Manual for Real-Time Quality Control of Stream Flow Observations

A Guide to Quality Control and
Quality Assurance for
Stream Flow Observations
in Rivers and Streams

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Revision History

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Endorsement Disclaimer

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Request to Manual Users

To gauge the success of the QARTOD project, it helps to be aware of groups working to utilize these QC tests. Please notify us of your efforts or intentions to implement QARTOD processes by sending a brief email to qartod.board@noaa.gov or posting a notice at http://www.linkedin.com/groups?gid=2521409.

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We greatly appreciate the efforts from hundreds of volunteers who have assisted in the develop of the series of QARTOD QC manuals and supporting documents, and we are rewarded by the work of those implementing these QC tests.

Acronyms and Abbreviations

ADCP	Acoustic Doppler Current Profiler
ADVM	Acoustic Doppler Velocity Meter
AOOS	Alaska Ocean Observing System
CeNCOOS	Central and Northern California Ocean Observing System
CO-OPS	Center for Operational Oceanographic Products and Services
CRC	Cyclic Redundancy Check
DMAC	Data Management and Communications
GCOOS	Gulf of Mexico Coastal Ocean Observing System
GLOS	Great Lakes Observing System
GOES	Geostationary Operational Environmental Satellite
GOOS	Global Ocean Observing System
IOOS	Integrated Ocean Observing System
MARACOOS	Mid-Atlantic Regional Association Coastal Ocean Observing System
NANOOS	Northwest Association of Networked Ocean Observing Systems
NERACOOS	North Eastern Regional Association of Coastal Ocean Observing Systems
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
PacIOOS	Pacific Islands Ocean Observing System
QARTOD	Quality Control/Quality-Assurance of Real-Time Oceanographic Data
QA	Quality Assurance
QC	Quality Control
RCOOS	Regional Coastal Ocean Observing System
SCCOOS	Southern California Coastal Ocean Observing System
SD	Standard Deviation
SECOORA	Southeast Coastal Ocean Observing Regional Association
SF	Stream Flow
UNESCO	United Nations Educational, Scientific, and Cultural Organization
USACE	U.S. Army Corps of Engineers
USGS	United States Geological Survey

Definitions of Selected Terms

This manual contains several terms whose meanings are critical to those using the manual. These terms are included in the following table to ensure that the meanings are clearly defined.

Codable Instructions	Codable instructions are specific guidance that can be used by a software programmer to design, construct, and implement a test. These instructions also include examples with sample thresholds.
Data Record	Data record is one or more messages that form a coherent, logical, and complete observation.
Index Velocity	Water velocity measured in some portion of a stream that is used as an index or predictor of the mean velocity in the channel.
Interoperable	Interoperable means the ability of two or more systems to exchange and mutually use data, metadata, information, or system parameters using established protocols or standards.
Message	Message means a standalone data transmission. A data record can be composed of multiple messages.
NWIS	NWIS is the USGS National Water Information System.
Operator	Operators are individuals or entities responsible for collecting and providing data.
Quality Assurance (QA)	QA means processes that are employed with hardware to support the generation of high quality data. (section 2.0 and appendix B)
Quality Control (QC)	QC means follow-on steps that support the delivery of high-quality data, requiring both automation and human intervention. (section 3.0)
Rating curve	The rating curve is a drawn curve showing the relation between gage height and discharge of a stream at a given gaging station.
Real-Time	Real-time means that: data are delivered without delay for immediate use; time series extends only backwards in time, where the next data point is not available; and sample intervals may range from a few seconds to a few hours or even days, depending upon the sensor configuration (section 1.0).
Sensor	A sensor is a device that detects or measures a physical property and provides the result without delay. A sensor is an element of a measuring system that is directly affected by a phenomenon, body, or substance carrying a quantity to be measured. (JCGM 2012)
Stage	Stage is the water level above some arbitrary point, usually with the zero height being near the river bed, in the river and is commonly measured in feet. From https://water.usgs.gov/edu/qa-measure-streamstage.html
Stream Flow (SF)	Stream flow is the water discharge that occurs in a natural channel. A more general term than runoff, stream flow may be applied to discharge whether or not it is affected by diversion or regulation. From https://water.usgs.gov/edu/dictionary.html

Thresholds	Thresholds are limits that are either defined by the operator or statistically generated.
Variable	A variable is an observation (or measurement) of biogeochemical properties within oceanographic and/or meteorological environments.

1.0 Background and Introduction

The U.S. Integrated Ocean Observing System (IOOS®) has a vested interest in collecting high-quality data for the 34 core variables (https://ioos.noaa.gov/about/ioos-by-the-numbers) measured on a national scale. In response to this interest, U.S. IOOS continues to establish written, authoritative procedures for the quality control (QC) of real-time data through the Quality Assurance/Quality Control of Real-Time Oceanographic Data (QARTOD) Project, addressing each variable as funding permits. This stream flow data manual is the twelfth in a series of guidance documents that address the QC of real-time data for each core variable.

Please refer to https://ioos.noaa.gov/project/qartod/ for the following documents:

1) U.S. Integrated Ocean Observing System, 2015. U.S IOOS QARTOD Project Plan - Accomplishments for 2012–2016 and Update for 2017–2021. 47 pp. https://doi.org/10.7289/V5JQ0Z71

2) U.S. Integrated Ocean Observing System, 2015. Manual for Real-Time Quality Control of Dissolved Oxygen Observations Version 2.0: A Guide to Quality Control and Quality Assurance for Dissolved Oxygen Observations in Coastal Oceans. 48 pp. https://doi.org/10.7289/V5ZW1J4J

3) U.S. Integrated Ocean Observing System, 2015. Manual for Real-Time Quality Control of In-Situ Current Observations Version 2.0: A Guide to Quality Control and Quality Assurance of Acoustic Doppler Current Profiler Observations. 51 pp. https://doi.org/10.7289/V5WM1BMZ

4) U.S. Integrated Ocean Observing System, 2015. Manual for Real-Time Quality Control of In-Situ Surface Wave Data Version 2.0: A Guide to Quality Control and Quality Assurance of In-Situ Surface Wave Observations. 64 pp. https://doi.org/10.7289/V5KK991T

5) U.S. Integrated Ocean Observing System, 2015. Manual for Real-Time Quality Control of In-Situ Temperature and Salinity Data Version 2.0: A Guide to Quality Control and Quality Assurance of In-Situ Temperature and Salinity Observations. 56 pp. https://doi.org/10.7289/V5V40SD4

6) U.S. Integrated Ocean Observing System, 2014. Manual for Real-Time Quality Control of Water Level Data Version 2.0: A Guide to Quality Control and Quality Assurance of Water Level Observations. 43 pp. https://doi.org/10.7289/V5QC01Q7

