmel et al., 2006).
- To confirm that the device is measuring the correct stage, a graduated staff gauge is commonly installed for reading.

16 Spot measurements of flow velocity at different depths can be carried out using mechanical or electronic flowmeters (e.g., General Oceanics current meter or the Sontek Flow Tracker, a hand-held acoustic Doppler velocity meter (Voulgaris and Trowbridge, 1998), which is good for shallow flow depths). These products range in price from affordable ($350-$700) to expensive ($10,000-$15,000).

- Mechanical flowmeters are fitted with a propeller that turns in the water current, driving an odometer whose readings are converted to currency velocity (cm/s) from a calibration chart provided by the manufacturer.
- Electronic flow meters have the same propeller attached to a Hall-effect sensor that, for a full propeller rotation, sends two pulses that are recorded in a data logger.

- Acoustic Doppler velocity meters measure the velocity of particles in the water using the Doppler shift effect (measuring flow speeds over different seasons across a year (more years, better), and relating that data to water level measurements at the same time allows for the construction of a rating curve for that channel.

17 Flow-area velocity sensors that measure stage and velocity are an attractive option that does not require a rating curve.

- However, they must be placed in the channel, which increases the likelihood of trapping residues and sediment.
- In addition, they must be constantly submerged, which may not happen in headwater streams. For this reason, we exclude them from this protocol.

18 Flow-area velocity meters can be used for spot discharge measurements, either because a rating curve is unavailable or to build a rating curve. Conservative tracer additions can avoid the need for flow profile measurements, but errors can arise if the channel has flow obstructions from vegetation and dead-flow zones.

Note

The introduction above contains a more detailed discussion of this issue.

Frequency of measurement

19 Within the LTAR context, monitor discharge continuously throughout the year. Measurement frequency is a function of the drainage area, its concentration time (how long it takes for runoff to reach its maximum value under constant rainfall), and, to some extent, the stage monitoring device.

Note

For headwater streams, the best measurement frequency will likely be between 1 and 5 minutes.

Concurrently sampled covariate metrics

20 It is useful to measure any variable that may explain changes in discharge values, including precipitation, irrigation if relevant, evapotranspiration (ET), and run-on (surface flow coming into the drainage area from uphill).

- The water or air temperature is useful for determining when freezing conditions occur, which can affect the flow.
- Water quality parameters (dissolved oxygen, pH, electrical conductivity, and temperature) are measured to monitor water quality for aquatic organisms.
- For instance, low flow velocities correlate with lower dissolved oxygen, which is also related to higher water temperatures.

> **Note**
>
> If nutrient or contaminant transport is of interest, concomitant water quality measurements are needed.

Calculations

21 **Conversion of water level to discharge value**

- Once measured, the level (stage) needs to be converted to a discharge value using the rating curve of the site, a curve that relates discharge in cubic meters per second to water level in meters.
- The rating curve may consist of an equation or a curve fitted to a series of stage–discharge pairs.
- Flumes have theoretical or empirical equations determined in a laboratory environment that assumes perfect conditions.
- However, field environments may diverge from this perfect environment (leveling of the flume, shape of the flume, turbulence, wind, etc.), and thus, site-specific calibration is recommended.
- Checking the physical integrity of the flume at regular intervals ensures that these conditions are verified and corrected promptly if needed.

22 **Rating curve determination**

- The rating curve is interpolated between stage–discharge points measured experimentally with flow velocity meters or conservative tracers.
- Once this curve is defined, regular measurements should verify that it has not drifted. For example, over time, sedimentation or bank-cutting of the channel can change the channel cross-sectional profile and hence discharge.
- In the case of drift, correct the rating curve and discharge data since the last check. Extrapolation using stages exceeding the data range used to construct the existing equation can entail large uncertainty.

Quality Analysis

23 Quality analysis (QA) defines the steps taken to ensure maximum quality of the data produced and minimize the need for corrective measures to improve data quality.

- Follow the general recommendations on quality analysis in the *LTAR Common Experiment measurement: Best practices for collection, handling, and analyses of water quantity measurements* protocol (Baffaut et al. 2024).
- Other beneficial QA practices include the operating manuals and manufacturers' descriptions of the necessary checks for your specific equipment and the information on QA practices provided by Sauer et al. (2010).

All these things may apply to your site. In addition, QA recommendations for measuring channelized surface flow discharge also include:

23.1 When checking data daily (recommended) or weekly (minimum), look for low voltage, missing data, a constant stage outside no-flow periods, excessive oscillation of the stage, sudden increase or decrease in the stage, and other anomalies. Any of these conditions requires a visit to the site and possible recalibration of the devices.

23.2 During regular maintenance visits, check for:

- Sediment or debris accumulated in or slightly upstream of the structure. Check these areas and remove these accumulations.
- Excessive sediment, debris, or drowned rodents in the stilling well. Check these areas and remove these items.
- Stage accuracy. The stage indicated by the monitoring device must match the water level determined by a different instrument or measured manually. The easiest approach is using a staff gauge at the site. If the difference is larger than 0.003 m (US Geological Survey standard, recommended) or 0.03 m (South Florida Water District, maximum allowed), make a note and recalibrate the monitoring device. Apply drift to stages recorded since the last stage check, then recalculate discharge values.
- Water bypasses the hydraulic structure. Rodents or erosion create holes and bypasses upstream and along an unsubmerged hydraulic structure. Holes need to be filled.
- Physical integrity of the hydraulic structure itself (e.g., leveling and shape). These checks depend on the type of structure and the material used for its construction.

If any of these aspects show departures from normal operating conditions, record these departures and the correction applied in a maintenance log.

