Technical Memorandum

To: Shelley Pridgen, Project Manager
From: David Maidment, Research Supervisor
Subject: TxDOT Project 0-7095 – Technical Memorandum 3
Project Title: Evaluate Improved Streamflow Measurement Technologies at TxDOT Bridges
Date: July 31, 2023

Technical Memorandum 3: Network Assessment

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3.1. Introduction

The purpose of this memorandum is to assess the current performance and capabilities of the stream gauge network installed for the "Evaluate Improved Streamflow Measurement Technologies at TxDOT Bridges" project.

The United States Geological Survey (USGS) traditionally employs a method of discharge computation relating continuously measured stage to an associated discharge (Rantz and others, 1982a, 1982b). This stage-discharge relation is built using numerous physical discharge measurements, which is labor intensive. A significant research objective is to evaluate the feasibility of methods alternative to the traditional USGS stage-discharge relation, namely the computation of discharge using surface velocimetry.

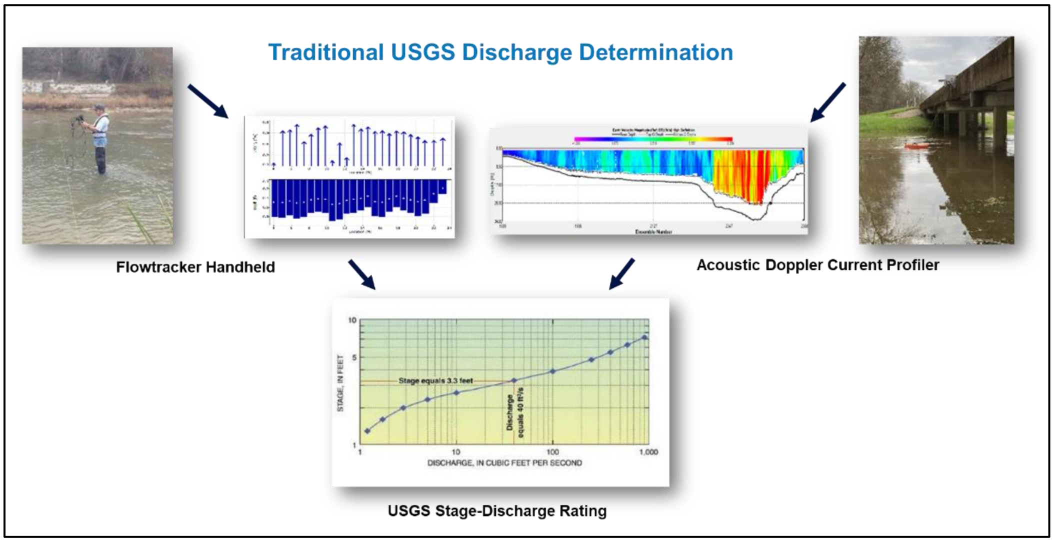


Figure 3.1.1 USGS Ratings are developed using direct field measurements to create a stage-discharge relation

Currently, gauges that compute discharge using surface velocimetry have not been widely documented by the USGS as being a comparable alternative to the traditional stage-discharge method of discharge computation. For this project, a total of 80 surface velocimetry gauges were used to record and compute stage and discharge data, respectively, for comparison with USGS traditional methods. The RQ-30 surface velocimetry gauge was selected because it measures both water level (also known as gauge height or stage) and velocity in a single instrument.

The project schedule calls for this report to be delivered by 31 July 2023. Delays in site selection caused delays in the installation of the stream gauges limiting the amount of data collected.

3.2. Gauge Equipment Assessment

3.2.1. Installation

The RQ-30 velocimetry gauge installed for this project requires less time to install compared to a traditional USGS gauge. Installation infrastructure for the RQ-30 gauge was furnished or fabricated before installation to reduce time and effort while on-site. Once bridge attachment permitting is complete, traditional USGS gauges can take up to one week to install while the typical RQ-30 velocimetry gauge could be operational in less than 4 hours, often allowing the opportunity to install two complete gauges in a single day. Quicker installation results in less roadway exposure for both installation crews and the public accessing TxDOT roadways.

Figure 3.2.1. Image of a completed RQ-30 gauge installation

A steel bracket was fabricated and hot-dip galvanized to secure a 24” by 24” powder coated aluminum enclosure to the bridge guardrail. All bridge attachments are held in place with concrete anchor bolts. USGS reference gauges are installed and surveyed to North American Vertical Datum of 1988 (NAVD88) datum to ensure water surface elevations are consistent and repeatable through the life of the gauge.

3.2.2. Equipment setup

Each RQ-30 velocimetry gauge consists of the following components:

- **Data Logger**: A data collection platform for recording and transmitting sensor data
- **Sensors**: Measuring devices used to observe gauge height and velocity remotely
- **Equipment Enclosure**: A weatherproof housing used to store and protect gauging equipment
- **Wire Weight Gauge**: A calibrated measuring device for determining water surface elevation
- **Power Supply**: A solar charged, 12-volt power source to run the gauging equipment.

Figure 3.2.2. Equipment housed in the gauge enclosure

The data logger selected for this project is the Sommer MRL-7 data collection platform because of its compatability with the RQ-30 sensor and its ability to transmit data wirelessly via celluar modems. The MRL-7 also allows for two-way communciation which allows technicians to troubleshoot or change internal settings on both the RQ-30 and data logger remotely if necessary. Data is transmitted over File Transfer Protocol (FTP) to data servers, where it is picked up by scripts and distrubuted to both the USGS database and the National Water Information System (NWIS).