7) U.S. Integrated Ocean Observing System, 2017. Manual for Real-Time Quality Control of Wind Data Version 1.1: A Guide to Quality Control and Quality Assurance of Coastal and Oceanic Wind Observations. 47 pp. https://doi.org/10.7289/V5FX77NH

8) U.S. Integrated Ocean Observing System, 2017. Manual for Real-Time Quality Control of Ocean Optics Data Version 1.1: A Guide to Quality Control and Quality Assurance of Coastal and Oceanic Optics Observations. 49 pp. https://doi.org/10.7289/V5XW4H05

9) U.S. Integrated Ocean Observing System, 2018. Manual for Real-Time Quality Control of Dissolved Nutrients Data Version 1.1: A Guide to Quality Control and Quality Assurance of Coastal and Dissolved Nutrients Observations. 56 pp. https://doi.org/10.7289/V5TT4P7R

10) U.S. Integrated Ocean Observing System, 2016. Manual for Real-Time Quality Control of High Frequency Radar Surface Currents Data Version 1.0: A Guide to Quality Control and Quality Assurance of High Frequency Radar Surface Currents Data Observations. 58 pp. https://doi.org/10.7289/V5T43R96

11) U.S. Integrated Ocean Observing System, 2017. Manual for Real-Time Quality Control of Phytoplankton Data Version 1.0: A Guide to Quality Control and Quality Assurance of Phytoplankton Data Observations. 67 pp. https://doi.org/10.7289/V56D5R6S

12) U.S. Integrated Ocean Observing System, 2017. Manual for Real-Time Quality Control of Passive Acoustics Data Version 1.0: A Guide to Quality Control and Quality Assurance of Passive Acoustics Observations. 45 pp. https://doi.org/10.7289/V5PC30M9

Please reference this document as:

U.S. Integrated Ocean Observing System, 2018. Manual for Real-Time Quality Control of Stream Flow Data Version 1.0: A Guide to Quality Control and Quality Assurance of Stream Flow Observations in Rivers and Streams. 45 pp. https://doi.org/10.25923/gszc-ha43

This manual is a living document that reflects the state-of-the-art QC testing procedures for stream flow observations. It is written for the experienced operator but also provides examples for those who are just entering the field.

2.0 Purpose/Constraints/Applications

The following sections describe the purpose of this manual, as well as the constraints that operators may encounter when performing QC of stream flow data and specific applications of those data.

2.1 Purpose

The purpose of this manual is to provide guidance to the U.S. IOOS and others with an interest in stream flow for the real-time QC of stream flow measurements using an agreed-upon, documented, and implemented standard process. This manual is also a deliverable to the U.S. IOOS Regional Associations and the ocean observing community and represents a contribution to a collection of core variable QC documents.

Most operators provide real-time data on a provisional basis, alerting users that post-processing is required to validate their data. However, even this provisional data should be quality controlled. Data released in real-time should be subjected to automated QC processes, which: 1) provide a quality-control indicator, 2) alert the operator when questionable or interesting data are presented, and 3) prevent the dissemination of bad data.

These practices for QC of stream flow data were developed by operators with experience using a variety of sensors and technologies. In-situ, real-time determination of stream flow is typically a derived quantity that can be based upon observations of water level (stage), in-situ single point/profiles of velocity, or remotely sensed surface velocity. The QARTOD manuals addressing water levels, in-situ currents, and high frequency radar surface currents can be used for the real-time QC of these observations. A rating curve (a pre-established relationship between the specific observation and total discharge) is then used to derive stream flow. Within this manual, references to measurement of stream flow or discharge are understood to refer to computed values using one of these specific observations and a rating curve. The tests described in the water level, in-situ currents, and high frequency radar surface currents manuals are similar in many instances to those described in this one. Operators who find test redundancy may wish to merge test procedures or carry test results forward from the specific observations to QC of the derived stream flow determinations.

Stream flow observations covered by these procedures are collected as a measure of discharge or input to bays or coasts[1] in real-time or near-real-time settings. These tests draw from existing expertise in federal (U. S. Geological Survey [USGS], U.S. Army Corps of Engineers (USACE) and state agencies, manufacturers and vendors, and private sector organizations engaged in such measurements. References to USGS installations use a different spelling for gage (versus gauge). The USGS spelling is attributed to the first Chief Hydrographer of the USGS, Frederick H. Newell (Follansbee 1994).

This manual differs from existing QC procedures for stream flow measurements in that its focus is on real-time data. It presents a series of nine tests that operators can incorporate into practices and procedures for QC of stream flow measurements. These tests apply only to the in-situ, real-time measurement of stream flow as observed by sensors deployed on fixed platforms, and not to remotely sensed stream flow measurements (e.g., satellite observations) or those made onsite by field personnel. Table 2-1 shows types of techniques and areas that are included and excluded in this manual. Those excluded are deemed to require substantially

[1]The coast means coasts of the U.S. Exclusive Economic Zone (EEZ) and territorial sea (http://oceanservice.noaa.gov/facts/eez.html) Great Lakes, and semi-enclosed bodies of water and tidal wetlands connected to the coastal ocean.

different QC tests, a different observational community, substantially greater resources, or they presently lack a real-time data delivery capability. Whenever possible, they will be included in later manual updates.

Table 2-1. Types of techniques and areas included and excluded in this manual.

Techniques Included	Technique Excluded
Stage (pressure, acoustic, microwave) Point velocity (impeller, sonic) Profiled velocities (ADCP, upward, downward, horizontal) Doppler surface current measurement	Satellite Aircraft

These test procedures are written as a high-level narrative from which computer code can be developed to execute specific tests and set data flags (data quality indicators) within an automated software program. Those implementing QARTOD tests have created a code repository (https://github.com/ioos/qartod) where operators may find or post examples of code in use. Although certain tests are recommended, thresholds can vary among data providers. The tests described here are designed to support a range of SF measurements and operator capabilities. Some well-established programs, such as the USGS National Real-Time Water Quality program (http://nrtwq.usgs.gov), with the highest standards have implemented very rigorous QC processes. Others, with different requirements, may utilize sensors or measurements with data streams that cannot support as many QC checks—all have value when used prudently. It is the responsibility of the users to understand and appropriately utilize data of varying quality, and operators must provide support by documenting and publishing their QC processes. A balance must be struck between the time-sensitive needs of real-time observing systems and the degree of rigor that has been applied to non-real-time systems by operators with decades of QC experience.

