



Protocol Implementation Plan for Monitoring Discharge in Greater Yellowstone Network Parks

Standard Operating Procedures Version 1.0



ON THE COVER

Discharge monitoring in Lower Layout Creek, Bighorn Canyon National Recreation Area, June 2015.
Photography by NPS.

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Standard Operating Procedures Version 1.0

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Introduction

The Greater Yellowstone Network (GRYN) is one of 32 Inventory and Monitoring Networks covering 270 national park units within the National Park System. These networks serve an important role in providing park resource managers with important scientific data on the status and condition of vital park resources. This role was established in the Natural Resource Challenge which directed parks to place a great emphasis on natural resource stewardship in meeting the National Park Service mission to “preserve unimpaired the natural and cultural resources and values of the national park system for the enjoyment, education, and inspiration of this and future generations.”

GRYN includes four national park units: Bighorn Canyon National Recreation Area, Grand Teton National Park, John D. Rockefeller, Jr. Memorial Parkway, and Yellowstone National Park. Combined, these parks span over one million hectares and represent a topographically complex and climatologically heterogeneous region. Park staff and subject matter experts recognized the diversity of ecosystems and, in particular, the ecological and societal importance of water to this region when identifying important park resources for long-term monitoring. Stream flow (or more generally, discharge) was identified as one of the selected vital signs in GRYN’s long-term Vital Signs Monitoring Plan (Jean et al. 2005).

Water resources in GRYN parks are diverse and include alpine lakes, rivers, perennial and ephemeral streams, springs, geysers, wetlands, and natural lakes and reservoirs. In addition, GRYN parks include one designated Wild and Scenic River (the Snake River) and one World Heritage Site (Yellowstone National Park). Yellowstone National Park was recognized as a World Heritage Site, in part, because of its unique aquatic resources; over 200 geysers and upwards of 10,000 geothermal resources are present inside park boundaries.

This standard operating procedures (SOPs) document and the accompanying protocol implementation plan narrative (Ray et al. 2017) provide the details of how GRYN will use established protocols from the Sierra Nevada Network (Skancke et al. 2017a, b) and Southwest Alaska Network (Shearer et al. 2015a, b) as guidance for the implementation of a discharge monitoring protocol for select rivers, streams, and spring outlets throughout GRYN parks.

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SOP 1: Discharge Measurement in Wadeable Waters

Version 1.00, September 2017

Change History

Original Version #	Date of Revision	Revised By	Changes	Justification	New Version #

Introduction

(Adapted from Shearer et al. 2015 – Southwest Alaska Network)

Discharge is the volume of water passing a given point on a river or stream bank per unit of time. Discharge is an essential parameter for characterizing hydrologic and water quality dynamics in moving waters; discharge estimates are used to define the hydrograph of lotic systems and relate standing concentrations of nutrients, ions, and contaminants to their movement through aquatic environments (Shearer et al. 2015). Rivers, streams, and springs within Greater Yellowstone Network (GRYN) parks range in size from large and unwadeable rivers that require bridge or cableway-based techniques for obtaining discharge estimates to first-order wadeable streams and developed springs. Fortunately, discharge measurements on large rivers are carried out by the U.S. Geological Survey (USGS). Other waters, including streams and spring outlets of interest within GRYN are wadeable. In these systems, the employment of current meter measurements by wading are preferred (Turnipseed and Sauer 2010). This standard operating procedure (SOP) describes the methods for determining discharge in wadeable streams using the Velocity Area Method (see Turnipseed and Sauer 2010), and includes information on site selection, equipment set-up and use, data collection, and calculation of discharge.

To estimate discharge (Q), a cross-section of the stream is selected and then divided into evenly spaced “cells.” When possible, excess growth of macrophytes or other objects such as boulders or large woody debris is removed from the vicinity of the cross-section (transect) area prior to beginning measurements. A measuring tape is then stretched perpendicular to the stream flow and used to divide the stream into a minimum of 20 cells. This ensures that no more than 5% of the cross-sectional area will be represented by each velocity measurement. If hydraulic irregularities are detected, additional cells are established to account for noticeable anomalies (Gore 1996). Once the transect defined by the tape is established, cell width (w) and cell depth (d) are documented and used to calculate cell area (a). Corresponding stream velocity (v) measurements are recorded using each cell. Discharge (Q) is then computed using the Velocity Area Method (see Turnipseed and Sauer 2010) from these measurements using the following equation:

$$Q = \sum_{i=1}^n a_i v_i$$

Where Q is the total discharge, in cubic feet per second,
 a_i is the cross-sectional area of each cell, in square feet, for the i th cell of the n cells into which the cross section is divided, and
 v_i is the corresponding mean velocity, in feet per second, of the flow normal to the i th cell, or vertical.

Under wadeable conditions (see Lane and Fay 1997), velocities will be measured using an electromagnetic Marsh McBirney velocity meter affixed to a graduated, stainless steel, top-set wading rod (Nolan and Shields, 2000). Other flowmeters are available, however this SOP will focus on use of the Marsh McBirney Flo-Mate because GRYN already has this flowmeter.

This procedure is conducted with a two-person crew that includes data recorder and an observer who operates the flowmeter. Both crew members should be familiar with the field methods for obtaining accurate velocity readings and the calculations required to convert velocity, depth, and width readings into discharge estimates.

Marsh-McBirney Flo-Mate

The Marsh-McBirney Flo-Mate Model 2000 is a portable flowmeter that uses an electromagnetic sensor to measure velocity in water or any other conductive liquid. As water moves through the magnetic field, voltage is generated. The magnitude of the voltage is proportional to the velocity at which the water moves through the magnetic field (Marsh-McBirney 1990). This SOP highlights the operational features of the digital flowmeter. Personnel should be familiar with the basic operation of the meter and should carry a laminated copy of the operating manual in the field.

Features

- The sensor uses digital filtering to remove electrical noise that may be present in the flow.
- A 'noise' flag is displayed if electrical noise interferes with normal operations.
- A 'conductivity lost' flag will be displayed and velocity readings are blanked out when conductivity is lost. This occurs when the sensor is out of the water, and may also occur when the batteries are low.
- If conductivity is lost for more than 5 seconds, the emission of the electromagnetic current is turned off. The entire unit will power down if the sensor remains dry for more than 5 minutes.
- A 'low battery' flag is displayed when the battery voltage is getting low. Battery life varies from 1 hour (alkaline) to 15 minutes (NiCad) once the low battery flag is displayed. If the voltage is too low, the unit will turn off. The unit operates on 2 D-cell batteries. Consult the manual for other battery options.
- There are 19 data storage locations in which velocity readings can be saved and recalled.

Calibration

The Flo-Mate sensor must be free of any oil or grease build-up to work properly. If the sensor appears to have a grimy film, wash it using warm tap water and a mild soap. Unless the sensor is used in highly contaminated liquids, the sensor generally should remain free of oil/grease accumulation. The sensor can be factory calibrated by returning the meter to Hach Flow Support Services (<https://www.hachflow.com/contact/>). Hach recommends an annual factory calibration check. The Flo-Mate is also calibrated locally by conducting the ‘zero adjust check’ inside the laboratory in a 5-gal bucket of tap water, according to the following steps.

1. Secure the sensor to a supporting rod (i.e., broom tick, rebar) placed horizontally across the top of a bucket.
2. Place the sensor and rod in the bucket, positioning it at least 3 inches from the sides and bottom of the bucket.
3. Let the sensor sit in the bucket for 5 to 10 minutes to allow all water movement to cease.
4. Set the filter value to 5 seconds.
5. Initiate the zero start sequence by pressing the STO and RCL button at the same time. The number 3 will appear on the screen.
6. Decrement to zero with the down arrow button. The number 32 will appear.
7. The unit will decrement itself to zero and turn off. The unit is now zeroed and ready for field use.
8. Zero stability equates to a ± 0.05 ft/sec (0.012 m/sec) reading.
9. Note: each button in this sequence must be pressed within 5 seconds of the previous one. If the time between button entries is longer than 5 seconds or an incorrect button is pressed during the sequence, the unit will display an ERR 3 reading. Turn the unit off and on and start the sequence again.

Operation

The Flo-Mate has two operating modes: Real-Time and Recall. In the Real-Time mode, current velocity readings are displayed and the ‘period bar’ is dynamic based on the set filter time (Figure 1-1). In the Recall mode, velocity readings are displayed from memory and the period bar is static.

The meter always powers up in Real-Time mode, and proceeds through the sequence shown in Figure 1-1. The software version is displayed first, and then the meter runs through a segment test. When the test is complete, the unit displays the current velocity reading. If the sensor is out of the water, a ‘conductivity lost’ flag appears and there is a dashed line in place of the velocity reading. If the battery is low, a ‘low battery’ flag is displayed. If the battery voltage is adequate, no flag appears. Extra batteries should always be carried in the field and this is particularly important during cold weather.

In Real-Time mode, the user can select or change various settings including units (English/metric), filter time (set time period for integrating a velocity reading), and type of integrated reading (Fixed Point Averaging or Time Constant Filter). The user manual should be consulted for a complete list of settings and options.

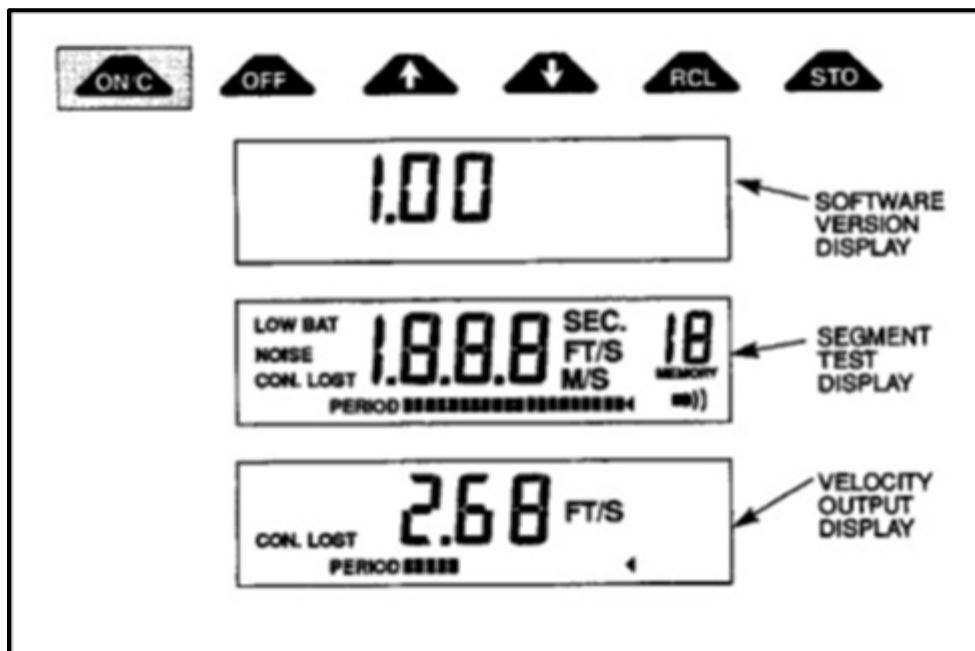


Figure 1-1. Start-up sequence display for the Marsh-McBirney Flo-Mate flowmeter. Once the unit has completed a segment test, the current velocity readings and units will be displayed. The period bar will be dynamic based on the filter time entered in seconds.

Although most GRYN data are recorded using the metric system, discharge measurement can be recorded using English or metric units, but discharge is summarized using English units in cubic feet/second (ft^3/s or cfs) to maintain consistency with USGS Water Data for the Nation (<https://waterdata.usgs.gov/nwis>). To simplify these calculations GRYN recommends that measurements (depth, width, and velocity) are also summarized using English units. To set the flowmeter to record velocity in English units (ft/s), press the OFF and ON buttons simultaneously and scroll through the settings to select ft/s.

The fluid dynamics surrounding the sensor often cause velocity readings to fluctuate, making it difficult to assign a single true reading. The Flo-Mate offers two methods of stabilizing velocity readings: Fixed-Point Averaging (FPA) and Time Constant Filtering (rC). These methods dampen the velocity readings based on a filter time period (FPA: 2-120 seconds; rC: 2-30 seconds). Press the up and down arrow buttons simultaneously to move between these two settings.

The FPA method is the preferred setting for GRYN velocity measurements. When switched to that setting, the display will read FPA and the velocity output will be updated at the end of each averaging period based on the set filter time. If the flow is relatively calm and uniform, the filter should be set to **45** seconds. If the flow is more irregular, the filter should be set to **90** seconds. The

filter time should be set to the flow conditions requiring the most time within a cross-section. While it is possible to reset or adjust the filter time as needed in the midst of a channel cross-section, it is easier and safer to select a filter time that accommodates the range of channel conditions before beginning the cross-section profile. The user may decide to adjust the recommended filter times (above) as needed.

To set the filter time, press the up arrow button and then use the up or down arrow to set the time in seconds. Be sure to record the filter time on the data sheet.

Note: filter times may vary on the same reach based on the seasonal/annual hydrograph. The rising limb of the hydrograph may require a longer filter time, whereas low flow or base flow conditions may require a shorter filter time.

Wadeable Discharge Datasheet

The master datasheet for wadeable discharge measurement is an Excel file called the *GRYN_wadeable_discharge_sheet_2017_V1* (Figure 1-2), located at *U:\Monitoring\Active_Vital_Signs\Water_Resources\Protocol\Discharge_Measurement* on the GRYN server.