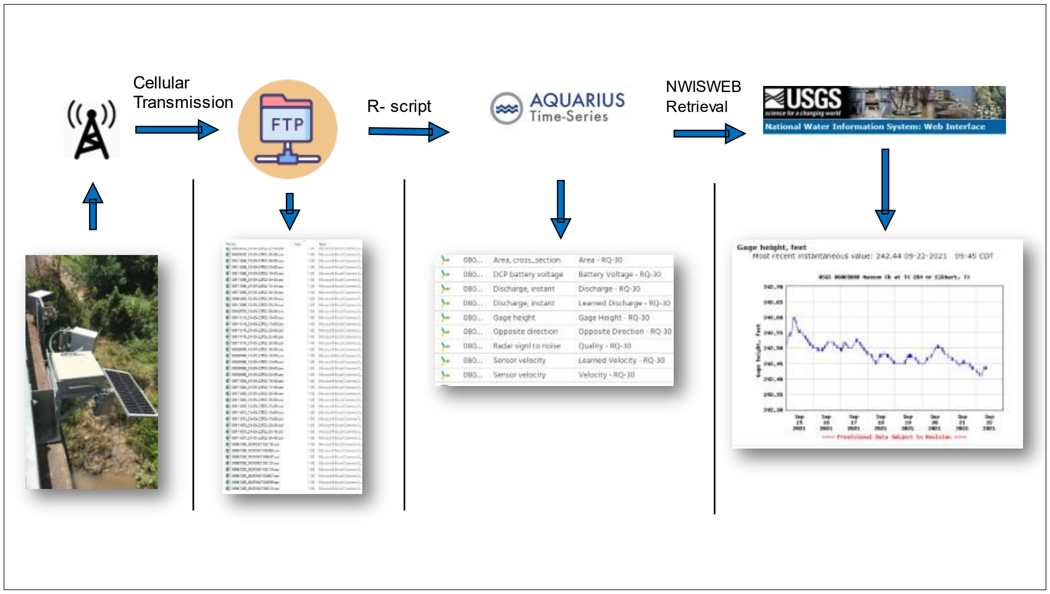


Figure 3.2.3 Transmission of data from the gauge to the public

Each logger controls a RQ-30 sensor that encompasses both a non-contact water level radar and a surface velocity radar. The sensor is mounted to the bridge guardrail and communicates to the MRL-7 via a wired RS-485 connection. The RQ-30 is triggered to perform and record stage and velocity readings at 5-minute intervals and transmitted at 15-minutes intervals. Velocity readings are a continuous measurement of surface velocity over a user-determined timeframe specified during setup.

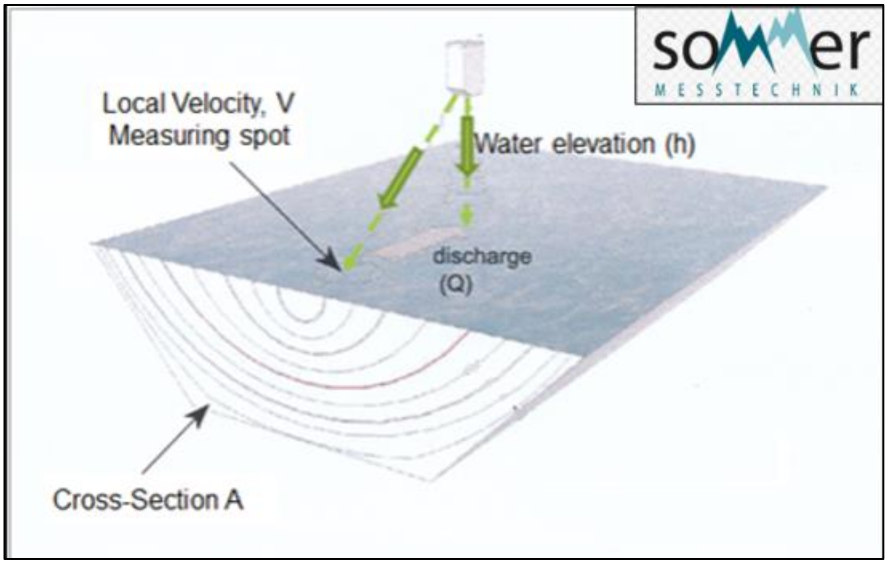


Figure 3.2.4 Conceptual drawing of an RQ-30 gauge sensor

A wire weight gauge, surveyed to North American Vertical Datum of 1988 (NAVD 88), serves as the reference gauge. The wire weight gauge determines water surface by lowering a weight attached to a steel cable to the water surface. When the weight contacts the water surface, a calibrated dial is read to determine the stage at that time.

The gauge is powered by a 35 amp-hour 12-volt battery which is continuously charged with a 20-volt solar panel attached to the gauge enclosure. Batteries are considered a consumable part of the stream gauge and are expected to be replaced as needed.

3.2.3. Equipment Resilience

Data loggers, sensors, solar panels, batteries, and transmission components run continuously throughout the life of a stream gauge. These components reside outdoors and are subject to temperature fluctuations, bridge vibration, and equipment malfunction that can affect the reliability of the system.

The equipment selected for this project has been functioning for between 1 and 3 years. During this time, the MRL-7 data loggers have functioned well when no external issues were present. External issues such as incorrect or loose wiring, user error, incorrect settings, limited cellular signal coverage, sensor malfunction, and system power loss can cause temporary outages of data that are not attributed to the overall function of the data collector. The most common problem observed with the MRL-7 is the loss of cellular function in areas of weak cellular data services.

Transmissions were reliant on the signal quality of the cellular data network. Efforts were made during the reconnaissance phase of the project to ensure data could be sent and received onsite using cellular phone applications such as “Speed Test”.

The RQ-30 sensor functioned according to designer specifications except for low velocity resolution. Low velocity measurements often had large variances in final recorded data. The intended use of these gauges is to provide information to better inform TXDOT regarding flood related decisions, therefore limitations identified during low flow conditions are not considered to be a concern for the practicality of the network for its intended purpose as a flood support stream gauge.

Stage and velocity components of the sensor functioned correctly with one exception. Stage data on 5 of the 80 RQ-30 gauges malfunctioned by reading a single stage value repeatedly regardless of changing stage. This sensor malfunction was remedied by cycling power to the RQ-30 sensor remotely which allowed the sensor to resume normal operation.

3.3. Data Assessment

To compare the RQ-30 velocimetry gauge to traditional methods, the USGS initially divided the 80 gauges into 3 tiers:

Tier 1 – Traditional Methods: 10 gauges. These shall be installed and maintained in a comparable manner to standard USGS gauge sites. This includes regular stream gauging at the site to produce a stage-discharge rating curve. In this manner the calibration needed to adapt the velocity and depth measurements from the RQ30 gauges to produce correct discharge measurements can be evaluated.

Tier 2 – Moderately Checked: 20 gauges. USGS professional field staff shall conduct site visits at 6- to 8-week intervals and conduct opportunistic visits with attention to flood-like or greater stages. This gauge height verification interval is consistent with national procedures. The USGS will also site one or more passive crest-stage gauges (CSGs) reasonably with regard to local hydraulic situations, to record the highest gauge height between successive site visits.

Tier 3 – Minimally-Checked: 30 gauges. The USGS shall provide site visits for gauge-height-only verification approximately quarterly and shall site one or more passive CSGs reasonably with regard to local hydraulic situations, to record the highest gauge height between successive site visits.

This approach was followed briefly before considering all sites as “Tier 2” gauges. The change was made because the sites selected as “Tier 1” and “Tier 2” were not receiving sufficient rainfall for high flow discharge measurement. The comparison of RQ-30 derived data against traditional USGS methods was dependent on the physical measurement of discharges at these sites. Discharge measurements were not limited to predetermined tiered categories to expand the coverage of comparison.

3.3.1. Parameters of Recorded Data

There were 9 parameters recorded bythe RQ-30 gauge:

DCP battery voltage (V): Voltage of the gauge battery at the time of transmission.