High-quality observations require sustained QA and QC practices to ensure credibility and value to operators and data users. QA practices involve processes that are employed with hardware to support the generation of high-quality data, such as a sufficiently accurate, precise, and reliable sensor with adequate resolution. Other QA practices include: sensor calibration; calibration checks and/or in-situ verification, including post-deployment calibration; proper deployment considerations, such as measures for corrosion control and anti-fouling; solid data communications; adequate maintenance intervals; and creation of a robust quality control process. Post-deployment calibration (instrument verification after recovery) issues are not part of the scope of this manual. However, QC and QA are interrelated, and both are important to the process; therefore, QA considerations are briefly addressed in appendix B.

QC involves follow-on steps that support the delivery of high-quality data and requires both automation and human intervention. QC practices include such things as format, checksum, timely arrival of data, threshold checks (minimum/maximum rate of change), neighbor checks, climatology checks, model comparisons, signal/noise ratios, verification of user satisfaction, and generation of data flags (Bushnell 2005).

The process of ensuring data quality is not always straightforward. QA/QC procedures may be specific to a sensor technology or even to a particular manufacturer's model, so the establishment of a methodology that is applicable to every sensor is challenging.

2.2 Constraints

Many measurements of the 34 U.S. IOOS core variables of interest utilize similar sensing technologies but require substantially different QC methods. However, QC tests should not be overly generic, so these variables must be divided and grouped so that specific meaningful tests are appropriate to the variables included in the group. In this manual, stream flow measurements that are sufficiently common in nature to have similar QC checks are identified.

2.2.1 Data Processing Methodology

The type of sensor used to derive SF data and the system used to process and transmit the measurements determine which QC algorithms are used. In-situ systems with sufficient onboard processing power within the sensor may substantially process the data to produce derived products, such as an average velocity of a specified time period. Some sensors may sample at high-rate or burst mode (e.g., 1 Hz). These samples are used to produce the derived value that is transmitted (e.g., hourly value). Statistical information about the high-rate sample distributions may also be used and transmitted as real-time QC parameters (e.g., sample standard deviations and outliers). If ample transmission capability is available, expanded data streams may be transmitted ashore and subsequently quality controlled from there. Conversely, when data transmission capability is constrained, observations may be compiled and transmitted less frequently. However, they are still considered to be real-time, since there will always be a most recent observation. To accommodate a range of different operator methodologies, three levels of QC are proposed: required, strongly recommended, and suggested.

When onboard processing is used to reduce transmission of high-frequency samples, apply associated corrections, and generate the resultant observation to be transmitted, operators should have a full understanding of the algorithms employed. These processes are often proprietary, and when not fully revealed by the vendor or manufacturer, the operator should sufficiently test the system to gain the needed understanding.

Real-time stream flow discharge values are typically computed by making one or more index measurements, such as water stage, water velocity at a single point, or profiles of water velocity (both horizontal or vertical profiles). These observations are converted to discharge by applying a pre-existing relationship between the index and total discharge—the rating curve. Traditional methods to compute discharge are described in Rantz et al. 1982, Kennedy 1983, and Sauer 2002. A comprehensive explanation of the development of ratings and discharge computations for ADVM velocity observations is provided in Levesque and Oberg (2012).

Figure 2-1 shows a typical stage – discharge rating curve. Such curves are frequently updated to accommodate new data points or a shifting river bed.

The stability and accuracy of rating curves are topics of considerable debate. They can change gradually as a stream bed evolves or rapidly during a storm event. Beavers, ice dams, evolving watersheds, and many other disturbances impact the quality of the relationship. The high discharge end of the curve may have few data points, and accuracy may be reduced. Such concerns cannot be addressed in real-time (as defined here) at present. They must be evaluated during post-processing QC of SF observations. However, careful selection of the test thresholds to be used can ensure that the limits of the rating curve in use are properly applied—where the rating curve becomes questionable, so does the derived SF.

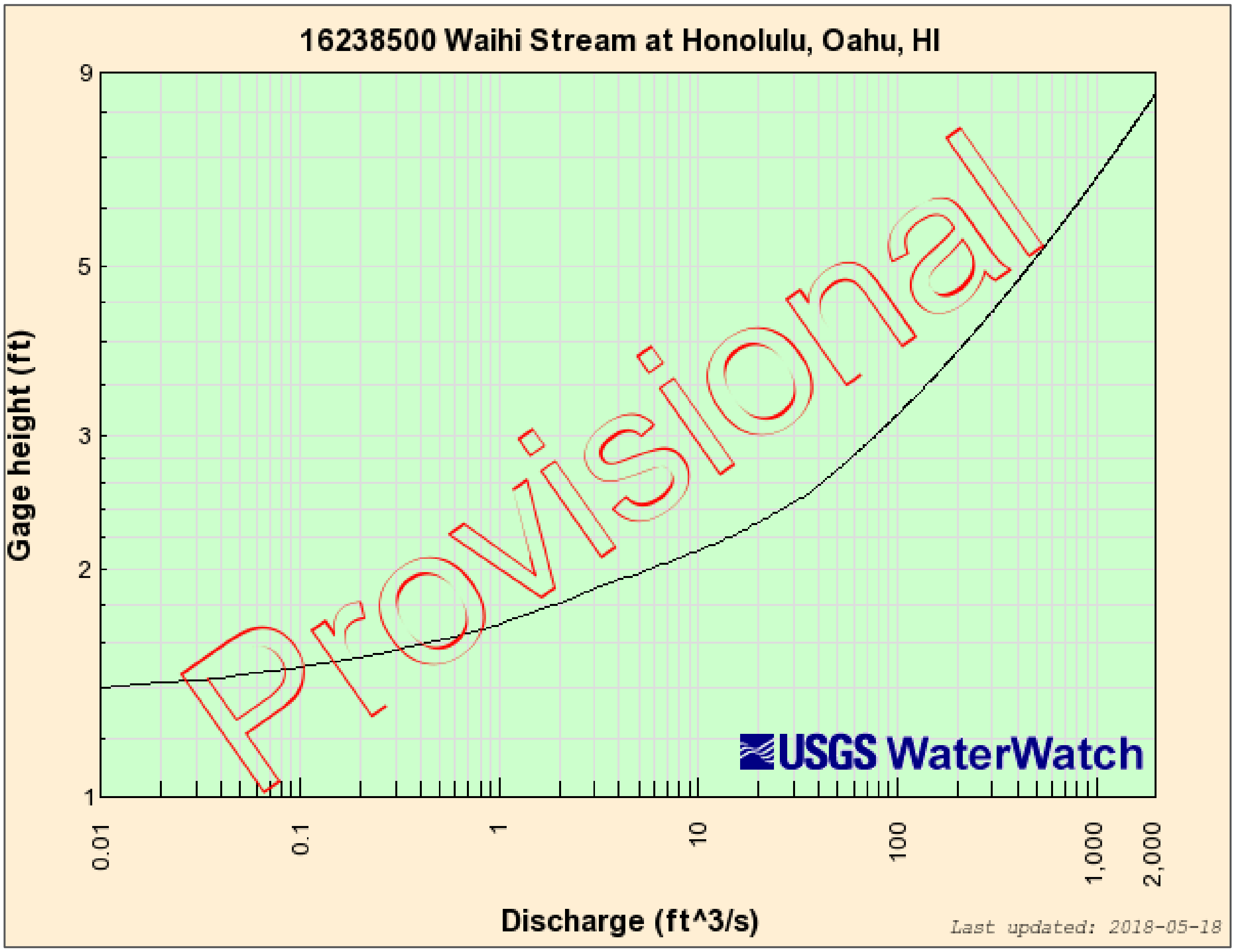

Figure 2-1. A typical stage – discharge rating curve. Graphic credit: USGS.