Before leaving for the field, this file should be opened and renamed using the ‘save as’ option and the following naming convention: the waterbody code_Q_date (yyyymmdd). For example, a discharge measurement made at Lower Layout Creek (LCR2) on 12 August 2015 should be labelled *LCR2_Q_20150812*.

The file contains three relevant worksheets – *wadeable_rep1*, *wadeable_rep2*, and *wadeable_rep3* for an original and replicate measurement of discharge and a third worksheet used to characterize discharge if there is a relative difference greater than 10% between the replicate measurements (*wadeable_rep1* and *wadeable_rep2*). The worksheets can be printed out on Rite-in-the-Rain paper, included in field gear, and later entered into the digital spreadsheets. Because the electronic versions populate automatically, it can also be useful to enter the data directly using the field laptop.

Wadeable

FILE HOME INSERT PAGE LAYOUT FORMULAS DATA REVIEW VIEW

Paste Cut Copy Format Painter Clipboard Font Alignment Number Conditional Form Formatting Tab

Calibri 11 A A Wrap Text Merge & Center \$ % , .00 →.0

160

1 **GRYN Wadeable Stream/Spring Discharge Worksheet** **Version 1.0** **2/28/2017**

2 **Park:** **Date:** **Observer:**

3 **Stream/Spring:** **Time:** **Recorder:**

4 **Site:** **Replicate#:**

5 **Staff Reading:** **Flowmeter:**

6 **Flow Severity:** **Filter Time (sec):**

7 **Hydrograph Limb:** **Weather Conditions:**

8 **Total Channel Width:** **RWE:**

9 **# cells:** **LWE:**

10

11

12 **Distance** **Depth** **Depth** **Velocity** **Q** **% of total Q**

13 **ft** **ft** **0.6 ft** **0.8 ft** **0.2 ft** **v 0.6** **v 0.8** **v 0.2** **v avg** **ft/s** **ft/s** **ft/s** **ft/s** **ft/s** **ft/s**

14 **Wetted Edge** **0** **0.6 ft** **0.8 ft** **0.2 ft** **ft/s** **ft/s** **ft/s** **ft/s** **ft/s** **ft/s** **ft/s** **ft/s** **ft/s** **ft/s**

15 **cell 1** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0**

16 **cell 2** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0**

17 **cell 3** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0**

18 **cell 4** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0**

19 **cell 5** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0**

20 **cell 6** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0**

21 **cell 7** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0**

22 **cell 8** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0**

23 **cell 9** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0**

24 **cell 10** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0**

25 **cell 11** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0**

26 **cell 12** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0**

27 **cell 13** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0**

28 **cell 14** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0**

29 **cell 15** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0**

30 **cell 16** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0**

31 **cell 17** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0**

32 **cell 18** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0**

33 **cell 19** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0**

34 **cell 20** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0**

35 **cell 21** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0**

36 **cell 22** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0**

37 **cell 23** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0**

38 **cell 24** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0**

39 **cell 25** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0**

40 **cell 26** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0**

41 **cell 27** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0**

42 **cell 28** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0**

43 **cell 29** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0**

44 **cell 30** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0**

45 **Total Q:** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0** **0**

46

47

48 Discharge estimates from reps 1 and 2 should be within **10%** of each other. If the values are not within **10%** of each other take a 3rd measurement and average the 3 measurements.

49

50 **Rep1 (cfs):** **0** **Rep1 and Rep2**

51 **Rep2 (cfs):** **0** **% Difference:** **#####** **3rd Replicated Needed:**

52 **Rep 3 (cfs):** **0**

53

54

55

Figure 1-2. Electronic field form for calculating discharge in wadeable streams and spring outflows. Most cells are populated automatically when the highlighted cells are filled in.

Measurement Techniques

The discharge measurement field techniques presented in this section are based on methods described by the USGS (Rantz 1992). As stated above, a cross-section of the stream is selected and is initially divided into at least 20 increments (cells). Cell width (w), cell water depth (d), and stream velocity (v) are recorded at each cell. Depth and velocity measurements should be taken at the cell midpoint (Figure 1-3). The techniques described in this SOP require a Marsh-McBirney Flo-Mate flowmeter, a top-setting rod, and a measuring tape. A checklist of additional field gear needed to conduct a wadeable discharge measurement is listed below.

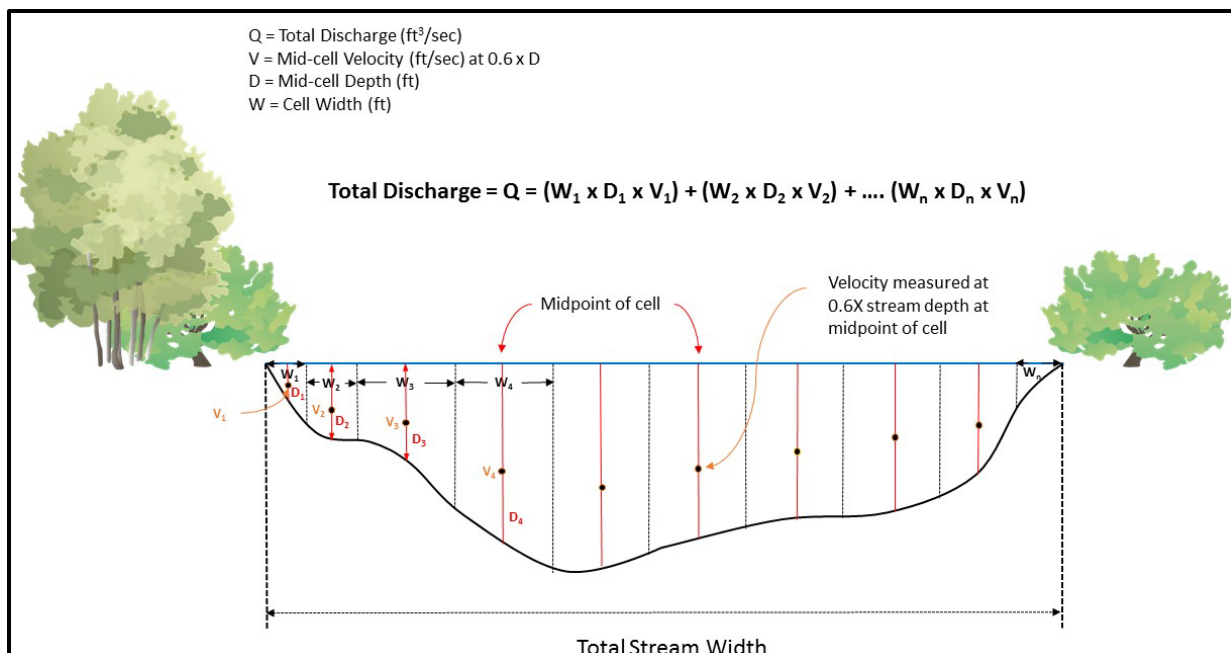


Figure 1-3. Simplified illustration of the technique for calculating discharge through a series of width, depth, and velocity measurements and application of techniques described in this SOP.

Checklist of field equipment and supplies needed for wadeable discharge measurements in GRYN parks.

- ☐ Top-setting wading rod
- ☐ Marsh-McBirney Flo-Mate digital flowmeter
- ☐ Open reel measuring tape (English units in tenths of feet)
- ☐ Stakes/rebar (for anchoring tape to each bank)
- ☐ Calculator
- ☐ Extra D-cell batteries (4)
- ☐ Hard copy of datasheets (3 per site)
- ☐ Rating curve (if available)
- ☐ Floating objects
- ☐ Stopwatch/timer
- ☐ Camera
- ☐ Park radio with extra battery
- ☐ SPOT
- ☐ First aid kit
- ☐ Bear deterrent spray
- ☐ Personal flotation device (1 for each observer)
- ☐ Multi-tool
- ☐ Personal gear for field crew

Field personnel are required to wear personal floatation devices (PFDs) while conducting discharge measurements. If flow conditions appear to be unsafe (i.e., flow appears unwadeable or lots of debris in channel) or if excessive precipitation or runoff are expected, do not attempt a stream crossing. Instead, try to obtain velocity readings using the alternative techniques described below. Read and follow all safety information and guidelines in the JHAs (see Appendix A in Ray et al. 2017) and in this SOP, including filing a plan with Park dispatch or resource staff to inform them of your location and intended field work.

Selecting a Site

If a Rating Curve Already Exists

If a rating curve has been developed for a site within a stream or spring outflow, make an observation near the staff gage site. Read the staff gage and estimate the discharge for the reach using the known rating curve equation. Use this as a guide to determine how many cells were used previously to adequately characterize discharge in a stream or spring outflow. Each cell should represent approximately 5%, but no more than 10%, of the total discharge. As a rule, 20-25 cells will be required to characterize discharge in most wadeable waters in GRYN parks.

The selected cross-section should be in reasonable proximity to the staff gage to avoid the need for adjusting measured discharge based on the rating curve developed for the gage site. However, a distance of approximately 0.5 mile (approximately 0.75 kilometer) between the gage and the selected cross-section is acceptable if necessary to provide both a good stage-measurement site and a good discharge-measurement site (Rantz 1992).

If a Rating Curve Does Not Exist

If the measurement is to be obtained from a site where there is no pre-existing rating curve, the selected channel cross-section should be fairly uniform in depth, and flow should be parallel to the banks and fairly uniform throughout the cross-section.

General guidelines for site selection, adopted from Rantz (1992), suggest that

- the general course of the stream or spring outflow should be straight for approximately 300 feet (approximately 100 meters) upstream and downstream from the selected cross-section (i.e., not on the inside or outside of a bend);
- the total flow should be confined to one channel (when possible) at all stages, and no flow should bypass the site as subsurface flow;
- the streambed should be free of aquatic macrophytes, and not subject to scour and fill;
- the banks should be permanent, high enough to contain floods, and relatively free of overhanging vegetation;
- unchanging natural controls should be present in the form of a bedrock outcrop or other stable riffle for low flow and a channel constriction for high flow; and
- reaches with obvious bed irregularities, such as large boulders, should be avoided.

Some rivers and streams in GRYN parks do not conform to these guidelines (e.g., portions of Soda Butte Creek). In braided sections of these streams, we will attempt to select uniform cross-sections with a stable bottom and complete discharge estimates in each braided channel. These separate discharge estimates will be summed to estimate total discharge for a location.

Dividing the Cross-Section Width into Cells

After selecting the best cross-sectional site within a reach, measure first the wetted width of the channel at the site.

- If the channel is relatively narrow and the flow is calm, use a measuring tape to determine the channel width. Stretch the tape across the channel and secure it on each bank. Record the right and left wetted edge (looking downstream) and document the total ‘wetted’ channel width to the nearest tenth of a foot.
- An alternative to using a measuring tape to measure the total channel width of a large wadeable channel is using a range finder. If no obvious markers exist at the waterline, sight on objects that are on the shore, but be sure to subtract the extra distance from the total width. Failure to do so will result in an overestimate of discharge.

Next, divide the total width into 20-25 evenly spaced cells (Figure 1-3).

Note: in a channel with an irregular depth profile, cell width may vary as deeper cells should be sampled more frequently.

Measuring Cell Depth and Velocity

All velocity measurements are based on the total depth within each cell. Therefore, the depth must be measured and recorded first. Velocity is measured by the flowmeter at a single point. However, discharge is based on the ‘mean vertical velocity’ within each measured cell. Mean vertical velocity is derived from the depth-integrated measurements within the vertical profile. It can be estimated from several velocity measurements using established quantitative relationships.

Estimating Mean Vertical Velocity

The USGS recognizes six methods for estimating mean vertical velocity using quantitative relationships. The ‘vertical-velocity curve method’ is the most labor intensive and is the basis for coefficients used by other methods that are more common and less labor intensive. The ‘two-point method’ involves recording velocities at 0.2 and 0.8 of the total depth in a given cell. These values are averaged to estimate the mean vertical velocity. This method, relative to those described below, provides the most consistent and accurate results (Buchanan and Somers 1968) and is the one used most frequently by the USGS. This method is not used in waters ≤ 2.5 feet (0.76 meters) deep because the sensor is too close to the surface and the bottom to provide accurate readings in shallow water conditions. In conditions where depths are ≤ 2.5 ft, the ‘six-tenths-depth method’ is used. The other three methods used by the USGS are for measuring velocity in more complicated situations. GRYN will avoid cross-sections where we cannot employ the ‘two-point method’ and ‘six-tenths-depth method’ techniques described below.

Two-Point Method

In brief, the ‘two-point method’ requires three measurements per cell; the total depth in the cell, and the velocities at 0.2 and 0.8 depths from the water surface. For example, if the total depth measurement was 5 ft, velocity would be recorded at 1 ft and 4 ft below the water surface. The two velocity values are then averaged to estimate mean vertical velocity. This method is based on both field observations and mathematical theory explained in Buchanan and Somers (1968).

Six-Tenths-Depth Method

The ‘six-tenths-depth method’ will be used most commonly in the shallow, wadeable waters of GRYN parks. This method requires two measurements per cell: the total cell depth and the velocity at 0.6 depth (see Figure 1-4) from the water surface. This method is used when the total depth is ≤ 2.5 ft, or the water depth is changing rapidly and there is not enough time to measure velocity accurately using the two-point method.