Gauge Height (ft): Level of the water surface, measured every 5 minutes.

Velocity (ft/s): Water surface velocity in-line with the RQ-30 sensor

Learned velocity (ft/s): Water surface velocity determined internally by machine learning algorithms within the RQ-30

Discharge (cfs): Instantaneous discharge value as calculated by the RQ-30 with Velocity.

Learned Discharge (cfs): Instantaneous discharge value as calculated by the RQ-30 with Learned velocity.

Quality: A signal-to-noise ratio determined internally by the RQ-30 that evaluates the velocity return signal to the level of background noise experienced by the radar during a reading.

Opposite Direction: The ratio of velocity distributions in the forward and opposite directions.

Area (ft^2): Cross section area according to the water level and discharge table internal to the RQ-30.

3.3.2. Cross Sections

To compute discharge using velocimetry, a cross sectional area must be determined as Discharge = Velocity x Area. For this project, cross sections were determined using LiDAR, global navigation satellite systems (GNSS), and total station surveying. All datums were established based on North American Vertical Datum of 1988 (NAVD 88).

During the establishment of each RQ-30 gauge, a survey was conducted to create a cross section which was entered into the RQ-30 for discharge computation. The above water portions of the cross-sectional survey were obtained by using a total station to define features within the channel. Below-water portions of the cross-sectional survey were obtained by means of Acoustic Doppler Current Profiler (ADCP) bathymetry data when on-site conditions, such as water depth, prevented direct elevation observations.

When multiple survey methods were required to complete a cross section survey, data was entered into the USGS program AreaComp3 to assist in computing a cross-sectional area. For instance, combining ADCP data with traditional level and stadia or depth sounding observations to create a stage area-rating.

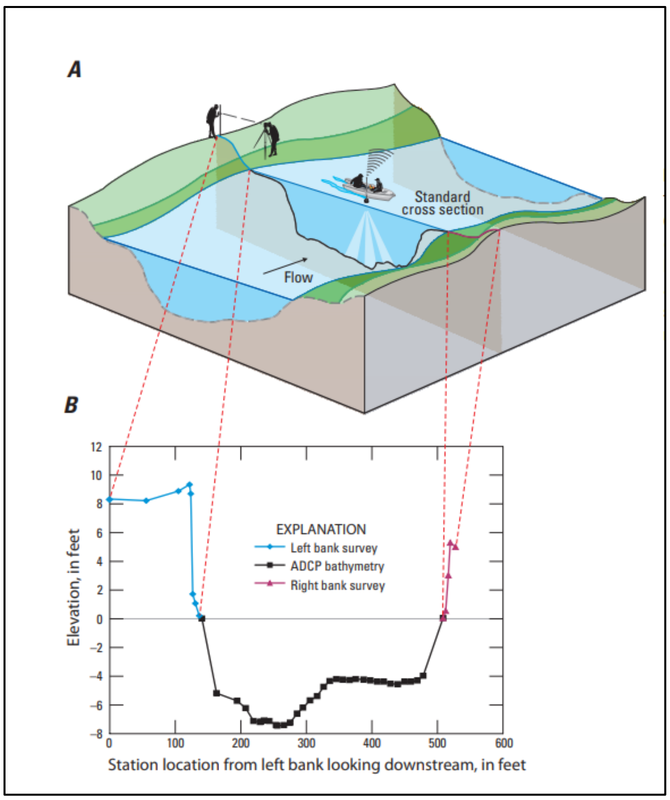


Figure 3.3.1 Example of a cross section survey involving multiple techniques (Levesque and Oberg, 2012)

The cross-sectional area of a stream is determined by the geometry and the stage at any given time. If the surveyed cross-section experiences a scour or fill condition, both natural and manmade, a change in velocity distribution could occur. Changes in cross-sectional area commonly occur after flood events and often require a resurvey of the cross-section to maintain an accurate velocity-discharge relation.

It is common practice within the USGS to perform routine cross-sectional surveys on an annual basis for the first three years after the initial establishment of the gauge. After the three years of routine annual cross-sectional surveys the frequency is typically reduced to a three-year cycle if certain criteria are met:

1. The standard cross-section does not show substantial change in geometry. This is often based on direct observations while on site and the hydrographers judgment if a resurvey is warranted.
2. A comparison of the stage-area rating created from the annual surveys indicates no substantial percent difference from the initial survey.

The USGS program AreaComp3 was used to compare cross sections and determine the differences in channel geometry over time. An emphasis was made on high-flow comparisons because low-flow channel geometries are sensitive to minor variations in the survey location. The results of each comparison were assessed for substantial area differences, as described in Techniques and Methods 3-A23, "Computing Discharge Using the Index Velocity Method".

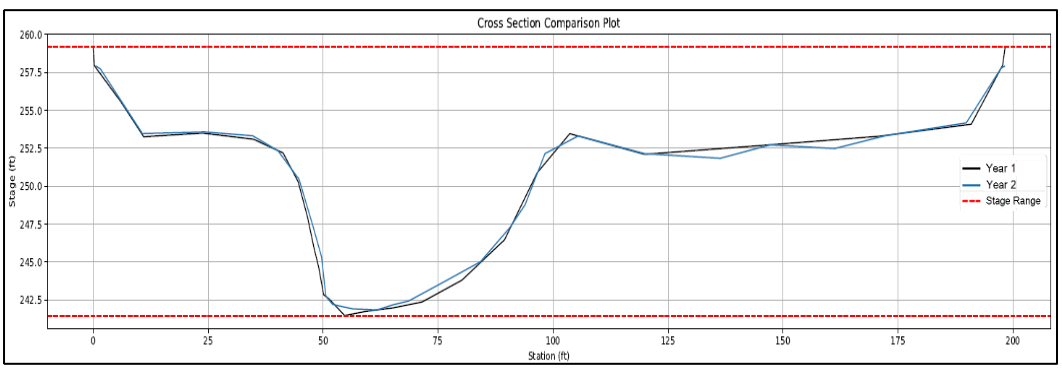


Figure 3.3.2. Example of a typical cross section comparison plot for computing differences in area

In Figure 3.3.2, an example of two annually surveyed cross sections at one gauge are compared using the USGS program AreaComp3. The difference in area at lower stages is the most variable from year to year because the percent change in area is highly sensitive to small variations in channel geometry. As the stage increases, discrepancies between year 1 and year 2 area computations are alleviated because high flow channel geometry is largely unchanged.