More recently, discharge measurements can be derived from satellite-based observations of river width, using a technique called mass-conserved flow law inversion (Gleason et al. 2018). While this technique has great promise for remote discharge measurements, it is not considered operational at this time.

2.2.2 Traceability to Accepted Standards

To ensure that sensors used to derive stream flow produce accurate data, rigorous calibrations and calibration checks must be performed in addition to QC checks. Most operators rely upon manufacturer calibrations and conduct calibration checks only before deployment. These calibration checks are critical to ensuring that the manufacturer calibration is still valid. Manufacturers describe how to conduct these calibration checks in their user manuals, which are currently considered QA and further addressed in appendix B.

Calibrations and calibration checks must be traceable to accepted standards. The National Institute of Standards and Technology (NIST) (http://www.nist.gov/index.html), a provider of internationally accepted standards, is often the source for these standards. Calibration activities must be tailored to match data use and resources. Calibration cost and effort increase dramatically as accuracy requirements increase. Fundamental NIST standards such as mass and volume may be required when conducting calibration checks on sensors used to produce SF measurements. Where NIST standards are not available, an active research effort generally exists among operators and manufacturers regarding the use of primary and secondary standards for instrument calibration and calibration checks.

2.2.3 The Effect of Dynamic Environments on Sensor Data

SF measurements can be challenging for many reasons: extremely rapid changes can occur during storms, stream bed changes affect the ratings curves, and stream flows computed in regions near or within tidal influences become quite complex.

As with many other real-time QC challenges, the question is how to deal with extremes associated with a phenomenon in a data time series, but yet identify questionable data values that may have similar characteristics. One option is to allow a tighter QC requirement for the data, highlighting the event with a suspect flag and requiring a human review. This way, the event is both acknowledged as substantial if real, and identified as potentially questionable in the absence of causal forces.

2.2.4 Sensor Deployment Considerations and Hardware Limitations

Stream flow sensors can be deployed in several ways. The typical constraints of field data collection apply—including cost, power, data transmission, bio-fouling, vandalism, and electronics in a challenging environment. Examples of these deployment options are shown in figs. 2-2 and 2-3.

Figure 2-2 shows a typical modern USGS installation of a station on a fixed bridge. In addition to a microwave altimeter to measure water level, the station includes measurements of wind speed and direction, air temperature, barometric pressure, and rainfall. It is solar powered, and data is telemetered through NOAA's GOES geostationary satellite.

Figure 2-3 shows an illustration of a side-looking ADCP mounted on a slanted rail to enable easy retrieval of the ADCP for maintenance. Consideration of beam-spreading and side-lobe interference must be carefully considered for such an installation.

Figure 2-2. This USGS gauge is mounted on a fixed bridge and utilizes a microwave altimeter to measure water levels. The station also includes wind speed and direction, air temperature, barometric pressure, and rainfall sensors. Photo credit: M. Bushnell.

Figure 2-3. This illustration shows a possible deployment of a side-looking ADCP on a slanted rail system. Photo credit: SonTek.

Instrumentation

To make stream flow observations, operators employ a variety of sensors. Listed below are descriptions of several types of sensors that generate data that could be subjected to the tests described herein. The list is not comprehensive, and operators must determine if these tests apply to their particular stream flow sensor.

Table 2-2 provides examples of manufacturers and sensors (in no particular order) that are typically used to observe stream flow, and fig. 2-4 shows several sensors listed in table 2-2. Some manufacturers have changed names, and some sensors are not currently marketed; however, data from these devices may still be generated, and they are included here as valid representatives of the technology.

As with most sensors, the effects of bio-fouling must be considered. Bio-fouling varies seasonally and geographically and can often be the limiting factor in determining the deployment duration.

Table 2-2. Commonly used sensors for stream flow observations.

Manufacturer/Sensor	Variables Measured	Measuring Principle
Codar / RiverSonde	Cross-channel surface velocity profiles	UHF Bragg scatter
OTT / Radar Level Sensor	Water level	Microwave
OTT / Surface Velocity Radar 100	Surface currents	24 GHz Doppler backscatter
SonTek IQ and Argonaut Series	Vertical current profiles	Acoustic Doppler
SonTek SL Series	Horizontal current profiles	Acoustic Doppler
Sutron Compact Constant Flow (CF) Bubbler	Water level	Pressure
TRDI / ChannelMaster	Horizontal current profiles	Acoustic Doppler
TRDI Workhorse Monitor or Sentinel	Vertical current profiles	Acoustic Doppler
WaterLOG / Nile Series 502/504/517	Water level	Microwave