Using the Wading Rod to Determine Various Depths

The top-setting wading rod consists of a sliding rod incremented in feet and a depth gage rod incremented in tenths of feet (Figure 1-4). The top of the depth gage rod has a plate with a tenths scale from 0 to 10. The double lines on the body of the depth gage rod indicate half-foot increments and the single lines represent tenths of a foot. Each fractional depth (0.6, 0.2, and 0.8) can be determined based on the total depth by moving the sliding rod as described below.

Note: the wading rod and flowmeter can be unwieldy to carry, even in calm channel conditions. Therefore, in the interest of safety, the recorder should stay as close as possible to the wader/observer (i.e., within earshot) and make calculations and call out distances.

Total Depth

Place the depth gage rod firmly on the substrate. Holding the rod in a vertical position, use the double and single increment lines on the depth gage rod to measure the total water depth in tenths of a foot (e.g., 2.7 ft in Figure 1-4).

0.6 Depth

Line up the foot scale of the sliding rod with the tenths scale on the top of the depth rod to match the total depth value. For example, if the total depth is 1.7 ft (as in Figure 1-4), align the 1 ft mark on the sliding rod with the 7 tenths mark on the top of the depth rod.

0.2 Depth

To calculate 0.2 depth, multiply the total depth by 2 and repeat the above process with that value. For example, if the total depth is 2.7 ft, then $2 \times 2.7 = 5.4$. In this example, you would then match the 5 ft mark on the sliding rod with the 4 tenths mark on the top of the depth rod.

0.8 Depth

To calculate 0.8 depth, divide the total depth by 2 and repeat the above process. For example, if the total depth is 2.7 ft, then $2.7/2 = 1.35$ and you would match the 1 ft mark on the sliding rod to a point halfway between the 3 and 4 tenths marks on the top of the depth rod.

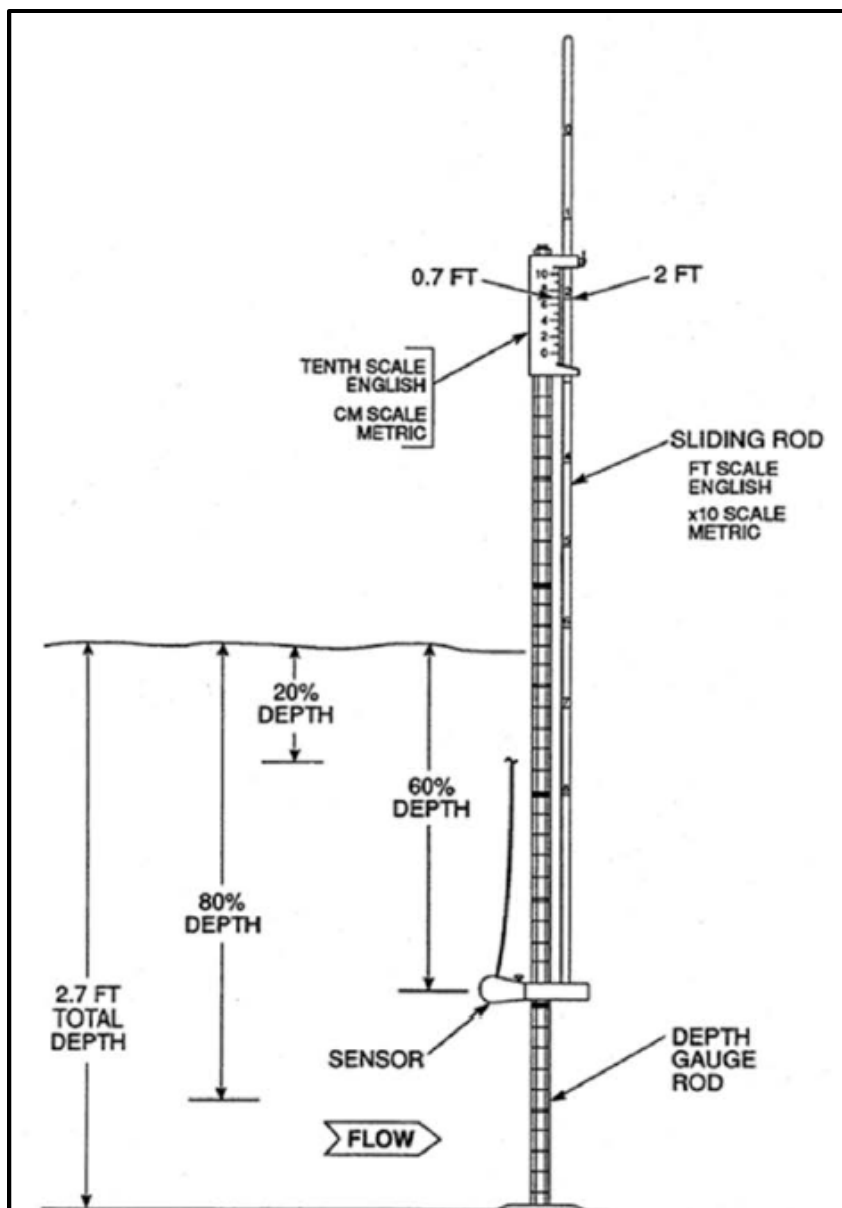


Figure 1-4. Illustration of a top setting wading rod. The technique for setting the flowmeter sensor at 0.6 (e.g., six tenths), 0.2, and 0.8 of the total depth are shown.

Measuring Velocity

The recorder should complete the information section of the datasheet (Figure 1-2). Noting the hydrographic limb and weather conditions will be helpful for comparing readings through time for a given site. If the team is using a range finder, the recorder should operate the range finder and guide the observer to the next cell midpoint. Most work in GRYN parks will be accomplished using a tape and the observer will locate the midpoint of the cell visually from the tape.

The observer should check to see that the flowmeter is ready to operate (i.e., the sensor is connected to the wading rod; the batteries are adequate; the units are set to feet/second; fixed-point averaging is selected; and the filter is appropriate for flow conditions).

1. Starting on the near shore, determine the midpoint of the first cell. For example, if the wetted width (total width of the wetted channel) is 50 feet and the number of cells is 20, then each cell width is approximately 2.5 feet and the first observation point is at 1.25 feet from the shore. Each subsequent measurement is 2.5 feet from the previous point. This will place the observation points at the center of each cell (Figure 1-3).
2. If the observer is using a measuring tape, follow the tape out to the proper position.
3. Once positioned at the desired location on the cross-section, the observer positions the wading rod to measure the total depth of the cell and calls out the value to the recorder. Based on this depth, decide which vertical velocity method to use.
4. If the six-tenths method is employed (most common for GRYN sites), no calculations are required. The observer can simply position the sensor by moving the sliding rod as described above, take a velocity reading, and call out the value to the recorder.

Note: prior to taking the reading, orient the sensor so it faces upstream, and be sure to stand downstream and to the side of the sensor to avoid inhibiting the flow.

5. If the two-point method is used, the recorder should calculate the 0.8 depth using the method described above and call out that depth to the observer. The observer adjusts the wading rod, makes a 0.8 depth reading, and calls out the velocity to the recorder. The recorder then calls out the 0.2 depth and the observer again adjusts the wading rod, makes a second velocity reading, and calls out the value.
6. Once the readings have been made, the observer moves on to the midpoint of the next cell.
7. Repeat Steps 2 through 6 until the stream or spring outfall cross-section is completed.
8. The recorder can use the time between velocity readings to calculate the area and discharge for each cell so that an estimated total discharge can be determined. This will enable a prompt comparison of the two discharge values to determine if an additional set (i.e., a third set) of measurements is needed (see Step 11).

Note: if the velocity readings are entered directly into the electronic datasheet on the field laptop, calculations will be done automatically.

9. If the site has a staff gage, take a staff reading after completing each channel cross-section. Be sure to record those readings on the datasheet.
10. If the site is not a gaged site, select a permanent object (large tree, boulder, etc.) and consider recording the UTM coordinates. Measure the shortest distance between the object and the edge of the water line. This will serve as an approximate reference for future discharge measurements until a staff gage can be established.
11. If conditions have remained unchanged (i.e., the stream isn't rising or falling rapidly), repeat the cross-section to obtain a second set of width, depth, and velocity measurements. Check to see whether the discharge values resulting from the two sets of measurements differ by less than 10%. If so, the two discharge values can be averaged. If not, consider increasing the filter time. Take a third set of measurements and average the three discharge values.

12. Establish a permanent photo point of the cross-section and photograph the site. As a rule of thumb, fill 80-90% of the frame with the channel cross-section and 10-20% with the horizon. Photograph the staff gage or permanent marker and any additional points of reference or flow conditions that should be documented.

Using Alternative Techniques

Quantitative measurements cannot always be obtained using the techniques described above. Equipment limitations and safety considerations may hinder wadeability. This usually occurs during storm events and seasonal runoff when discharge is too high to safely obtain cross-section measurements. However, peak discharge or large storm events may be key data points. In these situations, it may be possible to estimate discharge by alternative means. Examples include the 'float velocity method,' in which an object is timed as it floats downstream, and the 'dilution method,' in which a dye or salt plug is injected into the stream and a reading is made downstream of the injection site. The float velocity method is simple to employ and is described below. Additional information regarding the dilution method can be found in Rantz (1992).

Float Velocity Method

If a channel is not safe or suitable to conduct wadeable measurements, the float velocity method provides a reasonable estimate of discharge if the channel is not too wide or too deep (Rantz 1992; Harrelson et al. 1994). A team of two and a known cross-section area (see below) is required to complete this method. Other requirements include a measuring tape, a timer, and 5-10 floats made from natural material that will sink at least half way into the water (e.g., small wooden blocks that have been soaked in water). Inorganic objects (e.g., half-full water bottles) should be avoided as it may not be possible to retrieve them once they are introduced into the flow. For this reason, objects should be biodegradable and expendable.

1. Select a start and a finish point in a reach with good stream channel visibility. The distance between the points should be at least three times the wetted width.
2. Person A, stationed upstream of the start point, should toss the object into the thalweg, move to the start point, and call out when the object crosses that point.
3. Person B, located downstream at the finish point, should start the timer when the object crosses the start point (noted by Person A upstream), stop the timer when the object crosses the finish point, and records the total time elapsed between points. Person B should retrieve the object if possible.
4. Repeat the above two steps 5-10 times.
5. For each run, calculate the velocity (feet/second) by dividing the start-to-finish distance (in feet) by the time (in seconds). Take an average of the 5-10 velocity values.
6. Multiply the average velocity by 0.85 (the velocity adjustment coefficient). This coefficient converts a surface velocity into a corrected, depth-integrated velocity (Rantz 1992).
7. Finally, multiply the corrected velocity by the known cross-section area (i.e., start-to-finish distance (feet) x wetted width (feet) yielding an area in ft²) to estimate discharge (cfs). This

technique can be accurate to $\pm 10\%$ when conducted with attention to detail and under the right circumstances (e.g., relatively straight reach and uniform channel). Accuracy decreases in deep streams and/or high winds.

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SOP 2: Volumetric Discharge Measurements in Developed Springs

Version 1.00, September 2017

Change History

Original Version #	Date of Revision	Revised By	Changes	Justification	New Version #

Introduction

(Adapted from Schmitz et al. 2007 – SOP5 Data Collection of Water Quality Parameters)

Discharge is one of the most defining characteristics of springs and, not surprisingly, has been used to develop a spring classification system (Springer and Stevens 2009). Spring discharge reflects interactions among short- and long-term meteorological conditions, characteristics of recharge capture zones, and the groundwater environment (Schmitz et al. 2007). Discharge is also believed to be one of the first and principal spring parameters to respond to impacts or changes to groundwater and surface water availability (Bernaldez and Rey Benayas 1992; Erman 2004). Discharge measurements are necessary to contextualize changes to physicochemical indicators of spring water quality. Given this, consistent and accurate monitoring of spring discharge is needed to understand short and long-term changes in Greater Yellowstone Network (GRYN) parks (Schmitz et al. 2007).

Measuring Discharge

The method of measuring spring discharge varies with spring type, orifice morphology, and outflow discharge. For seeps, water table depth can be used to indicate changes in water quantity. Water table depth is measured in groundwater wells within or surrounding a seep. For springs that flow into a defined channel and have adequate discharge, an instream current velocity meter can be used (this is described in SOP 1: Discharge Measurement in Wadeable Waters in this document). Finally, discharge monitoring from developed springs with low flow velocities can be measured volumetrically (Weissinger and Moran 2015). For these low flow springs, discharge from a pipe or collected in a weir can be measured volumetrically by funneling discharge into a bucket or collection vessel for a set amount of time (e.g., 30 seconds), sometimes referred to as the ‘bucket method.’ The discharge pipe directs outflow waters to a release point (see photo below) where it can be captured. The duration of flow and the volume of water collected in the bucket, estimated with a graduated cylinder, are used to calculate discharge.



Discharge measurement location for the Mason-Lovell spring at Bighorn Canyon National Recreation Area. December 2012.

Materials

- Large bucket (e.g., 1 to 5 gallon)
- Stop watch
- 1-L graduated cylinder
- Field data form (Figure 2-1)

Procedure

1. Time the flow into the bucket; select a time that allows filling of at least one half of the total bucket volume. Then measure its volume with a 1-L graduated cylinder.
2. Record the volume and time in the Field Data Form (see Figure 2-1).
3. Repeat four times.
4. The average of the four trials will be entered into AQUARIUS for rating curve development.

[illegible]

Figure 2-1. Electronic field form for volumetric discharge measurements of spring outflows. Most cell are populated automatically when the highlighted cells are filled in.