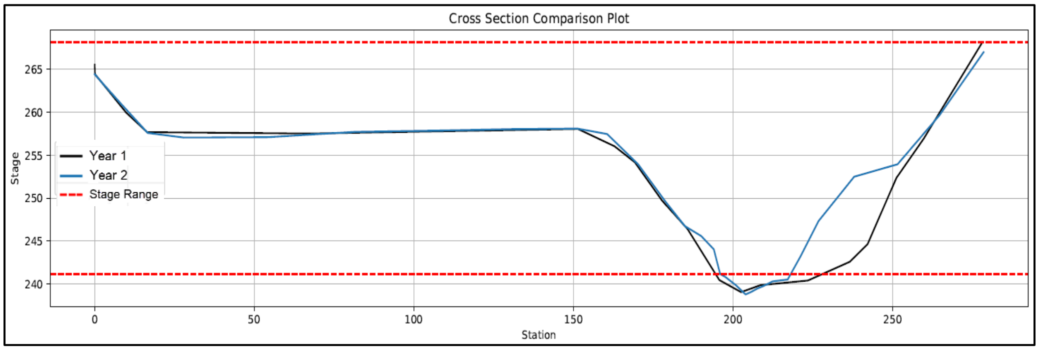


Figure 3.3.3. Example of a cross section comparison plot where channel modifications were made between surveys

The largest cross section area changes were found in channels where channel modifications were made by local entities. Modifications in the form of the addition of rip-rap banks, concrete channelization, or channel clearing caused the largest bank-full area differences year over year. Figure 3.3.3 shows the addition of rip rap on the right bank. In this example, bank-full area was decreased by approximately 30%. Cross sections that are observed to be changed by modification are re-surveyed as soon as possible to preserve the stage-area relation. Three sites were identified and resurveyed in during the project because of modification.

3.3.3. Gauge Height

The accuracy of measured water surface elevation using the RQ-30 was evaluated for each of the 80 installed stream gauges. An initial sensor calibration was performed for each instrument and was verified against a wire weight reference gauge at an interval of 8 – 12 weeks or when higher flow verification was possible. If water was not present in the channel during installation, stage was set to a dry channel bottom and later verified and calibrated when water was present. Gauges set to a dry channel are expected to be reading incorrectly during the first verification visit.

In addition to physical verifications made by field technicians during a range of flows, passive verifications were made using a Crest Stage Gauge (CSG) to verify peaks when field staff was not present. A CSG is a 2-inch metal pipe installed near the gauge that holds a wooden staff made of cedar and ground cork. As water rises on the pipe, intake holes allow water to enter the pipe elevating cork onto the staff. Technicians later measure these marks for peak verification.

Figure 3.3.4 Example of a crest stage gauge for measuring peak stage

Raw, unedited stage data is received and stored in the USGS database called Aquarius. Once a stage verification is made in the field, data are then corrected manually in the Aquarius software by technicians. The method of correction is dependent on the nature of the discrepancy but is often attributed to instrument drift. Once a correction is performed and validated with the USGS approval process, a "corrected" data set is published to the National Water Information System (NWIS).

To assess the overall drift in calibration of each radar stage sensor, a difference was calculated between raw stage values and corrected, published stage values at the time of each verification. To use this approach, stage corrections that were known to be attributed to gauge malfunction, datum error, user error, or incorrect siting were omitted from the assessment.

Figure 3.3.5 shows the amount of instrument drift experienced over 53 sites used in the analysis. Of the 423 stage verifications, 93% percent were observed to have a drift of 0.05 feet or less.

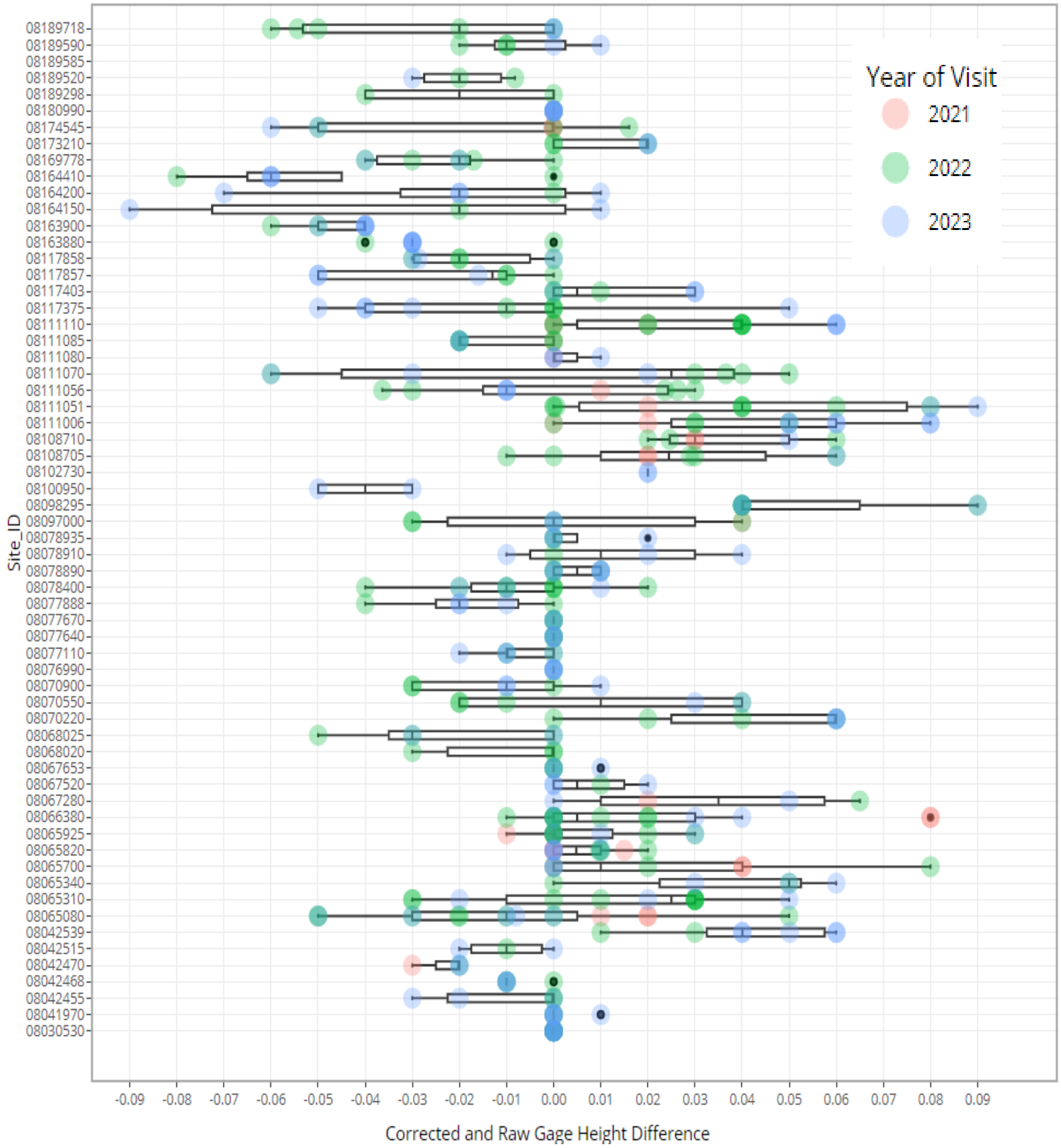


Figure 3.3.5 Box plot displaying the amount of drift observed at 53 stream gauges

Figure 3.3.5 also illustrates that there were no positive or negative biases regarding the direction of the instrument drift or trends of direction over time.