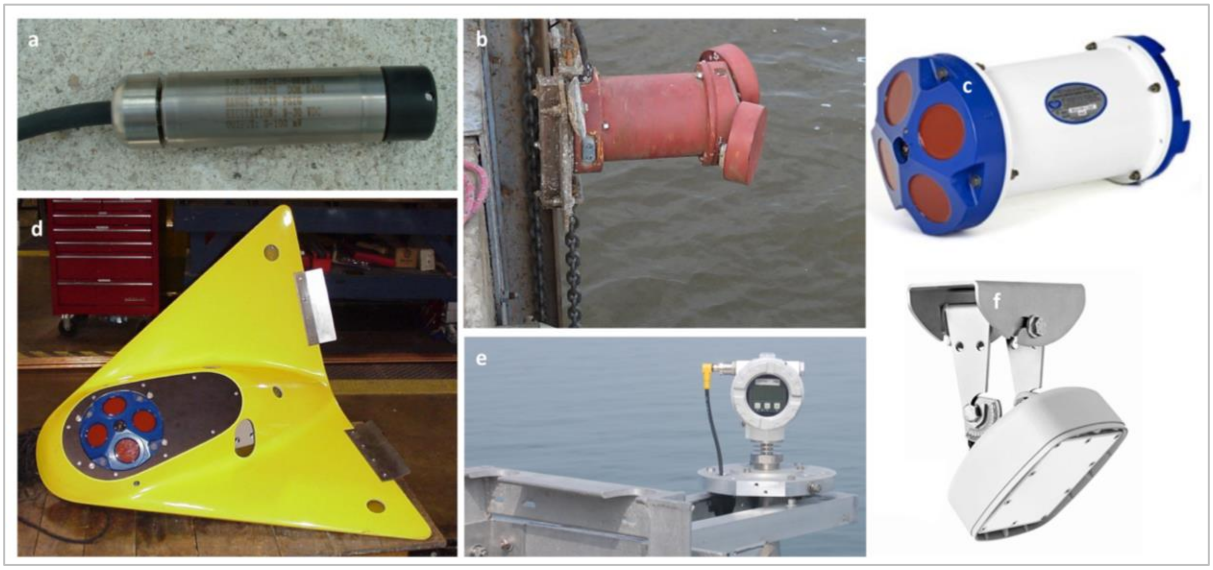

Figure 2-4. A small sample of devices used to collect data for stream flow determinations: a) KPI pressure sensor, b) SonTek SL ADP c) RDI ADCP, d) RDI ADCP in YSI fin, e) details, f) Xylem Design Analysis H3611. Photo credits: M. Bushnell, TRDI, Xylem.

Steps in a time series during a calibration, sensor swap, or cleaning provide valuable information for future service intervals, and (if caused by bio-fouling) can be highly dependent on both the site and season. Correcting a data shift like this is extremely difficult, so servicing schedules and the technology used should be carefully considered. Constant improvements in anti-fouling measures and sensor technology stability are being made. Operators should investigate which technology best suits their application, the field service budget, and data quality goals.

While outside the scope of the real-time tests described in this manual, QA is critical to data quality. Sensors require attention to proper QA measures both before and after the deployment. Operators must follow the manufacturer's recommendations for factory calibration schedules and proper sensor maintenance. Often, operators take field samples during deployment, recovery, or service to validate the performance of an in-situ sensor. If resources permit, it is recommended that samples be obtained mid-deployment without disturbing the sensor.

Also important, but beyond the scope of this document at present, is the determination and reporting of data uncertainty. Knowledge of the accuracy of each observation is required to ensure that data are used appropriately and aids in the computation of error bounds for subsequent products derived by users. All sensors and measurements contain errors that are determined by hardware quality, methods of operation, and data processing techniques. Operators should routinely provide a quantitative measure of data uncertainty in the associated metadata. Such calculations can be challenging, so operators should also document the methods used to compute the uncertainty. The limits and thresholds implemented by operators for the data QC tests described here are a key component in establishing the observational error bounds. Operators are strongly encouraged to consider the impact of the QC tests on data uncertainty, as these two efforts greatly enhance the utility of their data.

Sensor redundancy is key to obtaining measurements and ensuring that uncertainties can be assigned to those measurements. Stream flow measurements are not independent, being sensitive primarily to local conditions. Hence, comparing two adjacent instruments can assist in evaluation of data quality, as well as provide two (or more) independent estimates of a variable of interest. Variation in the estimated values can be useful in uncertainty calculations.

2.3 Applications of Stream Flow Data

Real-time observations of stream flow are important for a wide variety of applications, including water management, irrigation, cooling of nuclear power plants, monitoring stormwater runoff, and flood forecasts. For IOOS, river discharge is an important input into estuarine nutrient loading observations and modeling.

Other applications utilizing post-processed data do not require real-time QC but benefit from it through early detection of stream flow sensors' issues. Some examples of observing systems that may benefit from standardized real-time QC testing include the USGS National Water Information System (https://waterdata.usgs.gov/nwis), the USACE (http://www.rivergages.com), and the Water Survey of Canada (https://wateroffice.ec.gc.ca).

3.0 Quality Control

In order to conduct real-time QC on stream flow observations, the first pre-requisite is to understand the science and context within which the measurements are being conducted. Stream flow measurements are dependent upon many things such as season and location. The real-time QC of these observations can be extremely challenging. Human involvement is therefore important to ensure that solid scientific principles are applied to the process. Without credible science-based thought, good data might be discarded, and bad data distributed. It is also important to note that advances in stream flow sensor technology have eliminated many of the problems encountered in older devices.

Again, this manual focuses specifically on real-time data in stream and river environments, so the operator is likely to encounter aspects of data QC where the flags and tests described in the following sections do not apply because the data are not considered to be real-time. For example, in the absence of supplemental reference data points, drift often cannot be detected or corrected. Drift correction for stream flow sensors during post-processing is difficult even with a post-calibration in hand because drift in stream flow sensors is not always linear. Another example might be the ability of some data providers to backfill data gaps. In both of these examples, the observations are not considered to be real-time for purposes of QC checks.

3.1 QC Flags

Data are evaluated using QC tests, and the results of those tests are indicated using flags in the data files. Table 3-1 provides the set of flags and associated descriptions proposed by the International Oceanographic Data and Information Exchange (IODE) and adopted by the Intergovernmental Oceanographic Commission (IOC) in 2013. Operators may incorporate additional flags for inclusion in metadata records. For example, a stream flow observation may fail the gross range test and be flagged as having failed the test. Additional flags may be incorporated to provide more detailed information to assist with troubleshooting. If the data failed the gross range check by exceeding the upper limit, "failed high" may indicate that the values were higher than the expected range, but such detailed flags primarily support maintenance efforts and are presently beyond U.S. IOOS requirements for QC of real-time data.

Flags set in real-time should retain their original settings. Further post-processing of the data may yield different conclusions from those suggested in the initial real-time flags. However, by retaining the real-time flag settings, the historical documentation is preserved. The exception to the rule occurs for test 6 spike check, where the most recent point must be flagged as "2 Not Evaluated" until the next point arrives, and the spike check can be performed.

Table 3-1. Flags for real-time data (UNESCO 2013)

Flag	Description
Pass=1	Data have passed critical real-time quality control tests and are deemed adequate for use as preliminary data.
Not Evaluated=2	Data have not been QC-tested, or the information on quality is not available.
Suspect or Of High Interest=3	Data are considered to be either suspect or of high interest to data providers and users. They are flagged suspect to draw further attention to them by operators.
Fail=4	Data are considered to have failed one or more critical real-time QC checks. If they are disseminated at all, it should be readily apparent that they are not of acceptable quality.
Missing Data=9	Data are missing; used as a placeholder.