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SOP 3: Rating Curve Development in AQUARIUS from Automated Water-Level Measurements

Version 1.00, September 2017

Change History

Original Version #	Date of Revision	Revised By	Changes	Justification	New Version #

Introduction

Deriving empirical relationships between stream stage (i.e., surface or ground water level) and discharge estimates is critical to development of continuous discharge estimates for rivers, streams, and springs. The U.S. Geological Survey (USGS) has successfully developed rating curves for USGS-gaged waters shown in Tables 2 and 3 of the Greater Yellowstone Network (GRYN) Protocol Implementation Plan (Ray et al. 2017) and for waters across the U.S. For un-gaged waters, rating curves can be developed using a combination of discrete discharge estimates (described in SOP 1 for wadeable waters and SOP 2 for volumetric measurements of developed springs). Development of rating curves for un-gaged rivers, streams, and spring discharges is needed to characterize short and long-term changes in GRYN parks.

Rating Curve Development

Stage-discharge relationships can be developed for monitoring locations when regular site visits involving the simultaneous observations of stage and discharge are carried out. These relationships can be expressed as a rating table, rating equation, or, more commonly, a rating curve (Gordon et al. 2004). Rating curves typically involve many measurements (>30) across a range of flow conditions and over several years. Conventional rating plots include measurements of discharge on the x-axis and stage on the y-axis. If the relationship is strong, the resulting relationship on an arithmetic scale is parabolic; using a log-log plot, strong stage-discharge relationships will be linear. In stream cross-sections that are relatively stable, the stage-discharge relationship will remain relatively fixed. However, scouring or other changes to a stream channel could cause shifts to a rating curve. Sand-bottomed channels are known to change during high and low flow conditions and associated stage-discharge relationships require regular updates.

Here we describe the use of AQUARIUS software (Aquatic Informatics™ Inc., Vancouver, British Columbia) for the development of rating curves. Rating curves can also be developed using other software tools (e.g., Graphical Rating and Shift Application Tool [GRSAT]), however, our approach follows tools built within the AQUARIUS environment and described by Aquatic Informatics

(<https://na32.salesforce.com/a06?fcf=00B50000006dCHb>). Readers are encouraged to review all training videos provided through Aquatic Informatics to get a complete list of capabilities associated with the Rating Curve Development Toolbox in AQUARIUS.

Importing Raw Data into AQUARIUS

Use the AQUARIUS Whiteboard environment to import raw automated measurements into AQUARIUS. Double click on Import from File tab in the Whiteboard environment. An Import from File icon that takes you to the Import from File Toolbox panel will appear on the whiteboard (Figure 3-1).

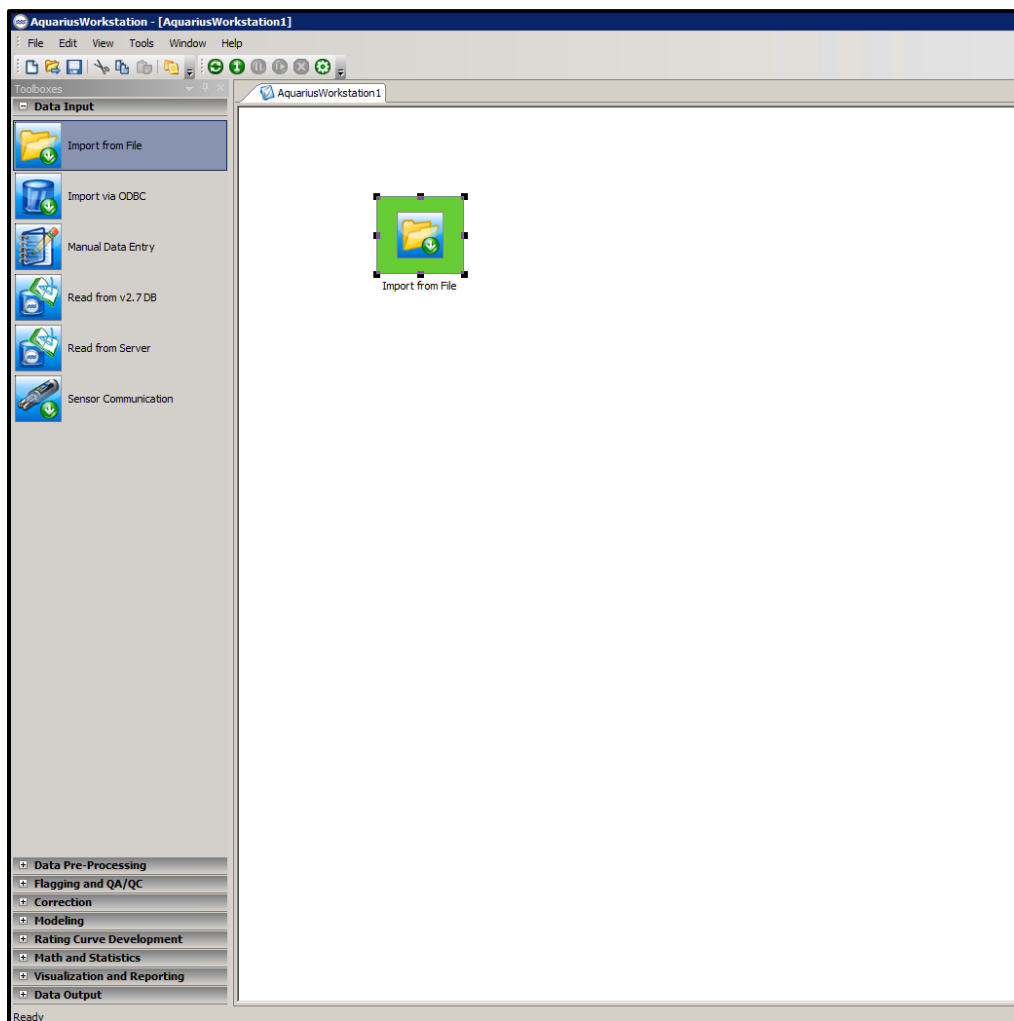


Figure 3-1. AQUARIUS Whiteboard with Import from File toolbox icon. Double-click this icon to load time series data and rating curve measurements used for developing a rating curve.

This toolbox will allow you to import a times series; in our case, we will import a time series associated with automated level loggers. A similar approach could be used to incorporate a time series associated with automated flowmeters deployed at un-gaged sites. Time series data can be imported from a file or from a previously saved Whiteboard session. You will also need to import

your rating measurements or your combined stage and discharge measurements. Raw files should be imported in a .csv format and configuration files (.cfg) will be created for both the time series data and for the rating measurements.

Load both the .csv and .cfg files by clicking the Load File(s) button in the Import from File Toolbox panel. If loaded, a summary of the time series file will be displayed in the lower right pane of the toolbox (Figure 3-2). In this example, a total of 1,528 samples loaded from automated daily stage measurements from upper Layout Creek in Bighorn Canyon National Recreation Area (NRA) are shown.

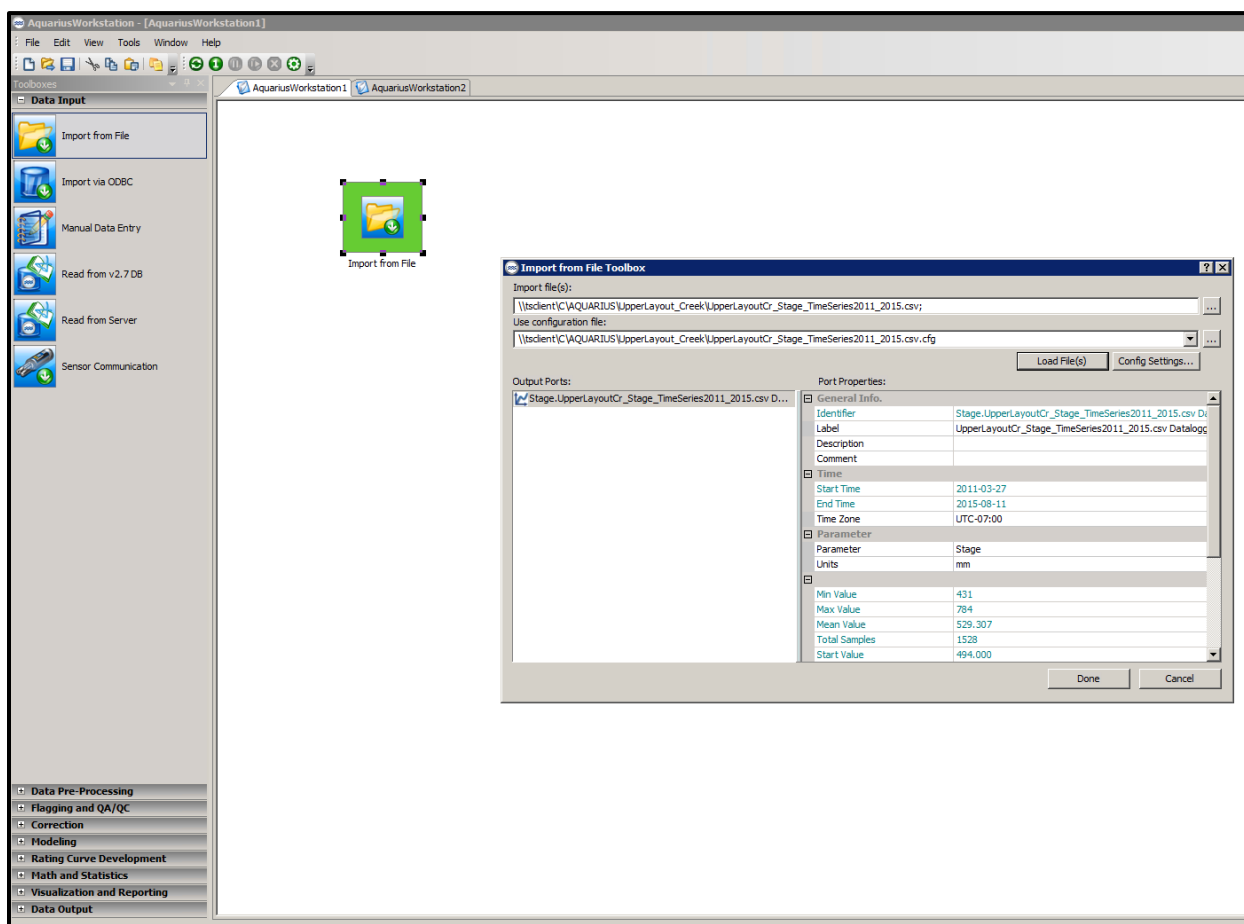


Figure 3-2. Import from File Toolbox panel showing time series file and configuration files were successfully loaded. The lower right pane of the toolbox provides a brief summary of the loaded file.

As mentioned earlier, load the manual rating curve measurements of stage and discharge associated with the automated stage time series (described above) as a .csv file. This time, however, make sure to create a configuration file that is for Rating Measurements (see Figure 3-3).

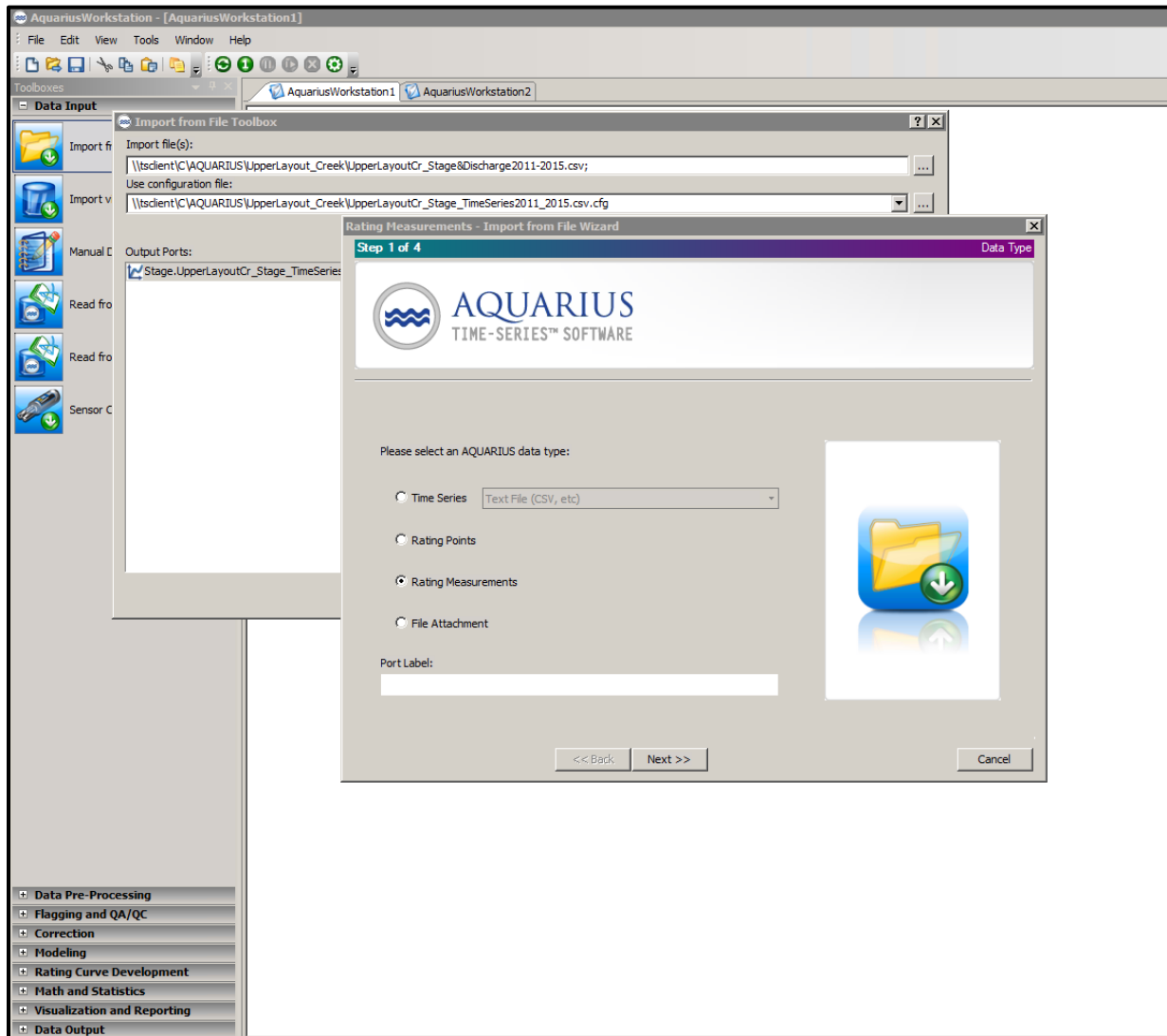


Figure 3-3. Import from File Wizard reflecting a Ratings Measurement data type needed for developing a rating curve. After you select Rating Measurements click Next and characterize the configuration of your .cfg file.