3.3.4. Velocity

Velocity is a parameter of data that is not widely measured continuously at traditional USGS stream gauges. The RQ-30 measures surface velocity using the

Doppler frequency shift method. The addition of continuously measured velocity allows for the non-contact computation of discharge.

3.3.4.1. Raw Velocity

Raw velocity is the unaltered measurement of surface velocity recorded by the RQ-30. Velocity is typically observed where water flows the fastest within the main channel. When the velocity sensor is triggered by the MRL-7 data collector, it records the average of continuous velocity readings over a specific time. The averaging time used for this project was 40 seconds.

RQ-30 manufacturer specifications state a measurement range of 0.08 to 16 meters per second, or 0.26 to 52 feet per second. Unless ideal conditions were met, it was observed that velocities below approximately 0.8 feet per second were often not registered. Velocities above 0.8 feet per second experienced fluctuations attributed to flow characteristics in the sample location. Wave action, turbulence, debris, and eddy velocities caused minor to major variations in consistent velocity readings. Higher velocity averaging times helped to alleviate these fluctuations, but erroneous spikes in velocity data still occurred.

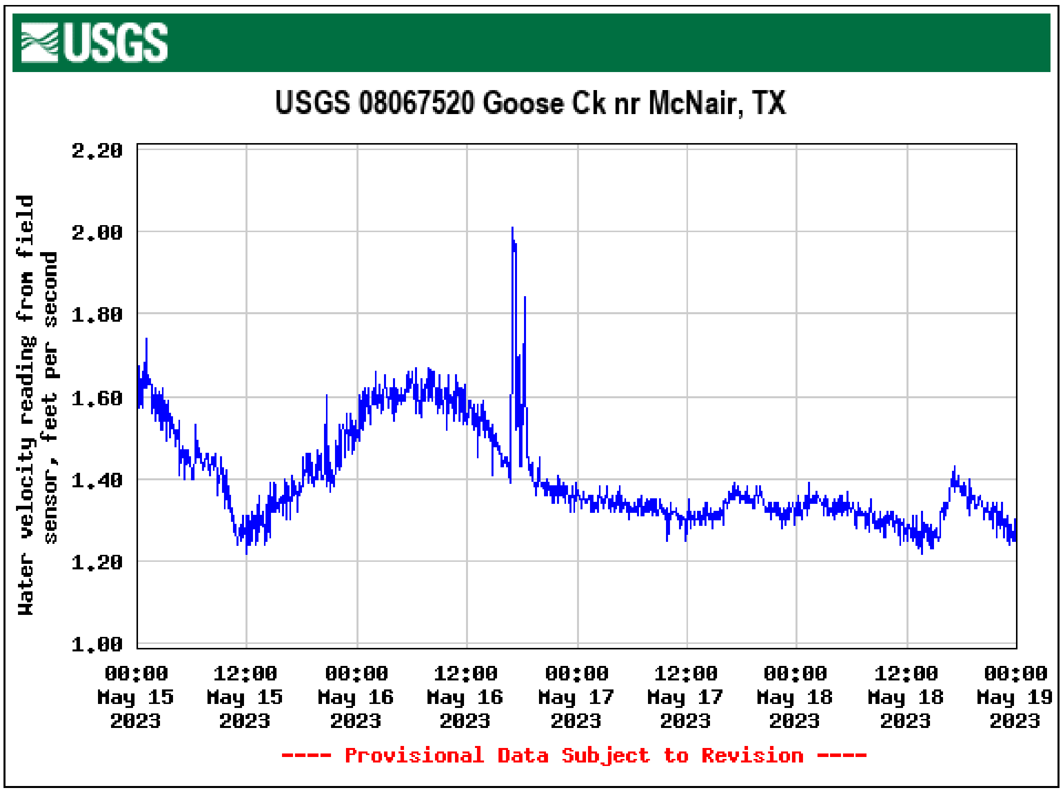


Figure 3.3.6 Example of the observed fluctuations in raw velocity

3.3.4.2. Learned Velocity

Learned velocity is recorded from a stage-velocity rating derived within the RQ-30 sensor. The stage-velocity relation is recorded into a table that updates as new velocity information is available for a given stage. By building this stage-velocity relation values for surface velocity are readily available regardless of temporary sensor interference. Learned velocity minimizes outlier raw velocities that may occur during turbulent flows, eddy velocities, or heavy debris in the water way.