3.2 Test Hierarchy

This section outlines the nine real-time QC tests that are required or recommended for selected stream flow sensors. Tests are listed in order of increasing complexity, and generally, decreasing utility and are divided into three groups. The tests in group 1 are required for all stream flow data measurements collected for U.S. IOOS. Operators must consider each test in group 2 and group 3 to determine if it can be applied in their particular instance—not all tests can be implemented in all situations. Table 3-2 shows the test hierarchy.

Table 3-2. QC Tests in order of implementation

Group 1 *Required*	Test 1 Test 2 Test 3	Gap Test Syntax Test Gross Range Test
Group 2 *Strongly Recommended*	Test 4 Test 5 Test 6 Test 7	Climatological Test Spike Test Rate of Change Test Flat Line Test
Group 3 *Suggested*	Test 8 Test 9	Multi-Variate Test Neighbor Test

Some effort will be needed to select the best thresholds, which are determined at the local level and may require multiple iterations of trial and error before final selections are made. This manual does not provide overly generic guidance for selecting thresholds because doing so may not yield a good starting point at the local level. Although more tests imply a more robust QC effort, valid reasons may exist for not invoking a particular test in some instances. Where a test from group 2 or group 3 cannot be implemented, the operator should document the reason it does not apply. Such flexibility is needed to support the U.S. IOOS effort, since the number of tests conducted and the justification for not applying some tests are useful for evaluating an operator's skill levels.

Some effort will be needed to select the best thresholds, which are determined at the operator level and may require multiple iterations of trial and error before final selections are made. A successful QC effort is highly dependent upon selection of the proper thresholds, which should not be determined arbitrarily but can be based on historical knowledge or statistics derived from recently acquired data. Although this manual provides some guidance for selecting thresholds based on input from various operators, it is assumed that operators have the expertise and motivation to select the proper thresholds to maximize the value of their QC effort. Operators should openly provide thresholds as metadata for user support. This shared information will help U.S. IOOS to document standardized thresholds that will be included in future releases of this manual.

3.3 QC Tests

A variety of tests can be performed on the data to indicate data quality. Testing the integrity of the data transmission itself using a gap test and syntax test is a first step. If the data transmission is not sound, further testing is irrelevant. Additional checks evaluate the stream flow core variable values themselves through various comparisons to the data stream and to the expected conditions in the given environment. The tests listed in the following section presume a time ordered series of observations and denote the most recent observation as SF_n, preceded by a value at SF_{n-1}, and so on backwards in time. They were developed from input by authors and reviewers of this manual, as well as from QARTOD workshops (QARTOD 2003-2009). The focus is primarily on the real-time QC of observation SF_n, SF_{n-1}, and SF_{n-2}. There are several instances when tests are closely related, e.g., the climatology test is similar to the gross range test, the multi-variate test can be similar to the rate of change test, etc. As such, there are opportunities for clever and efficient coding, which are left to the programmers.

3.3.1 Applications of QC Tests to Stream Flow Sensors

These nine tests require operators to select a variety of thresholds. These thresholds should not be determined arbitrarily but can be based on historical knowledge or statistics derived from more recently acquired data. Operators must document the reasons and methods used to determine the thresholds. Examples are provided in the following test tables; however, operators are in the best position to determine the appropriate thresholds for their operations. Some tests rely on multiple data points most recently received to determine the quality of the current data point. When this series of data points reveals that the entire group fails, the current data point is flagged, but the previous flags are not changed. This action supports the view that historical flags are not altered. The first example is in test 7, the flat line test, where this scenario will become clearer. For additional information regarding flags, see U.S. IOOS (2017) posted on the U.S. IOOS QARTOD website.

Test 1) Gap Test (Required)

Check for arrival of data.		
Test determines that the most recent data point has been received within the expected time window (TIM_INC) and has the correct time stamp (TIM_STMP). **Note:** For those systems that don't update at regular intervals, a large value for TIM_STMP can be assigned. The gap check is not a panacea for all timing errors. Data could arrive earlier than expected. This test does not address all clock drift/jump issues.		
Flags	**Condition**	**Codable Instructions**
Fail=4	Data have not arrived as expected.	NOW – TIM_STMP > TIM_INC
Suspect=3	N/A	N/A
Pass=1	Applies for test pass condition.	N/A
Test Exception: None.		
Test specifications to be established locally by operator. **Example:** TIM_INC= 1 hour		

Test 2) Syntax Test (Required)

Check to ensure that the message is structured properly.		
Received data record (full message) contains the proper structure without any indicators of flawed transmission such as parity errors. Possible tests are: a) the expected number of characters (NCHAR) for fixed length messages equals the number of characters received (REC_CHAR), or b) passes a standard parity bit check, CRC check, etc. Many such syntax tests exist, and the user should select the best criteria for one or more syntax tests. **Note:** Capabilities for dealing with flawed messages vary among operators; some may have the ability to parse messages to extract data within the flawed message sentence before the flaw. Syntax check is performed only at the message level and not at the sub-message level.		
Flags	**Condition**	**Codable Instructions**
Fail=4	Data record cannot be parsed.	REC_CHAR ≠NCHAR
Suspect =3	Data record can be parsed.	REC_CHAR ≠NCHAR
Pass=1	Expected data record received; absence of parity errors.	N/A
Test Exception: None.		
Test specifications to be established locally by operator. **Example:** NCHAR = 128		

Test 3) Gross Range Test (Required)

Data point exceeds sensor or operator selected min/max.		
All sensors have a limited output range, and this can form the most rudimentary gross range check. No values less than a minimum value or greater than the maximum value the sensor can output (SF_SENSOR_MIN, SF_SENSOR_MAX) are acceptable. Additionally, the operator can select a smaller span (SF_USER_MIN, SF_USER_MAX) based upon local knowledge or a desire to draw attention to extreme values.		
Flags	**Condition**	**Codable Instructions**
Fail=4	Reported value is outside of sensor span.	SF_n < SF_SENSOR_MIN, or SF_n > SF_SENSOR_MAX
Suspect=3	Reported value is outside of user-selected span.	SF_n < SF_USER_MIN, or SF_n > SF_USER_MAX
Pass=1	Applies for test pass condition.	N/A
Test Exception: None.		
Test specifications to be established locally by operator. **Examples:** SF_SENSOR_MAX = 10,000 ft^3/sec (limited by the rating curve maximum, for example) SF_SENSOR_MIN = 0 ft3/sec SF_USER_MAX = 6000 ft3/sec SF_USER_MIN = 500 ft3/sec		

Test 4) Climatology Test (Strongly Recommended)