Once the time series stage data and the rating measurement data have been loaded, wire the data into the Rating Curve Development Toolbox (Figure 3-4). In brief, wiring is accomplished by putting the cross-hairs of the cursor on the desired time series data output ports (shown on the right side of the Import from File toolbox icon) and right-clicking on the selected time series. Once you've selected the time series, move your cursor to the desired input ports of the Rating Development icon.

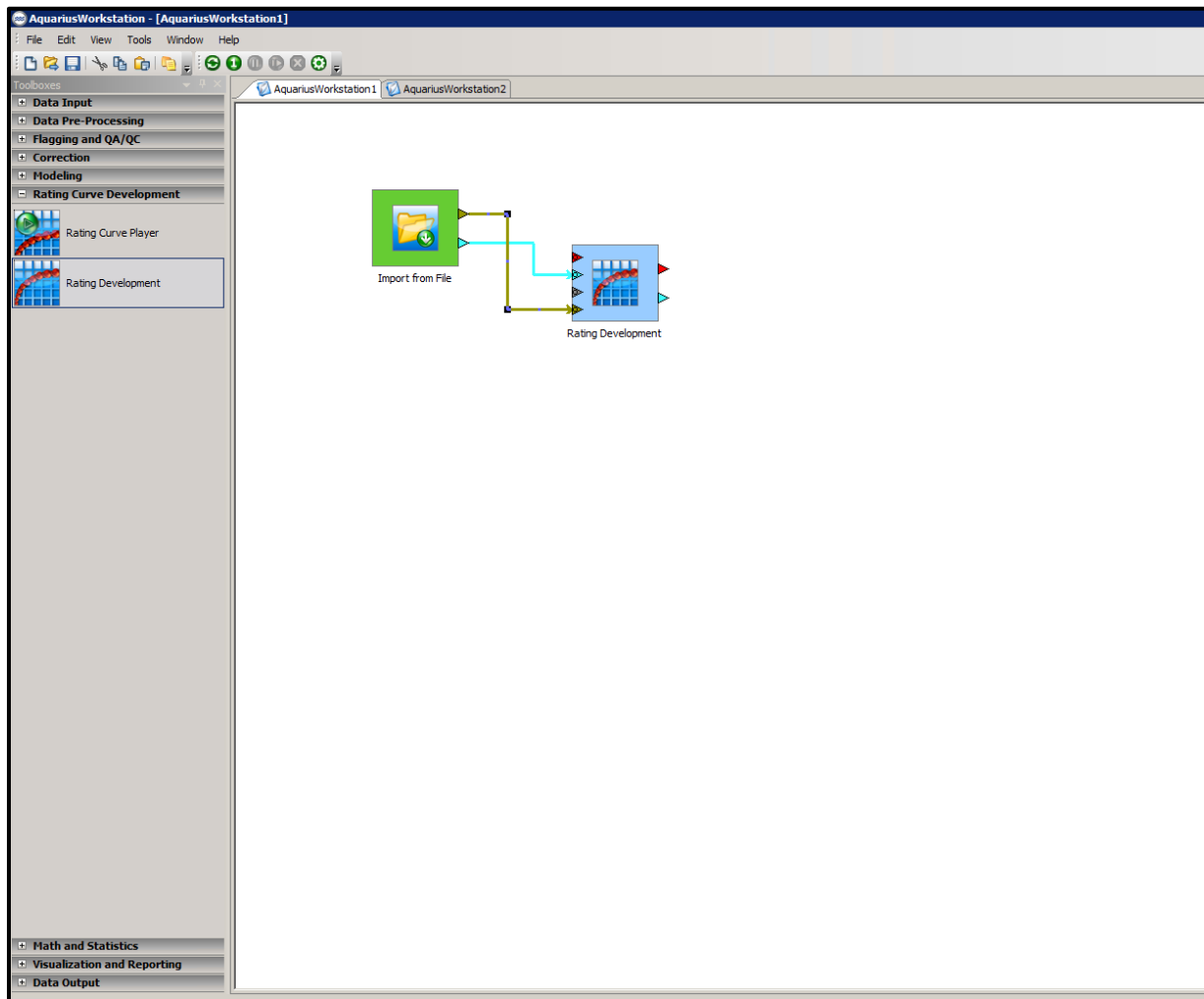


Figure 3-4. Once loaded, time series stage data and rating measurements should be wired into the Rating Curve Development Toolbox.

Developing a Rating Curve

Once your data have been wired into the Rating Curve Development Toolbox, double click on the Rating Curve Development icon. The Rating Curve Development Toolbox will open and display your rating measurement data (Figure 3-5). In the toolbox it is possible to quickly scan through your rating curve measurements in the Rating or Time Series views. Using this function, outliers or suspect points can quickly be identified and flagged using the ratings views.

This display also makes it possible to determine whether low flow and high flow measurements can be incorporated into a single rating curve or, alternatively, if they require multiple curves to more accurately portray the physics of a given cross-section. The AQUARIUS Rating Curve Development Toolbox allows you to parse your data by ‘turning on’ or ‘turning off’ rating measurement values that are associated with one or multiple curves. This same approach can be used to ‘turn off’ suspect or flagged data that would not aid in developing the relationship between manually measured discharge estimates (see SOPs 1 and 2) and automated stage measurements.

For our example with upper Layout Creek in Bighorn Canyon NRA we will use all of the rating measurement points collected between 2011 and 2015 and shown in Figure 3-5.

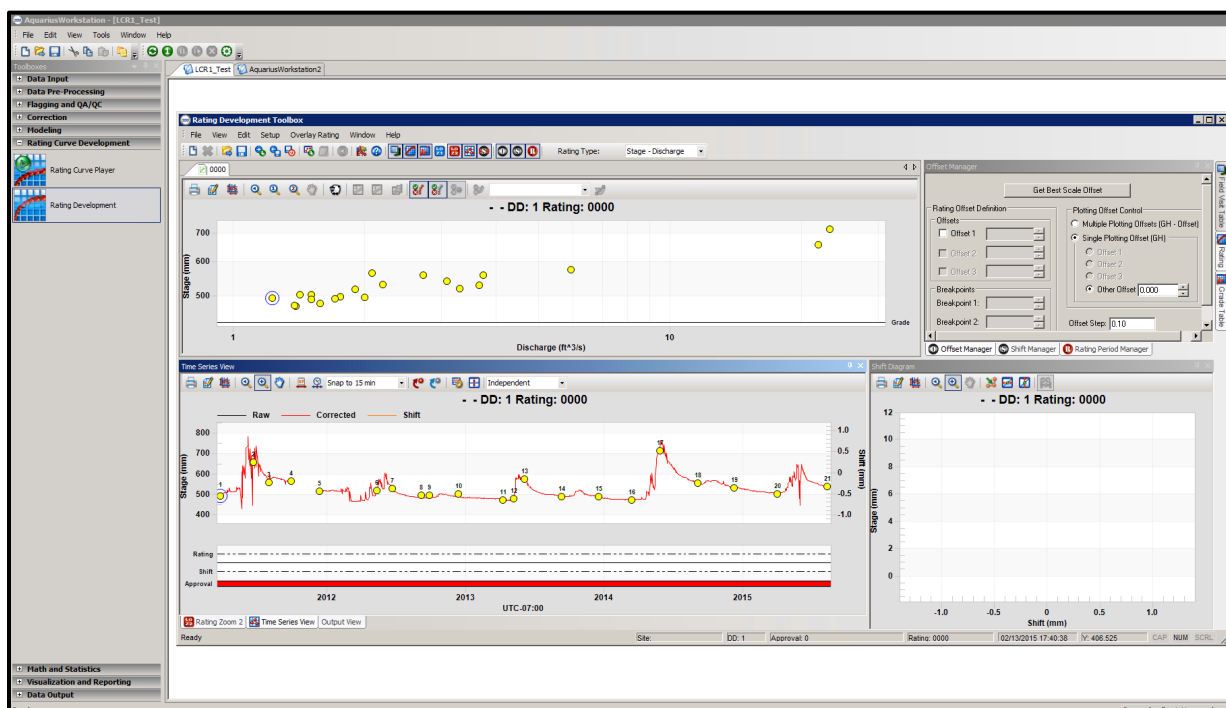


Figure 3-5. Rating Curve Development Toolbox showing rating measurements for upper Layout Creek in Bighorn Canyon NRA. The lower left pane shows the continuous time Series (stage data in red) and individually identified discrete measurements in yellow.

An important initial step in developing a rating curve in the AQUARIUS rating curve environment is estimating the offset for the automated stage (i.e., level logger) recorder. The offset or y-intercept is used to adjust the stage value to an arbitrary datum so that a stage that represents a discharge of 0 ft^3/s can be estimated. A tool within AQUARIUS's offset manager can be used to calculate an offset using the Get Best Scale Offset button in the Offset Manager pane. This tool is designed to assist in estimating the offset using the rating measurements. A rough estimate of the offset can also be determined by plotting your data and carefully examining where a best fit trend line (in log-log space) intersects the y-axis.

Once an initial estimate of the offset has been determined, fine adjustments to the offset value can be attempted to best portray a straight line between the rating measurements (again in log-log space). These minor adjustments to the offset will allow you to minimize the distance (residuals) between the rating measurements and produce a best fit line or rating curve to the rating measurements. You can use the statistic box to visualize how adjustments to the offset and the linearization of the data affect your root mean square error. For the upper Layout Creek example, an offset of 383 mm was used as offset for the lower set of discharge measurements or measurements below a discharge of 2.2 ft^3/s . For this example and for many channelized streams, it appears that the lower set of points or bottom of the rating curve and the upper set up points or top of rating curve are defined by a distinct set of channel physics that define the flow above and below a break point (Figure 3-6).

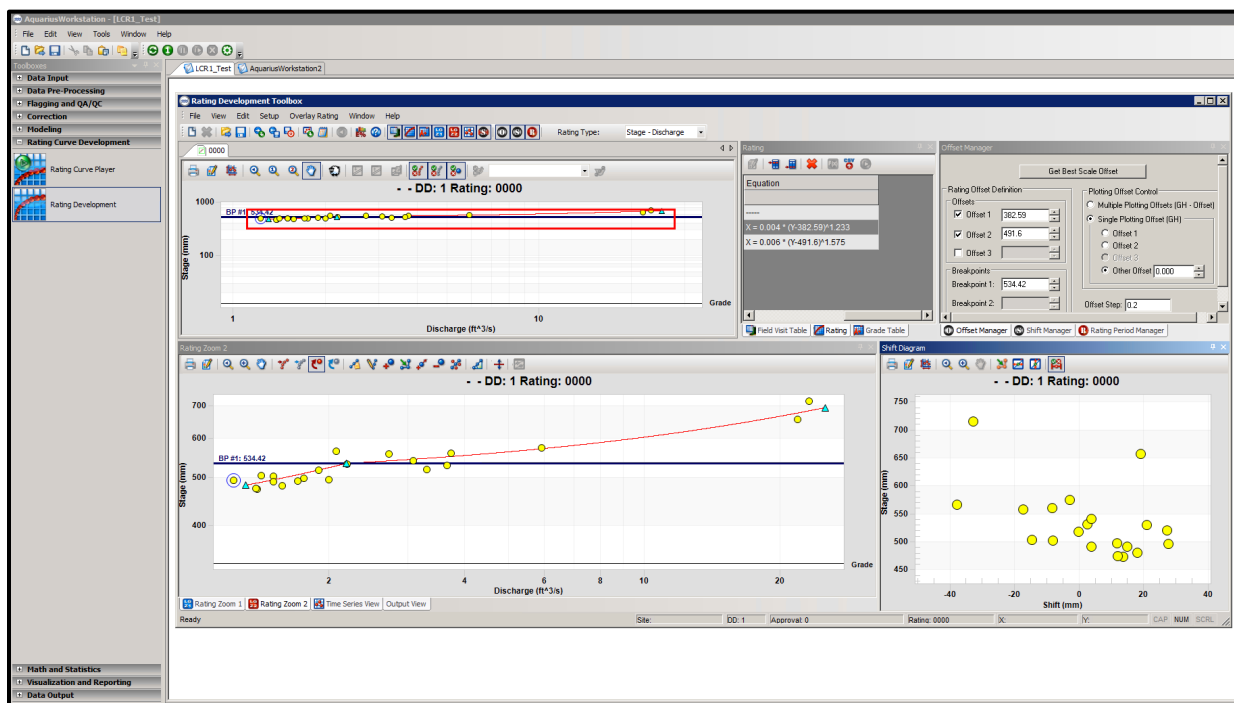


Figure 3-6. Rating Curve Development Toolbox showing rating measurements for upper Layout Creek in Bighorn Canyon National Recreation Area. The lower left pane shows the rating curve and the individual (i.e., discrete) measurements of discharge and stage in yellow. The blue line represents the breakpoint between the lower and upper set of points. The breakpoint shown is at 534 mm stage height or approximately 2.2 ft^3/sec . The Offset Manager pane allows users to define a rating curve separately for the points above and below the breakpoint.