Quality control

24 Perform quality control (QC) of stage records regularly.

- We recommend quarterly QC or at least every six months so that the technicians remember the conditions over that period.
- Access to the maintenance log is necessary for this process.
- Graphical inspection of the variation in stage values and other metrics such as precipitation, temperature, and device voltage is also necessary.
- Commercial software packages provide that capability. Alternatively, develop in-house software.

25 Record any replacement or gap-filling of the data with the following information: what was done, why it was done, what period the change covers, who made that change, and when it was made. Again, commercial software packages do these things automatically. If you develop review and quality control process software of your own, record this information.

26 The time needed for quality control of stage data can vary depending on raw data quality.

- If everything works as planned, the time needed to review three months of data is short, around one hour. This review can take several hours when multiple adjustments are required.
- As for QA, follow the recommendations on quality control in the *LTAR Common Experiment measurement: Best practices for collection, handling, and analyses of water quantity measurements* protocol (Baffaut et al. 2024).
- The following considerations are in addition to these recommendations. Once familiar with the equipment and the discharge behavior at the site, you may want to enhance your QC process.

26.1 Use the maintenance log to identify periods in which data may be suspicious.

26.2 If data are missing, assess if this happened during a dry period or if there should have been flow.

1. If data are missing during a known dry period (which you can assess using the precipitation and temperature record), assign a value of zero during this period. Record this assignment.
2. If data are missing during a flow period (or if you do not know whether flow occurred), check for data from a secondary sensor. If secondary data are available, replace the missing segment with these data. If the secondary sensor also fails or is absent, flag the period as “missing data.” You can return later and estimate the stage or the discharge values from records at other stations, a model, or interpolation based on the shape of the hydrograph. After estimating and replacing the missing data, flag the new data as estimated values.

26.3 If the maintenance log indicates a likely drift or shift, correct the stage over the period since the last good check or recalibration. Flag the data as estimated or corrected and record the nature of the correction.

26.4 If the maintenance log or temperatures indicate icy conditions, note these conditions in the data.

26.5 If the maintenance log indicates the removal of a blockage in, downstream, or upstream of the structure, flag the data for it. Removing the obstruction will likely cause important oscillations and a substantial stage shift. If you know when the blockage started, adjust the data over that period. If you cannot determine when the blockage started, adjust the stage data over the period since the last good measurement check or device recalibration. In any case, flag the adjusted data as estimated.

Golden standard: Quality evaluation and uncertainty of each data point

27 Quantifying the quality of discharge data will considerably help investigators decide which datasets to include in an analysis across multiple LTAR sites. It will also allow combining datasets of different quality into the same study, such as in the water budget analysis (Baffaut et al., 2020).

- Multiple factors contribute to the quality of discharge data, the foremost being the accuracy of the stage measurement. This accuracy depends on the measurement device (the specs will define the measurement accuracy) and the external conditions affecting the measurements. These conditions may not be constant; they may vary in time and concern a given period of recording. Thus, assign a quality grade to each data point (at each time step), not the entire series.

28 Identify and note special conditions during the quality control phase.

- Any factor harming the stage measurement and requiring an adjustment or a replacement of the data effectively degrades data quality.
- For internal use of the data, keep track of these conditions.
- Assign flags as proposed in the *"Quality Assessment and Quality Control"* section in the *USDA LTAR Common Experiment measurement: Best practices for collection, handling, and analyses of water quantity measurements* protocol (Baffaut et al., 2024). These flags include pass, missing, or estimated.

Archiving

29 **Metadata**

- Include a map of the drainage area boundary in the metadata, along with the coordinates of the monitoring site and the size of the drainage area.
- When using a flume, specify its type and size. If a weir is used, describe its physical characteristics, the ground cover upstream and downstream of the weir, and the drop in elevation downstream of the weir.

- Weirs can be submerged at high flows, at which point a rating curve is necessary. In this case, describe how the rating curve was developed.
- If no structure is used (not recommended), describe how the rating curve was built and adjusted.
- In all cases, specify if there is a stilling well.

30 To audit the data, keep all versions of the data, including raw data, deletions, corrections, and any gap-filling or replacements. Record changes, deletions, or replacements and indicate when, why, and by whom they were implemented.

31 Upload stage and discharge data to a public repository at a frequency compatible with the LTAR data-sharing principles and guidelines.

Recommendations for data collection

32 Table 1. Summary of recommendations for measuring channelized discharge.

A	B	C	D
Attribute	**Preferred**	**Minimum**	**Comments**
Spatial scale	Headwater streams	See comments	Measurements at one point in a channel can represent water and chemical exports from the upstream watershed
Frequency	Continuous throughout the year	Synoptic surveys	The frequency depends on the study purpose and the drainage area size; however, in many cases, continuous monitoring will be needed, and the non-growing season can be an important time for water and chemical export
Covariate metrics	Precipitation, air or water temperature, run-on, irrigation, ET	Precipitation, irrigation, run-on	For QC and analysis purposes. “Run-on” refers to surface flow entering the defined area of interest from uphill. ET is useful for studies relating land use change to discharge
	Chemical variables, water quality parameters (dissolved oxygen, pH, temperature, electrical conductivity)		If habitat quality for aquatic organisms (stream ecology) or chemical export is of interest

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Additional Resources

A very basic streamflow measurement tutorial is provided by the USGS:

- https://www.usgs.gov/special-topics/water-science-school/science/how-streamflow-measured

Tracer approaches are described in detail here:

- **https://books.gw-project.org/groundwater-surface-water-exchange/chapter/stream-tracer-methods/**

Useful online information can also be found from companies selling discharge measurement equipment:

- **https://www.otthydromet.com/**
- **https://www.fondriest.com/environmental-measurements/measurements/hydrological-measurements/streamflow-measurements/**