Test that data point falls within seasonal expectations.		
This test is a variation on the gross range check, where the gross range SF_Season_MAX and SF_Season_MIN are adjusted monthly, seasonally, or at some other operator-selected time period (TIM_TST). Expertise of the local user is required to determine reasonable seasonal averages. Longer time series permit more refined identification of appropriate thresholds.		
Flags	**Condition**	**Codable Instructions**
Fail=4	Because of the dynamic nature of SF, no fail flag is identified for this test.	N/A
Suspect=3	Reported value is outside of user-identified climatology window.	SF_n < SF_Season_MIN or SF_n > SF_Season_MAX
Pass=1	Applies for test pass condition.	N/A
Test Exception: None.		
Test specifications to be established locally by operator: A seasonal matrix of SF_{max} and SF_{min} values at all TIM_TST intervals. **Examples:** SF_SPRING_MIN =3000 ft^3/sec, SF_SPRING_MAX = 8000 ft^3/sec		

Test 5) Spike Test (Strongly Recommended)

Data point *n-1* exceeds a selected threshold relative to adjacent data points.		
This check is for single value spikes, specifically the SF value at point n-1 (SF_{n-1}). Spikes consisting of more than one data point are notoriously difficult to capture, but their onset may be flagged by the rate of change test. The spike test consists of two operator-selected thresholds, THRSHLD_LOW and THRSHLD_HIGH. Adjacent data points (SF_{n-2} and SF_n) are averaged to form a spike reference (SPK_REF). The absolute value of the spike is tested to capture positive and negative going spikes. Large spikes are easier to identify as outliers and flag as failures. Smaller spikes may be real and are only flagged suspect.		
Flags	**Condition**	**Codable Instructions**
Fail=4	High spike threshold exceeded.	$\vert SF_{n-1} – SPK\_REF\vert > THRSHLD\_HIGH$
Suspect=3	Low spike threshold exceeded.	$\vert SF_{n-1} – SPK\_REF\vert > THRSHLD\_LOW$ $\vert SF_{n-1} – SPK\_REF\vert < THRSHLD\_HIGH$
Pass=1	Applies for test pass condition.	N/A
Test Exception: None.		
Test specifications to be established locally by operator. **Examples:** THRSHLD_LOW = 500 ft^3/sec, THRSHLD_HIGH = 1000 ft^3/sec		

Spike Test Example

In the example shown in fig. 3-1, a negative-going spike is seen in a USGS station on the St. Johns River near Christmas, Florida. The knowledgeable local operator is best prepared to determine if the spike is suspect or should be flagged as failed.

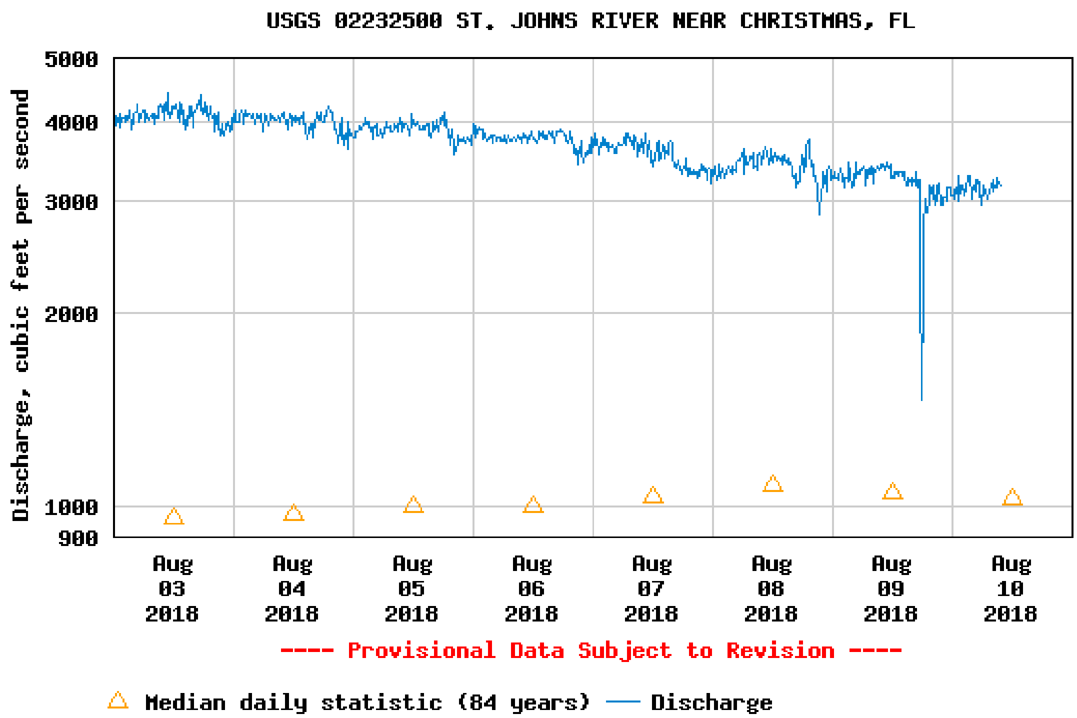

Figure 3-1. This negative-going spike would easily be captured with appropriate thresholds and identified as data that is suspect or failing real-time QC. Graphic credit: M. Bushnell using the USGS online graphics tools of the National Water Information System.

Test 6) Rate of Change Test (Strongly Recommended)

Excessive rise/fall test.

This test inspects the time series for a time rate of change that exceeds a threshold value SF_ROC_THRSHLD identified by the operator. SF values can change dramatically over short periods, hindering the value of this test. A balance must be found between a threshold set too low, which triggers too many false alarms, and one set too high, making the test ineffective. Determining the excessive rate of change is left to the local operator.

Flags	Condition	Codable Instructions
Fail=4	Because of the dynamic nature of SF, no fail flag is identified for this test.	N/A
Suspect=3	The rate of change exceeds the selected threshold.	If $\|SF_n - SF_{n-1}\|$>SF_ROC_THRSHLD, flag = 3
Pass=1	Applies for test pass condition.	N/A

Test Exception: None

Test specifications to be established locally by operator.
Example: SF_ROC_THRSHLD = 1000 ft^3/sec

Test 7) Flat Line Test (Strongly Recommended)

Invariate stream flow value.		
When some sensors and/or data collection platforms fail, the result can be a continuously repeated observation of the same value. This test compares the present observation (SF_n) to a number (REP_CNT_FAIL or REP_CNT_SUSPECT) of previous observations. SF_n is flagged if it has the same value as previous observations within a tolerance value EPS to allow for numerical round-off error. Note that historical flags are not changed.		
Flags	**Condition**	**Codable Instructions**
Fail=4	When the five most recent observations are equal, SF_n is flagged fail.	$SF_n \neq 0$ AND For i=1,REP_CNT_FAIL $SF_n - SF_{n-I} < EPS$
Suspect=3	It is possible but unlikely that the present observation and the two previous observations would be equal. When the three most recent observations are equal, SF_n is flagged suspect.	For i=1,REP_CNT_SUSPECT $SF_n - SF_{n-I} < EPS$
Pass=1	Applies for test pass condition.	N/A
Test Exception: Sensor failure introduces the possibility of repeated zero values, last valid value, or other fixed output. However, repeated zero or other SF values may be accurate. Operators must carefully choose how to flag data under these conditions.		
Test specifications to be established locally by operator. **Examples:** REP_CNT_FAIL = 5, REP_CNT_SUSPECT= 3		

Test 8) Multi-Variate Test (Suggested)

Comparison to other variables.