Within the AQUARIUS environment, it is possible to develop a rating curve to best capture the discharge dynamics above and below this breakpoint. Because a second best fit line will be used, another offset will be identified and the breakpoint will be set in the Offset Manager pane. These breakpoints need to be defined by rating curve measurements. In the case of upper Layout Creek a break point above and below 534 mm stage height (or approximately 2.2 ft³/s) was set and it represents the lower bound of the upper rating measurements. As was noted previously, fine adjustments to the second offset can be used to help linearize the data that makes up the upper portion of the rating curve in log-log space.

Once final adjustments to the offsets have been made, best linearize measurements in each section of the rating curve (using the rating curve error statistics that minimize error); the rating equations for the two sections of the rating curve is displayed in the Rating pane (Figure 3-7). For upper Layout Creek the lower end of the rating curve is characterized by the following equation:

$$\text{Discharge (cfs)} = 0.004 * (\text{Gage Height} - 382.59 \text{ mm})^{1.233}$$

The upper end of the rating curves is characterized by the following equation:

$$\text{Discharge (cfs)} = 0.006 * (\text{Stage Height} - 491.6)^{1.575}$$

Using the derived rating curve equations and the identified breakpoint determined in the AQUARIUS environment, time series records of stage (or other automated discharge surrogates) can be readily converted to time series estimates of discharge using Microsoft Excel. This approach can be applied to develop rating curves for waters in GRYN parks that lack USGS or U.S. Bureau of Reclamation (USBR) gages. Data and derived rating curves can be stored in AQUARIUS and exported to Microsoft Excel.

Additional tools, such as incorporating temporary shifts in the rating curve associated with environmental or biological features which temporarily alter the stage-discharge relationship (e.g., ice or woody debris accumulation), allow users to address short term changes to an established rating curve. Tools to address temporary shifts are not described here but available in the AQUARIUS environment.

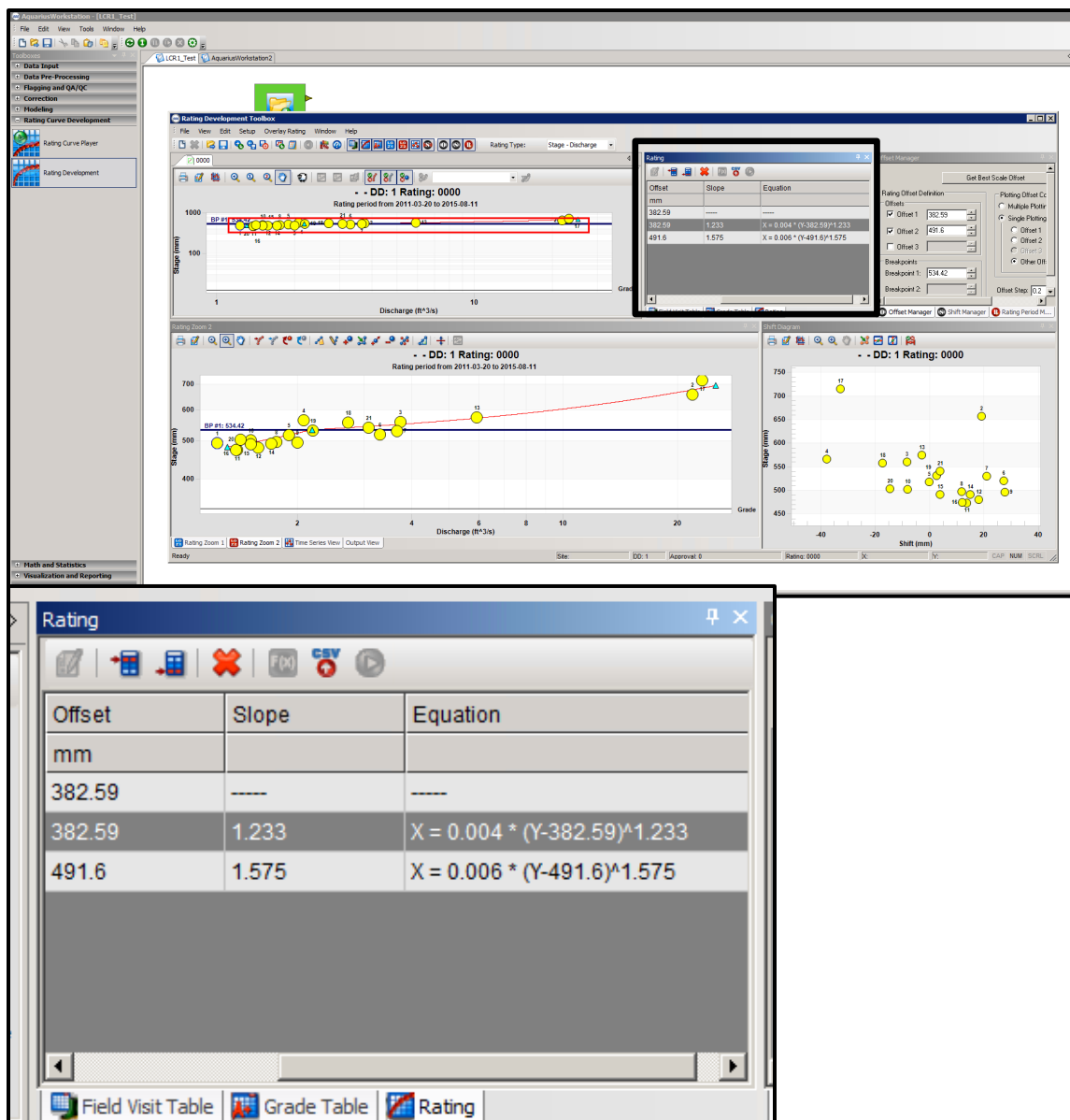


Figure 3-7. Rating Curve equation pane showing rating curve equations for the upper and lower portions of the upper Layout Creek rating curve for Bighorn Canyon NRA.

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SOP 4: How to Analyze, Track, and Report USGS Discharge Data

Version 1.00, September 2017

Change History

Original Version #	Date of Revision	Revised By	Changes	Justification	New Version #

Introduction

Documenting trends in discharge metrics is necessary to understand long-term and recent change in flow patterns for an individual river, stream, or spring or for flowing waters throughout a park, network, or region. Several studies have demonstrated the use of regression analysis to quantify regional changes in flow (e.g., Luce and Holden 2009; Madej 2011; Al-Chokhachy et al. 2017 as examples). Regression models can help document change in U.S. Geological Survey- (USGS) and National Park Service- (NPS) gaged rivers, streams, and springs in Greater Yellowstone Network (GRYN) parks.

The need for documenting changes in discharge patterns of lotic systems is increasingly important since nearly one fourth of all U.S. rivers (USGS 2005), 70% of rivers in the Pacific Northwest (Luce and Holden 2009), 89% in the Northern Rockies (Leppi et al. 2012), and a preponderance of sites in the Greater Yellowstone Area (Al-Chokhachy et al. 2017) have experienced changes in annual flow patterns. In the Greater Yellowstone Area, earlier peak flows, reductions of summer baseflows, declines in winter ice, and decreases in total annual flows were common among USGS-gaged rivers and streams. Additionally, the rate of change was faster for many of these metrics in recent decades relative to long-term (century-long) change (Al-Chokhachy et al. 2017).

Analysis

To evaluate temporal trends in river, stream, and spring discharge, both least squares and quantile regression approaches will be employed (Luce and Holden 2009; Al-Chokhachy et al. 2017). Discharge metrics (Table 4-1) employed as part of the GRYN Protocol Implementation Plan for Monitoring Discharge in the GRYN parks include attributes describing anomalous (e.g., peak discharge) and average conditions (e.g., annual average streamflow). For average conditions and a characterization of mean trends, ordinary least squares regression will be employed. For peak flows (e.g., anomalous flows) and a more careful understanding of 25th, 50th, and 75th percentile of peak flows, we will use quantile regression (Cade and Noon 2003). For each site-metric combination, we will complete a separate regression to test for trends in that metric as a function of year and also test for violations of model assumptions. Analyses are conducted in R System for Statistical Analysis and Graphics (commonly called 'R') and using the lm function and quantreg package (R Development Core Team 2017). The R code for performing analyses in the R script can be found at the end

of this SOP and saved under *U:\Monitoring\Active_Vital_Signs\Water_Resources\Protocol\Data analysis\R_Code* on the GRYN server. Given the high interannual variability in river and streamflow patterns (Stewart et al. 2005) an alpha value of 0.10 will be employed to assess significance of the relationship and minimize the chance of Type II errors (Al-Chokhachy et al. 2017).

Table 4-1. Monitoring metrics, objectives, and methods for GRYN parks based on conceptual models for river, stream, and spring ecosystems (Ray et al. 2017). All metrics will be based on daily estimates of discharge from USGS or from GRYN-managed spring locations.

Discharge Metric	Objective Number	Sampling Method	Data Collected
Instantaneous Discharge	1,2,3	Manual measurement of discharge; estimated from rating curve	Depth and velocity for discharge estimates from channels; volumetric estimates from springs; USGS data summaries from National Water Information System (NWIS)
Date of peak flow	2	Estimated from rating curve	USGS daily data summaries from NWIS; daily discharge summaries GRYN produced rating curves
Magnitude of peak flow	2	Estimated from rating curve	Same as above
Magnitude of winter peak flow	2	Estimated from rating curve	Same as above
3-day, 7-day, and 30-day high flow	2	Calculated	Same as above
3-day, 7-day, and 30-day low flow	1	Calculated	Same as above
3-day and 7-day low flow (in summer)	1	Calculated	Same as above
3-day and 7-day low flow (in winter)	1	Calculated	Same as above
Total annual river volume	3	Calculated	Same as above
Timing of half flow	3	Calculated	Same as above
Annual average streamflow	3	Calculated	Same as above

Plotting Discharge Metrics as a function of Year

For both USGS- and GRYN-maintained gages, discharge records will first be plotted against time using bivariate plots (see Figure 4-1). For GRYN-managed datasets collected with automated stage or flow loggers, bivariate plots will assist in identifying data points that represent unexplained outliers or that appear unrepresentative of actual flow (e.g., due to a runoff event, channel modification, icy conditions, or unreliable equipment readings); these points will be eliminated from the analyses (see Weissinger and Moran 2015).

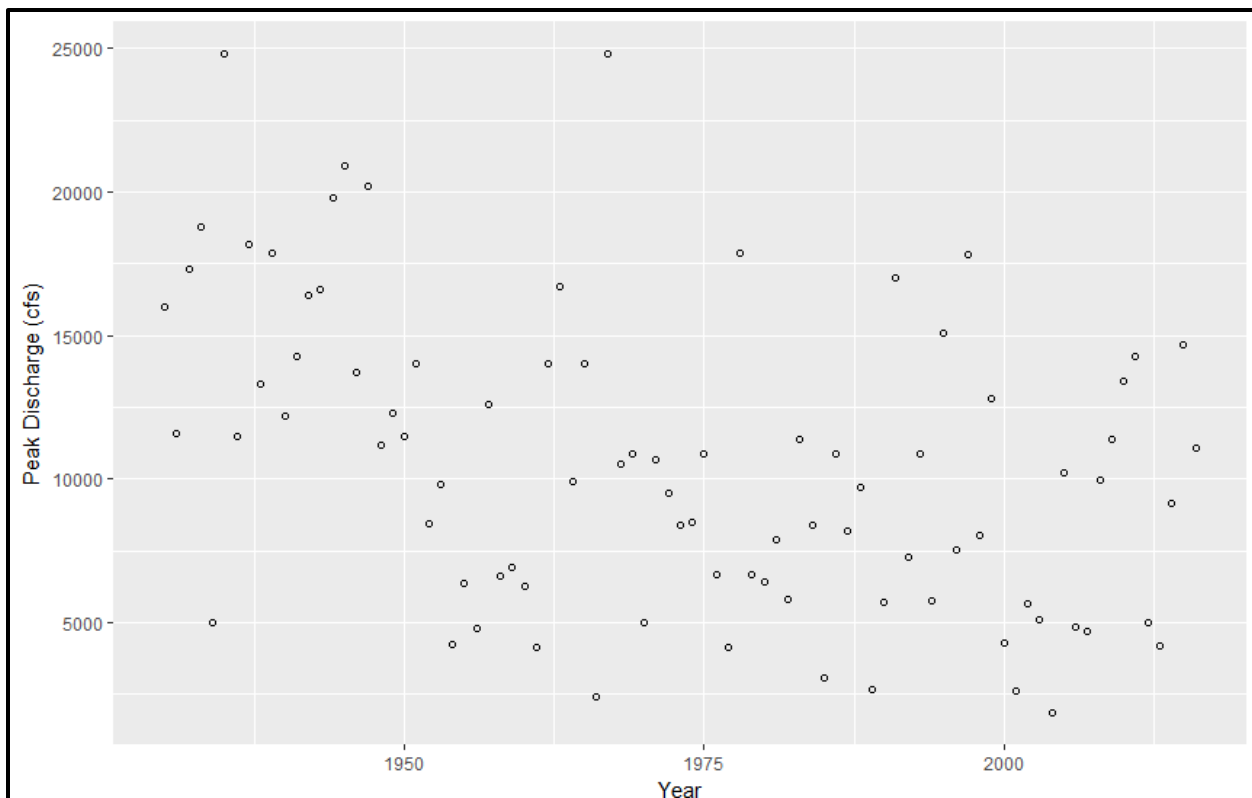


Figure 4-1. Bivariate plot of peak discharge (in cfs) as a function of year for the Bighorn River at Kane, Wyoming.