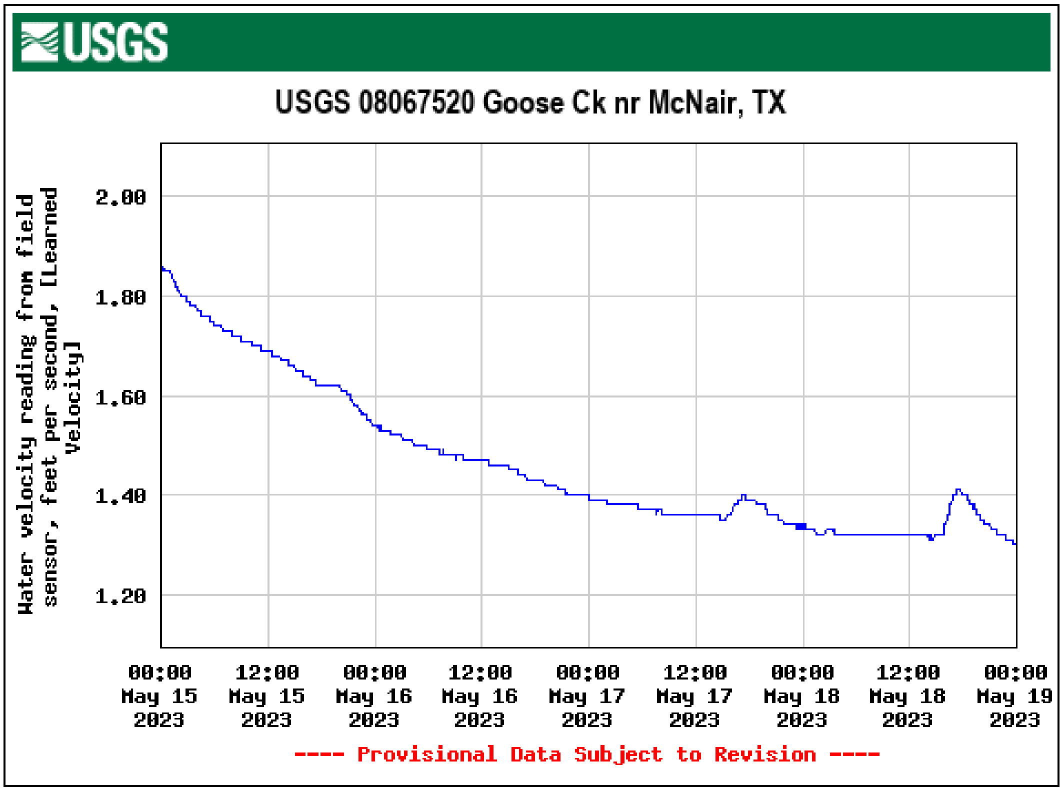


Figure 3.3.7 Example of how learned velocity can minimize velocity fluctuations

Figure 3.3.7 illustrates a learned velocity hydrograph for the data depicted in Figure 3.3.6. Unlike raw velocity, spikes and fluctuations are removed, but resolution can be sacrificed if velocities are dynamic from one event to another. For instance, If the learned velocity relation was created using backwater affected raw velocity readings, the learned velocity may be biased low. Likewise, if the learned velocity is based on normal unimpeded flows, backwater affected flows may be overestimated.

3.3.5. Discharge

The RQ-30 gauge computes discharge using

$$Q = (V * k) * A$$

Or

$$Q = V_{Average} * A$$

Where Q is Discharge, $V_{Average}$ is the average velocity at the gauge cross section, k is the k-factor coefficient, and A is the cross-sectional area at the stream gauge.

$V_{Average}$ is determined by multiplying the surface velocity at the gauge by a coefficient called the "k-factor". The k-factor adjusts a surface velocity to an average velocity dependent on the observed stream height and channel roughness properties. K-factors are determined using the RQ-30 specific software called "Q-Commander". Q-commander creates an initial k-factor from a user-derived roughness coefficient and the surveyed geometry of the cross section. For all installed sites, Manning's roughness coefficient was used, which represents the resistance to flow in channels and flood plains (Arcement, 1989). Following the initial setup, calibrations are made to adjust the k-factor profile accordingly.

Currently, 202 discharge measurements have been made. 136 measurements have been made greater than 20 cubic feet per second.

3.3.5.1. Raw Discharge

Raw discharge is a direct discharge calculation using the instantaneous raw velocity measured by the RQ-30 and multiplying by the cross-sectional area. The initial setup in the Q-Commander software requires a cross section, the location of the radar, and a user supplied roughness coefficient. These three inputs are used by Q-Commander to determine the k-factor relation between surface velocity and mean velocity. Once a k-factor relation is created, discharge is computed for all stages, regardless of its accuracy.

The uncalibrated raw discharge was computed using raw velocity, therefore the same fluctuations were observed in the raw discharge. The fluctuations in discharge are directly proportional to those in raw velocity which can cause large variations in discharge.

Figure 3.3.8 shows a high-water event recorded using the uncalibrated RQ-30 to compute high flow discharge. The USGS discharge unit values are truncated on the rising leg of the event while the RQ-30 computes the event to its entirety. The USGS discharge is truncated because the stage-discharge relation relies on measurements to complete an initial rating. Measurements can be difficult to obtain, and stations can go years without completing a rating for all ranges of stage.

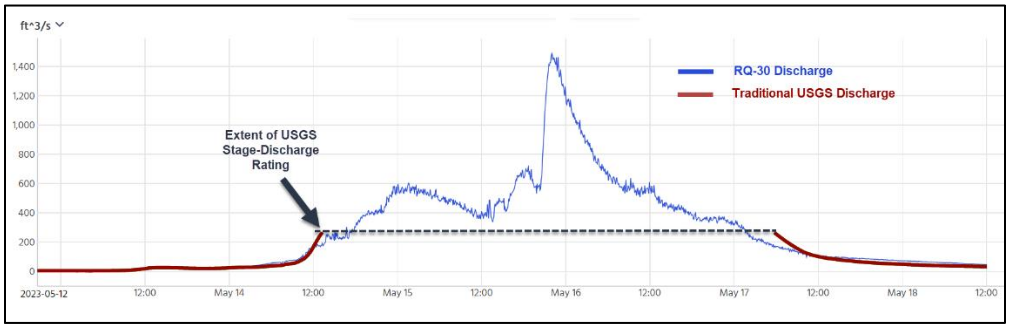


Figure 3.3.8 Example of USGS traditional discharge and RQ-30 raw discharge

The accuracy of the assigned roughness coefficient was found to be the largest source of error in computing a discharge before the RQ-30 gauge is calibrated. On-site roughness coefficients were selected using Cowan's method as described in Arcement and schneider. Roughness was then updated in the Q-Commander software to best fit the k-factor profile to the observed ADCP discharge measurements.

3.3.5.2. Learned Discharge

Learned discharge is computed by multiplying the learned velocity by the cross-sectional area. The output from learned discharge is generally smoother than the raw discharge as is derived from the learned velocity. Little is known about how the learned velocity work because the algorithms are proprietary.

Figure 3.3.9 illustrates an overall smoother hydrograph when compared to the raw discharge.