Ordinary Least Squares Regression

Ordinary least squares regression (OLS) will be used for discharge metrics summarizing average flow conditions (e.g., 7-day average low flow or average annual daily discharge; see Table 4-1). Ordinary least squares regression places a ‘best fit’ line through the scatter of observations employing a concept of least squares (Zar 1996). The best fit line is one that results in the smallest total sum of squares (for all response [Y] values). This sum of squares is called the residual standard error or residual sum of squares. In OLS regression, the β , or regression coefficient, refers to the slope of the best fit line. The sign and value of the regression coefficient provide an indication of the direction and magnitude of a trend. Positive β ’s indicate rising trends and negative β ’s indicate declining trends. The Y intercept, or value where $X = 0$, is known as the parameter α . The Y intercept has the same units as any other Y value. The assumption for regression analysis is that there is homogeneity of variances. OLS also assumes linearity or that the relationship between X and Y values typically fall on a single line. Lastly, it is assumed that observations for Y (i.e., a discharge metric) are independent of other Y observations (previous or future year discharge metrics).

Ordinary least squares regression is commonly used in discharge analyses (see Madej 2011; Al-Chokhachy et al. 2017 as examples). Interpretation of the results for our monitoring will include indicating whether β ’s are positive or negative (trend) and their overall magnitude (i.e., is the annual rate of change large [$\beta \gg 0$ or $\beta \ll 0$] or small [β is approximately 0]). Because discharge data are notoriously variable, an alpha value of 0.10 will be employed to assess significance of the relationship.

An example of OLS regression output summarizing 7-day average low flow discharge in the Bighorn River at Kane, Wyoming (Figure 4-2) indicates that low flows are increasing (positive $\beta = 4.703$ cfs/year) and the overall model fit is significant ($P < 0.001$, $R^2 = 0.148$ $F_{1,85} = 14.76$; see R output in Box 4-1).

Box 4-1.

Output from R lmtest

Residuals:

Min	1Q	Median	3Q	Max
-461.56	-204.05	-13.69	113.94	954.53

Coefficients:

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	-8550.019	2415.330	-3.540	0.000652 ***
bighorn\$Year	4.703	1.224	3.842	0.000234 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 286.7 on 85 degrees of freedom

Multiple R-squared: 0.148, Adjusted R-squared: 0.1379

F-statistic: 14.76 on 1 and 85 DF, p-value: 0.0002345

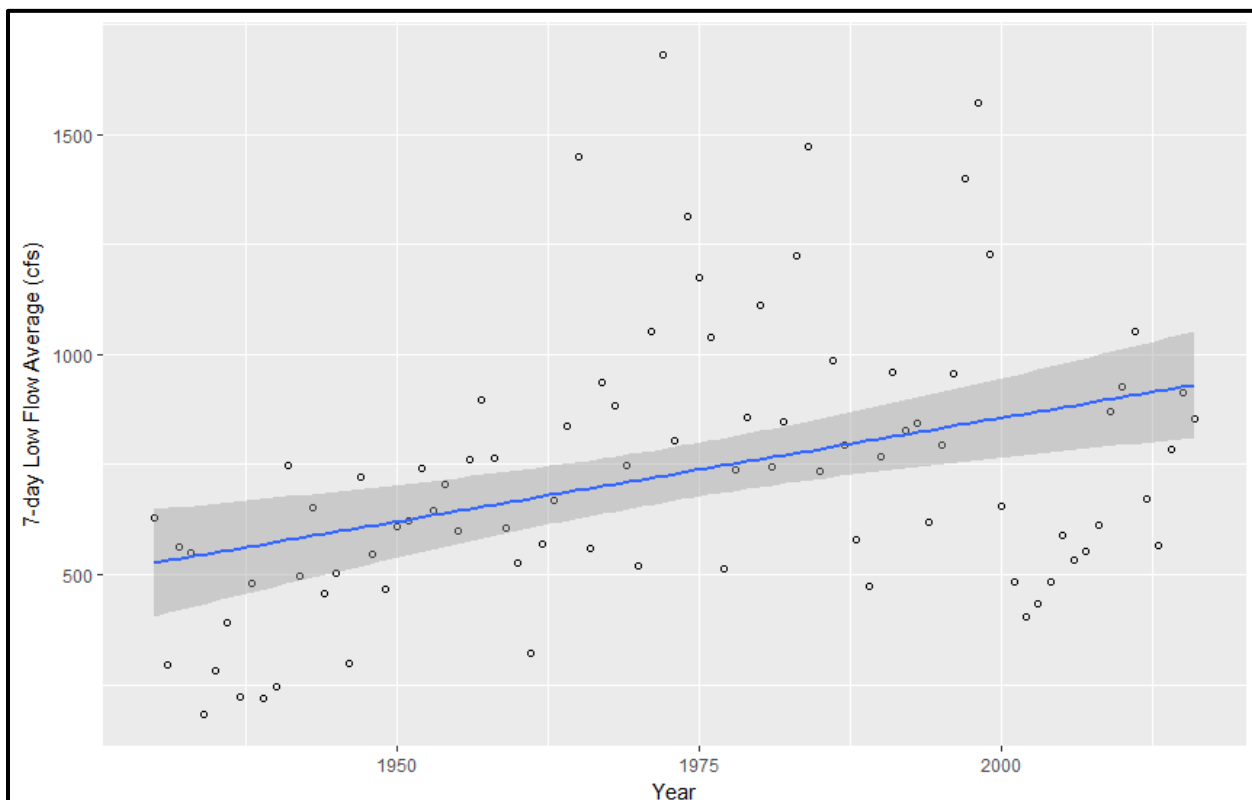


Figure 4-2. Bivariate plot with ordinary least squares regression (best fit) trend line summarizing the trend for 7-day low flows in the Bighorn River at Kane, Wyoming as a function of year.

A second example using ordinary least squares regression summarizes the relationship of average daily discharge (in cfs) for the Shoshone River near Lovell, Wyoming as a function of year (Figure 4-3). In this example, the trend (β) for flows is negative ($\beta = -3.939$ cfs/year), however, the overall model fit is not significant ($P = 0.2949$, $F_{1,48} = 1.12$; see R output in Box 4-2).

Box 4-2.

Output from R lmtest

Residuals:

Min	1Q	Median	3Q	Max
-591.44	-277.29	-82.13	271.92	1035.68

Coefficients:

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	8728.573	7407.558	1.178	0.244
shoshone\$Year	-3.939	3.719	-1.059	0.295

Residual standard error: 379.5 on 48 degrees of freedom

Multiple R-squared: 0.02283, Adjusted R-squared: 0.002475

F-statistic: 1.122 on 1 and 48 DF, p-value: 0.2949

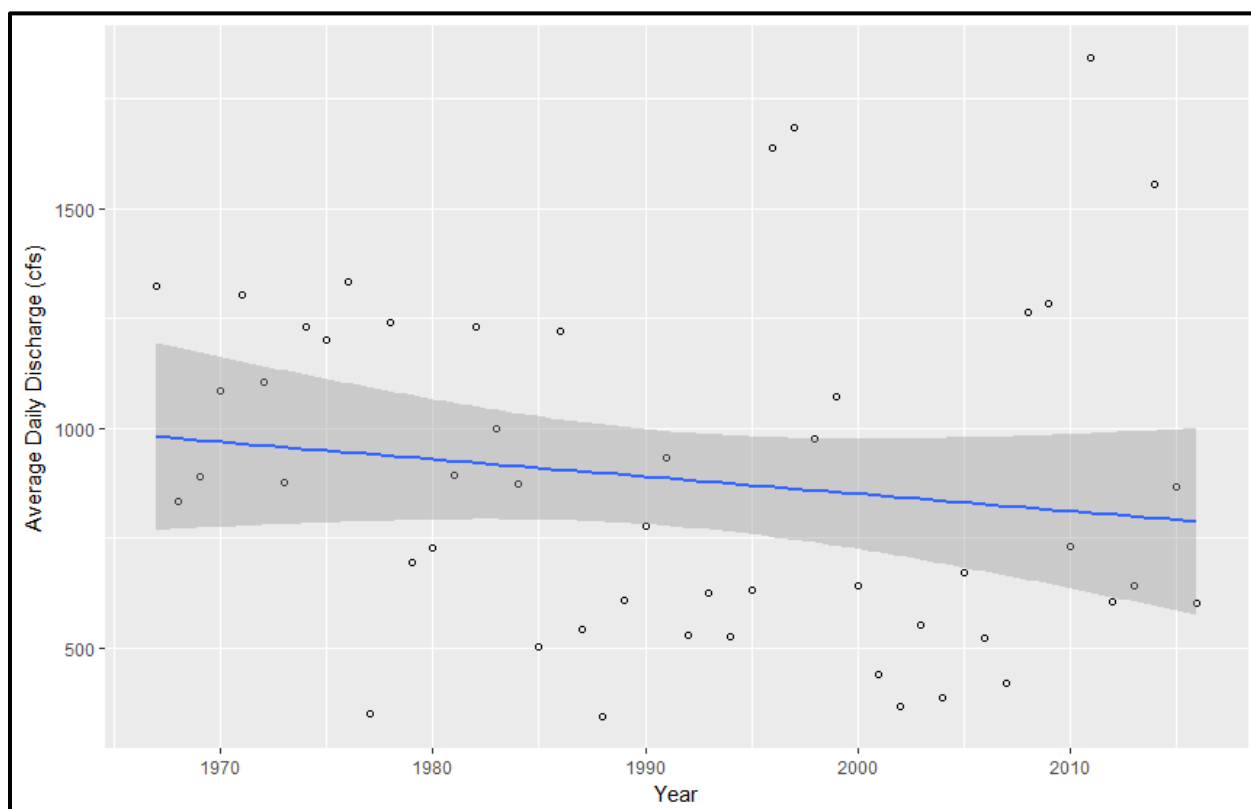


Figure 4-3. Ordinary least squares regression results for Shoshone River at Lovell, Wyoming for average annual daily discharge as a function of year.

Quantile Regression

Quantile regression will be used to summarize trends of more anomalous (e.g., peak discharge) metrics as a function of year. Quantile regression is well suited for summarizing anomalous discharge data; discharge data are notorious for having annual observations with unequal variance and an observation set characterized as having more than a single slope (Cade and Noon 2003). For example, Luce and Holden (2009) demonstrated that rivers in the Pacific Northwest show different trends in annual flow depending on which quantile of data was examined. Across 43 gages, the majority of USGS discharge stations showed significant declines in the 25th percentile of annual flows, while only five stations showed declines in the 75th percentile of annual flows (Luce and Holden 2009). Taken together, quantile regression is capable of showing a more complete set of responses in observations from large, multi-year discharge records.

An example of quantile regression (considering the median, 25th, and 75th percentile results; $\tau = 0.5$, 0.25, and 0.75) summarizes the estimated intercept and slope (i.e., trends) for 25th percentile, median, and 75th percentile of peak discharge observations in the Lamar River near the Tower Ranger Station in Yellowstone National Park (Box 4-3 and Figures 4-4 and 4-5). As you can see the slope values differ albeit with overlapping standard errors for each quantile. The trends for the median and 75th percentile of observations show significant positive slopes.

Box 4-3.

Summary of output from quantile regression

25th Percentile

Call: rq(formula = lamar\$PeakQ ~ lamar\$CalendarYear, tau = 0.25, data = lamar)

tau: [1] 0.25

Coefficients:

	Value	Std. Error	t value	Pr(> t)
(Intercept)	-19663.25000	29143.26559	-0.67471	0.50202
lamar\$CalendarYear	13.25000	14.89354	0.88965	0.37662

Median

Call: rq(formula = lamar\$PeakQ ~ lamar\$CalendarYear, tau = 0.5, data = lamar)

tau: [1] 0.5

Coefficients:

	Value	Std. Error	t value	Pr(> t)
(Intercept)	-37621.35593	23935.06725	-1.57181	0.12038
lamar\$CalendarYear	23.05085	12.26421	1.87952	0.06422

75th Percentile

Call: rq(formula = lamar\$PeakQ ~ lamar\$CalendarYear, tau = 0.75, data = lamar)

tau: [1] 0.75

Coefficients:

	Value	Std. Error	t value	Pr(> t)
(Intercept)	-60308.43750	32564.49473	-1.85197	0.06813
lamar\$CalendarYear	35.46875	16.51919	2.14712	0.03515

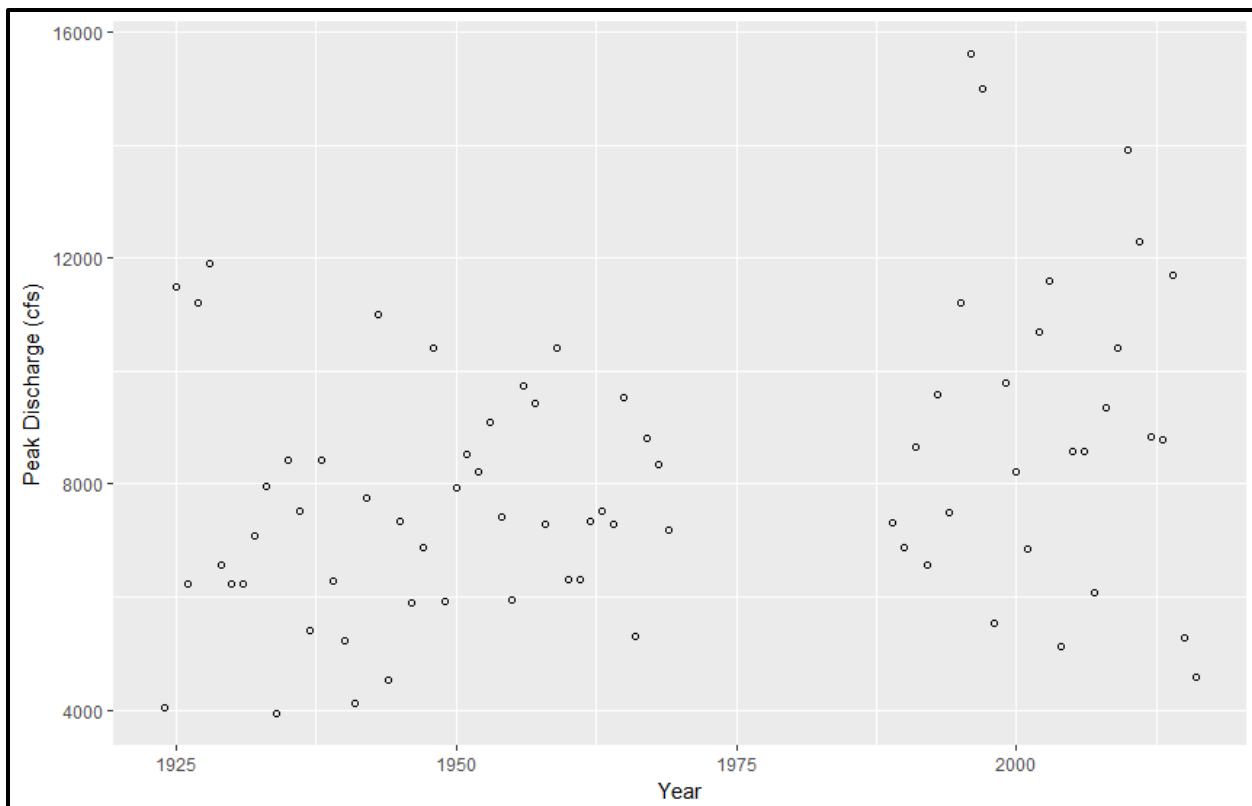


Figure 4-4. Bivariate plot of peak discharge (in cfs) for the Lamar River near Tower Ranger Station, Wyoming as a function of year.

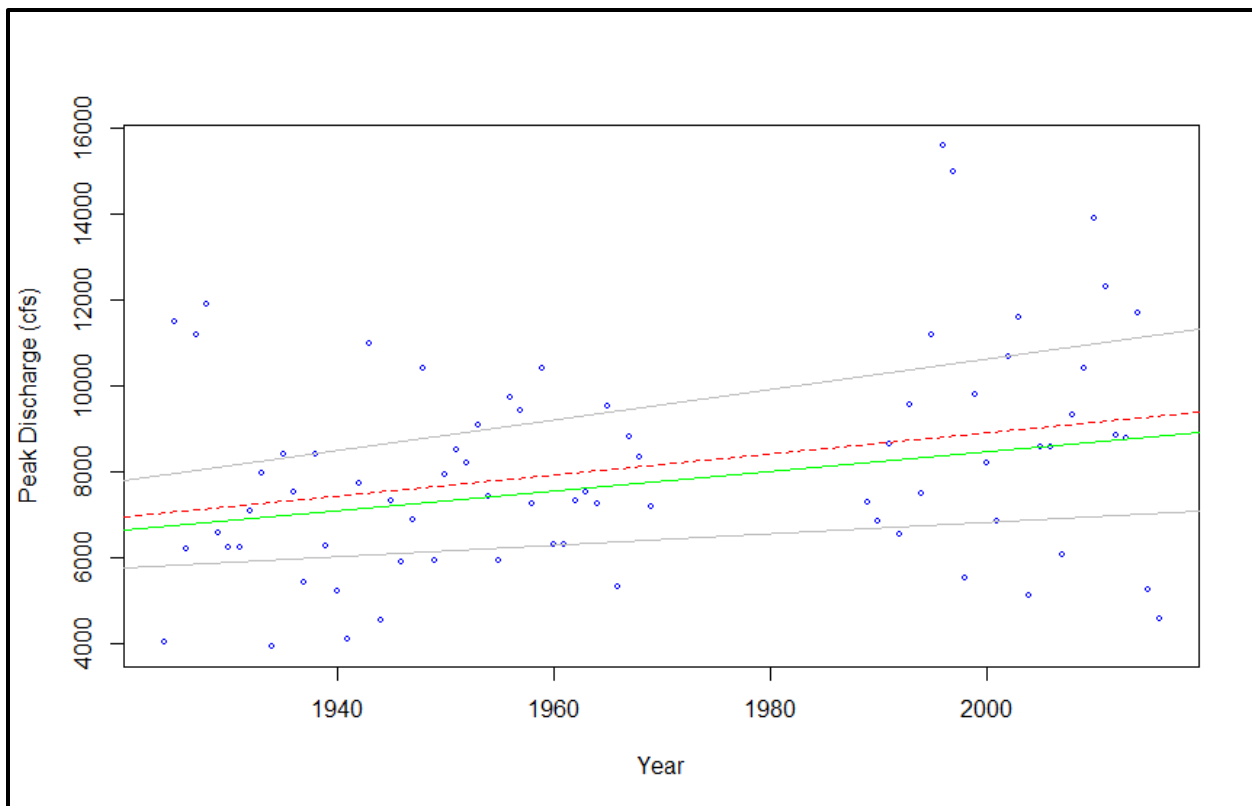


Figure 4-5. Scatter and quantile plot of peak discharge (in cfs) for the Lamar River near Tower Ranger Station, Wyoming as a function of year. Trends showing the ordinary least squares (i.e., mean) trend line are shown in red, the median ($\tau = 0.5$) trend is shown in green, and 25th and 75th quantile ($\tau = 0.25$ and 0.75) trend lines are shown in gray.

File Management and Storage

Discharge information collected from each USGS gaging station and necessary for the production of discharge metrics can be accessed through the USGS Water Data for the Nation website

(<https://waterdata.usgs.gov/nwis>). To access gaging station data

1. Navigate to the NWIS website: <https://waterdata.usgs.gov/nwis>
2. Select the Site Information option.
3. Select Site Information again to start your site query.
4. Select Site Name or Site Number (both provided in Tables 2 and 3 of the protocol implementation plan narrative) and click submit.
5. For Site Number, enter the site number in the text box, select exact match, and select Table of sites. Click submit.
6. Click on the site from the table of sites and this will take you the site page for that USGS site.
7. Download daily summary estimates of discharge by selecting daily data.
8. Select the parameter of interest (mean daily discharge) and select the output form as Table or Tab-separated. Indicate the period of record desired, select tab-separated, and select GO.

9. The output should be saved to a .csv file.
10. Discharge files containing daily estimates of discharge for individual USGS gaging stations should be saved annually to the *Data_Files* folder under the current year:
U:\Monitoring\Active_Vital_Signs\Water_Resources\Protocol\Discharge_Protocol_2016\DataFiles

Daily USGS discharge data can also be retrieved using ClimateAnalyzer (www.climateanalyzer.org).

1. From the home page, select Greater Yellowstone Area.
2. From the Greater Yellowstone Area interactive map, click on the desired USGS gaging station.
3. Select tables.
4. For Table Type, select daily data.
5. Select the Start Year or the year that begins the discharge data summary.
6. Select the End Year or the year that concludes the discharge data summary.
7. Download the file as a .csv file annually to the *Data_Files* folder under the current year.

Daily discharge files downloaded from either provider should be named using the first two letters from the station name followed by the abbreviation ‘R’ for river or ‘C’ for creek and also include the USGS ID Number. For example, the Gardner River near Mammoth, National Park (USGS Station ID 06191000) would be labelled as *GAR_06191000_2016* for data summarized through 2016. Similarly, *PAC_13011500_2015* would contain data from the Pacific Creek at Moran, Wyoming (USGS Station ID 13011500) gage through 2015.

RStudio for Data Analysis

Discharge metrics calculated from daily discharge or surface elevation data and used for status and trend evaluation are shown in Tables 6 and 7 of the discharge monitoring protocol implementation plan narrative (Ray et al. 2017). Metrics will be summarized in Microsoft Excel and analyzed using regression analysis following guidelines summarized above and employing the *lm* function and *quantreg* package. Bivariate plots will be generated using the *ggplot2* package (R Development Core Team 2017).

In brief, please follow the steps below for analyzing individual metrics for each site.

1. Open RStudio.
2. In the R Global Environment window, load the workspace or data file that will be summarized. Data files should be loaded as a .csv file from the *Data_Files* folder on the U: drive. Go ahead and set this folder as the working directory using the ‘*setwd*’ command in the console window.
3. Install the quantile regression ‘*quantreg*’ and ‘*ggplot2*’ data visualization packages.
4. Load the *quantreg* and *ggplot2* packages. R will download and install several files.
5. Access R code from the previous year analysis at
U:\Monitoring\Active_Vital_Signs\Water_Resources\Protocol\Data analysis\R_Code
6. Paste ordinary least squares or quantile regression R code into the R Console (example code is found at the end of this SOP) and is also available at

U:\Monitoring\Active_Vital_Signs\Water_Resources\Protocol\Data analysis\R_Code. Be sure to change file names and discharge/elevation metrics to summarize each metric for individual river, stream, spring, or reservoir locations.

7. In the R Editor be sure to update the comment section at the head of the file (year, station location, dates summarized, contact, R version, etc.) and provide a brief summary of what is contained in the file. Update the year in the data file names. In particular, make sure the input data file name in the R file exactly matches the name of the file on the U: drive. Be very attentive when checking file names.
8. Double check the text to make sure everything is correct.
9. Click the save icon in R to save your edits. Save the R files to the current year folder at *U:\Monitoring\Active_Vital_Signs\Water_Resources\Protocol\Data analysis*
10. Save the script to the data analysis folder (see above) using the naming convention described above. For example, a summary text file for the Gardner River near Mammoth, National Park (USGS Station ID 06191000) would be labelled as *GAR_06191000_2016_Rcode.txt* for data summarized through 2016.
11. Once the output from analyses for each site are confirmed, close the R file and exit R.

R Code:

Below are examples of the R code (R Development Core Team 2017) used to make plots and to carry out ordinary least square and quantile regression.

Creating Bivariate Plots

Bivariate plots can be produced using ggplot2 as follows:

```
> ggplot(bighorn, aes(x=Year, y=PeakQ)) +  
  geom_point(shape=1) + xlab("Year") + ylab("Peak Discharge (cfs)")
```

Ordinary least squares trend line can be added to the dataset as follows:

```
> ggplot(bighorn, aes(x=Year, y=X7.day.Low.Flow)) +  
  geom_point(shape=1) + geom_smooth(method=lm) + xlab("Year") +  
  ylab("7-day Low Flow Average (cfs)")
```

Quantile regression plot:

```
plot(lamar$Year, lamar$PeakQ, cex = 0.25, type = 'n', xlab = "Year", ylab = "Peak Discharge (cfs)")  
points(lamar$Year, lamar$PeakQ, cex = 0.5, col = 'blue')  
abline(rq(lamar$PeakQ~ lamar$Year, tau = 0.5), col = 'green')  
abline(lm(lamar$PeakQ~ lamar$Year), lty = 2, col = 'red')  
taus <- c(0.25, 0.75)  
for (i in 1:length(taus)) {abline(rq(lamar$PeakQ~ lamar$Year, tau=taus[i]), col = 'gray')}
```

Running Regression Models

Example Code for running Ordinary Least Square (OLS) regression is as follows:

```
olsreg<-lm(bighorn$X7.day.Low.Flow~ bighorn$Year)  
summary(olsreg)  
shoshone<-read.csv("ShoshoeR_AveDailyQ.csv");Shoshone  
names(shoshone)  
olsreg<-lm(shoshone$AveAnnDailyQ~ shoshone$Year)  
summary(olsreg)
```

Example code for running quantile regression is as follows:

```
lamar<-read.csv("LamarR_Q.csv");lamar  
names(lamar)  
help(package = "quantreg")  
quanreg <- rq(lamar$PeakQ~ lamar$Year, tau = 0.25, data = lamar)  
summary(quanreg, se = 'nid')
```

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