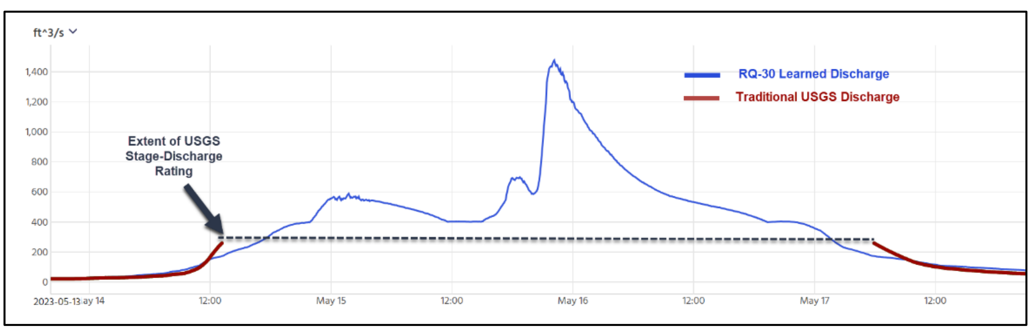


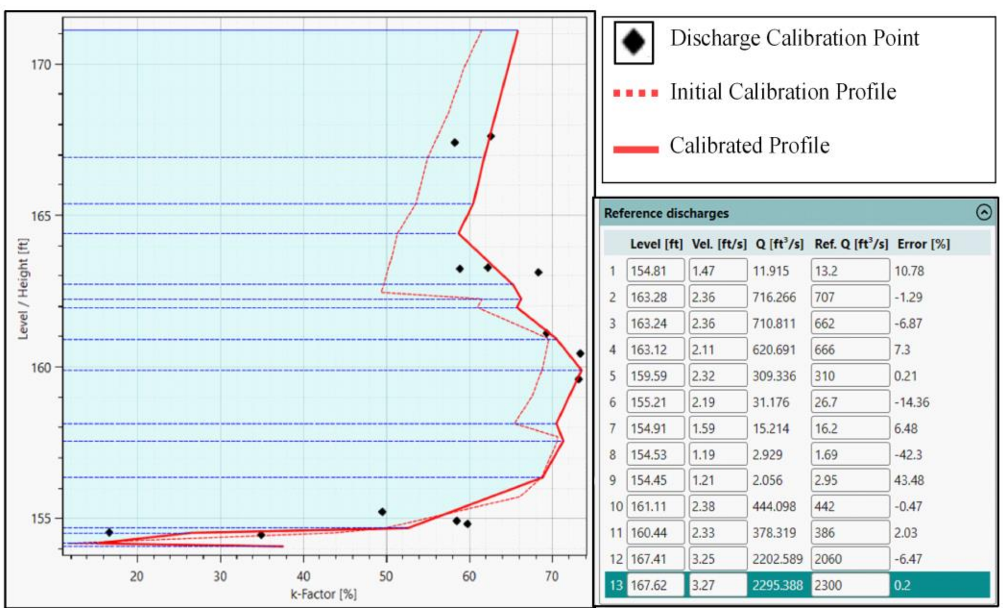
Figure 3.3.9 Example of USGS traditional discharge and RQ-30 Learned discharge

Learned discharge may not be suitable for sites that are affected by backwater, tidal influence, or highly dynamic channel conditions because actual changes in velocity may be assumed to be in error.

3.3.6. Discharge Calibration

While an initial setup of the RQ-30 gauge allows for the measurement of stage and discharge immediately, a calibration of the sensor yields more accurate results as new discharge measurements are made.

To perform a calibration, a stage, surface velocity, and physically measured discharge must be available. The measurement information is entered into Q-commander which creates a constraint on the k-factor profile relating surface velocity to the average velocity for the measurement gauge height. Changes to the initial roughness coefficient can then be used to adjust the k-factor profile to the measurement via the Q-commander software. Subsequent measurements are then used to provide additional constraints to adjust the k-factor profile manually, if necessary, as seen in Figure 3.3.10.



Reference discharges

	Level [ft]	Vel. [ft/s]	Q [ft³/s]	Ref. Q [ft³/s]	Error [%]
1	154.81	1.47	11.915	13.2	10.78
2	163.28	2.36	716.266	707	-1.29
3	163.24	2.36	710.811	662	-6.87
4	163.12	2.11	620.691	666	7.3
5	159.59	2.32	309.336	310	0.21
6	155.21	2.19	31.176	26.7	-14.36
7	154.91	1.59	15.214	16.2	6.48
8	154.53	1.19	2.929	1.69	-42.3
9	154.45	1.21	2.056	2.95	43.48
10	161.11	2.38	444.098	442	-0.47
11	160.44	2.33	378.319	386	2.03
12	167.41	3.25	2202.589	2060	-6.47
13	167.62	3.27	2295.388	2300	0.2

Figure 3.3.10 Example of a 13-point calibration of the k-factor profile in Q-Commander

Initially, at Tier 1 sites discharge measurements were made at all stages to determine how many measurements were needed to calibrate the gauge for accurate discharge throughout the entire range of observed flow. Prior to calibrating, the initial k-factor profile was used to determine the magnitude of the difference between the RQ-30 derived discharge and the physical verification measurement.

A calibration point was then created using the first verification measurement and all subsequent measurements were assessed against the 1-point calibrated RQ-30 derived discharge. The process was repeated until all measurements had been calibrated and assessed. Since these gauges are being assessed as flood decisions support tools, discharges below 20 cfs were omitted from calibration error calculation. Discharges under 20 cfs were omitted because lower flows are highly sensitive to small bathymetric changes resulting in large errors that do not represent the high flow measurement of discharge.

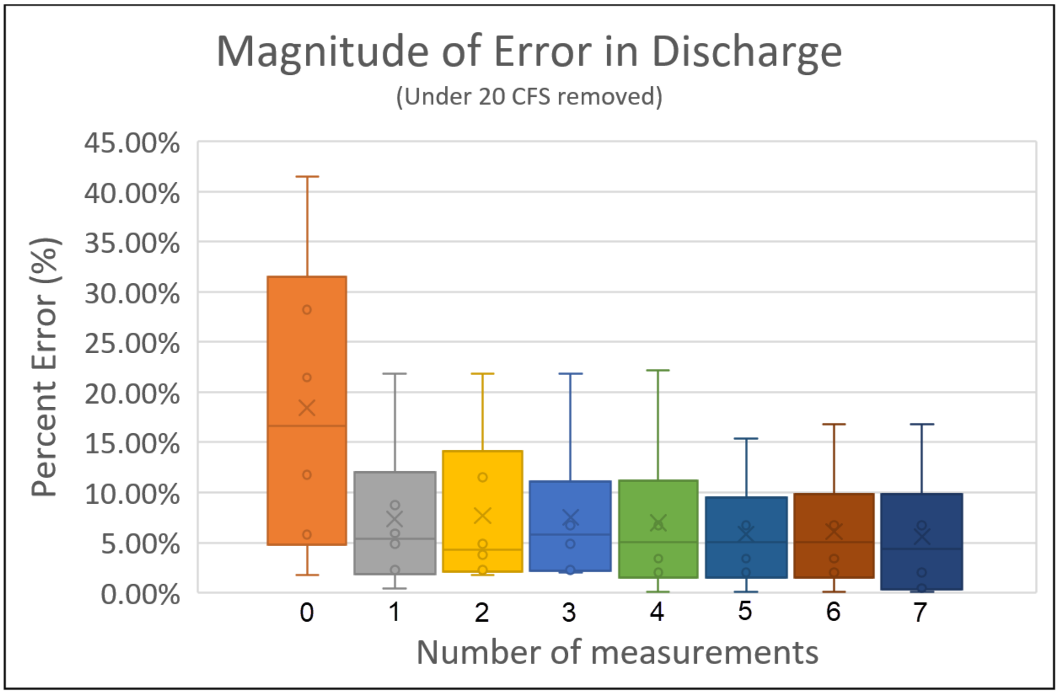


Figure 3.3.11 The magnitude of error between the RQ-30 computed discharge and the USGS verification measurements as calibrations are performed sequentially

Figure 3.3.11 shows that calibrating to each individual measurement decreases overall error but may require numerous measurements which are expensive and dependent on weather conditions. Using this approach, calibration of an RQ-30 sensor may not be any faster than traditional methods.

A second approach was explored after a pattern was recognized in the previous calibration assessment. The overall shape of the initial k-factor profile computed in the Q-Commander software closely resembles the finished, calibrated profile. Rather than making frequent measurements, targeted stages were selected and measured to constrain the original profile. Targeted measurements include the main channel, the transition between main channel and overbank, and overbank stages. Once the targeted measurements are made, the roughness coefficient is adjusted to best fit the calibration points.

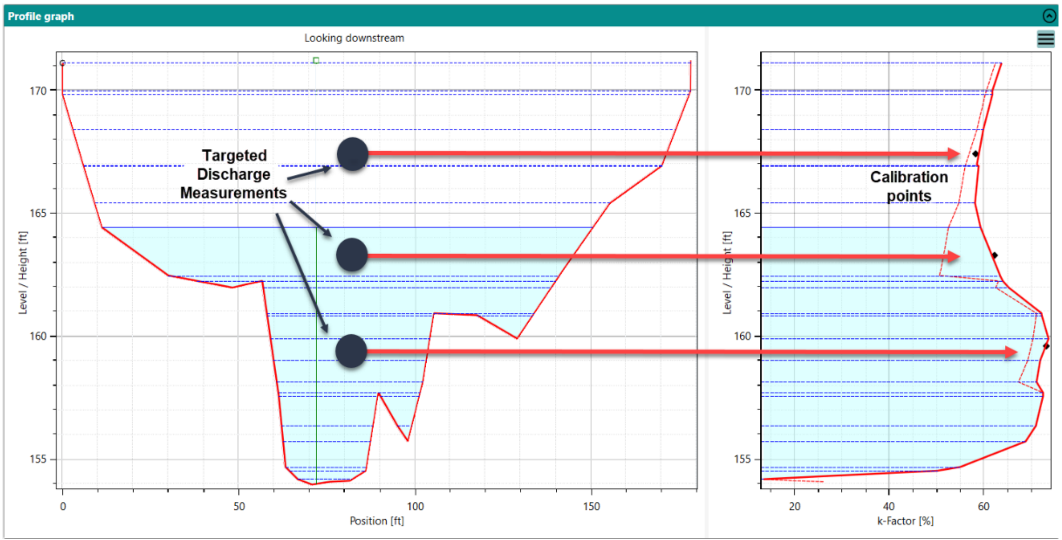


Figure 3.3.12 Channel geometries are targeted to constrain the k-factor profile

Figure 3.3.12 demonstrates a typical channel with overbank where three stages are targeted to expedite the calibration process. Each measurement constrains the software derived k-factor profile while closely preserving the original profile shape.

Figure 3.3.13 shows a calibration for the previous example when the targeted method is followed. In this example, an overall error of less than 10% was achieved for measurements greater than 20 cubic feet per second with 2 calibration points.

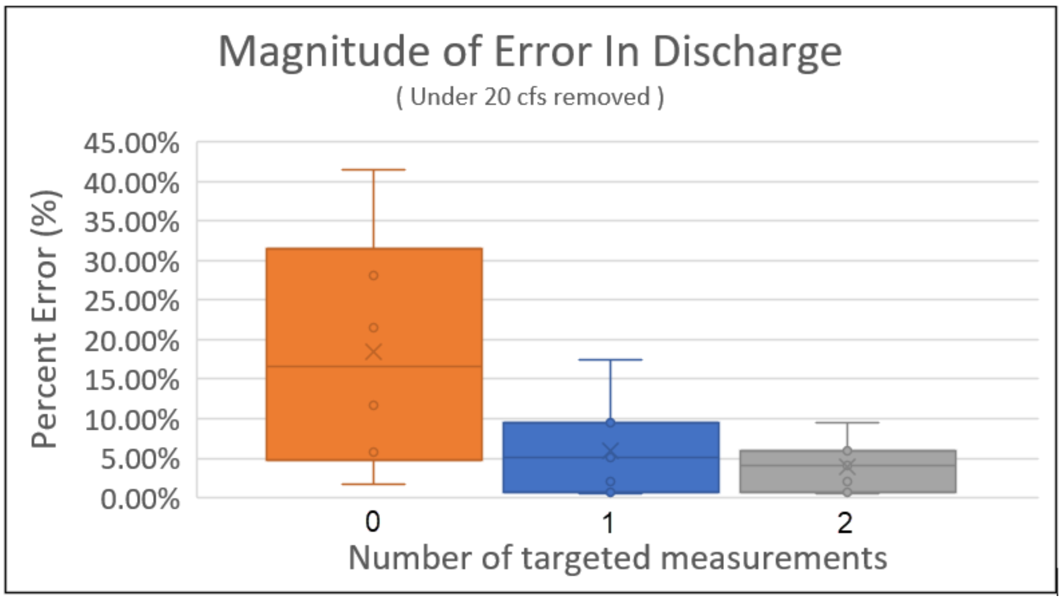


Figure 3.3.13 The magnitude of error for all measurements using the targeted calibration approach

3.4. Conclusions

The RQ-30 velocimetry gauge is not widely used by the USGS as a method of discharge computation. The datasets recorded during this project have progressed the current knowledge of velocimetry within the USGS, bringing it closer to an accepted method of computing discharge.

Water levels recorded by the RQ-30 proved to be precise and accurate if the initial calibration was correct when checked against stable references. The stage radar showed the ability to maintain precise water level elevation without the need for frequent calibrations or resets by technicians. By not needing to recalibrate the sensors as often, the standard frequency of 8-week maintenance visits could potentially be extended.

Cross sections surveyed during the project have shown little change caused by natural means, preserving the stage-area relation necessary for consistent discharge computation using velocimetry. Modifications made to the gauge cross-section were the only discernable differences that required a resurvey during the project. The Cross-sectional area at base flow conditions may be sensitive to flood events and directly affect the computation of discharge using velocimetry.

Velocity data was accurately recorded when flows were greater than approximately 0.8 feet per second. The range of measured velocities varied from 0.02 feet per second to 0.20 feet per second depending on the turbulence experienced from bridge piers, debris, and other eddy velocities created in the channel.

Although, the discovery of the targeted measurement approach to velocimetry discharge calibration has greatly reduced the time needed to calibrate a streamflow gauge, more data is needed to ensure the method is valid for all conditions. Site conditions such as high slope, variable bedforms, bridge disturbances, and backwater affected flows have not been fully assessed.

Acknowledgements

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