This is an advanced family of tests, starting with the simpler test described here and anticipating growth towards full co-variance testing in the future—perhaps through emerging machine learning techniques. To our knowledge, no one is conducting tests such as these in real-time. As these tests are developed and implemented, they should indeed be documented and standardized in later versions of this living stream flow manual.

In this simple example, it is a pair of rate of change tests as described in test 7. The stream flow rate of change test is conducted with a more restrictive threshold (SF_ROC_THRSHLD). If this test fails, a second rate of change test operating on a second variable (rainfall (RF) and rainfall rate of change threshold (RF_ROC_THRSHLD) would be the most probable) is conducted. If the rate of change test on the second variable *fails* to exceed a threshold (e.g., an anomalous step is found in stream flow and is lacking in rainfall), then the SF_n value is flagged.

Flags	Condition	Codable Instructions
Fail=4	Because of the dynamic nature of SF, no fail flag is identified for this test.	N/A
Suspect=3	SF_n fails the SF rate of change and the second variable does not exceed the rate of change.	If $\|SF_n – SF_{n-1}\|$ > SF_ROC_THRSHLD AND $\|RF_n – RF_{n-1}\|$ <RF_ROC_THRSHLD, flag = 3
Pass=1	N/A	N/A

Test Exception: None.

Test specifications to be established locally by operator.
Examples: SF_ROC_THRSHLD = 1000 ft^3/sec, RF_ROC_THRSHLD = 1 in/hr

NOTE: In a more complex case, more than one secondary rate of change test can be conducted. Wind and barometric pressure are possible secondary candidates, and they could be checked for anomalous rate of change values. In this case, a knowledgeable operator may elect to pass a high rate of change stream flow observation when any one of the secondary variables also exhibits a high rate of change. Such tests border on modeling, should be carefully considered, and may be beyond the scope of this effort.

The stream flow committee recognized the high value in full co-variance testing but also noted the challenges. Such testing remains to be a research project not yet ready for operational implementation.

Test 9) Neighbor Test (Suggested)

Comparison to nearby stream flow sensors.

The check has the potential to be the most useful test when a nearby second sensor is determined to have a similar response.

In a perfect world, redundant stream flow sensors utilizing different technology would be co-located and alternately serviced at different intervals. This close neighbor would provide the ultimate QC check, but cost prohibits such a deployment in most cases.

This test is the same as *8) multi-variate test – comparison to other variables* where the second variable is the second stream flow sensor. The selected thresholds depend entirely upon the relationship between the two sensors as determined by the local knowledge of the operator.

In the instructions and examples below, data from one site (SF1) are compared to a second site (SF2).

Flags	Condition	Codable Instructions
Fail=4	Because of the dynamic nature of SF, no fail flag is identified for this test.	N/A
Suspect=3	SF_n fails the SF rate of change and the second SF sensor does not exceed the rate of change.	If SF1n – SF1n-1|> SF1_ROC_THRSHLD AND |SF2n – SF2n-1|< SF2_ROC_THRSHLD, flag = 3
Pass=1	N/A	N/A

Test Exception: None.

Test specifications to be established locally by operator.
Examples: SF1_ROC_THRSHLD = 1000 ft^3/hr, SF2_ROC_THRSHLD = 1000 ft^3/hr

Neighbor Test Example

In the example shown below, the St. Johns River spike identified earlier is compared to the nearest station, located near Cocoa, Florida and approximately 15 miles (23 km) upstream of the Christmas, Florida site. With the proper thresholds applied, this test could be used to confirm the validity of the data at both sites. However, note the time offset between the two sites, which must also be applied if the neighbor site is distant. Furthermore, this time offset may be positive or negative—in this example the upstream gage lags the downstream gage, indicating the perturbation has propagated upstream. The complexity of tests using distant neighbor gages versus their utility must be evaluated by knowledgeable operators.

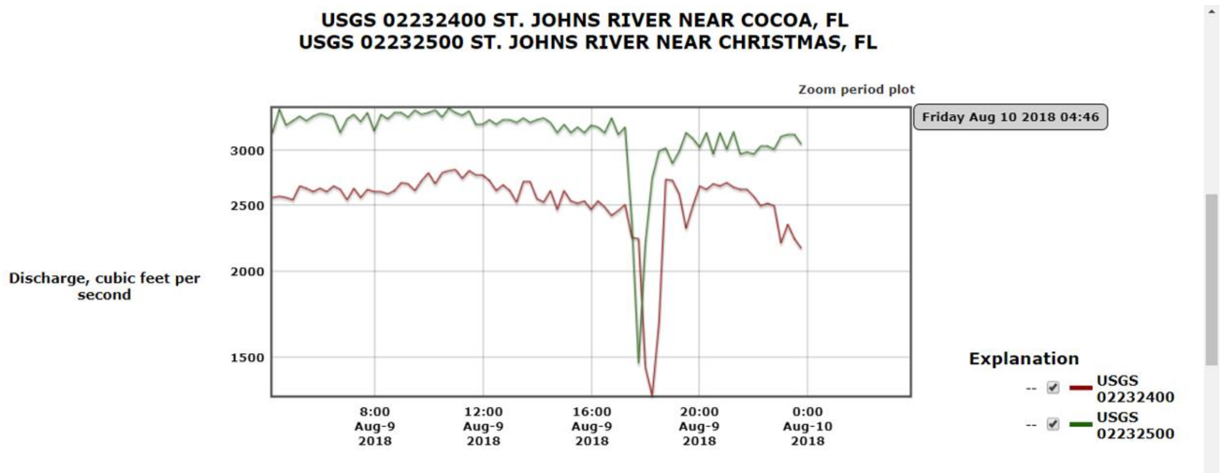

Figure 3-2. The two similar spikes seen in these neighboring gages validate both observations. However, the time lag in the two spikes means that only the first spike might be used to validate the second spike in real-time. Tests employing distant neighbors can quickly become complex. Graphic credit: M. Bushnell using the USGS online graphics tools of the National Water Information System.

4.0 Summary

The QC tests in this stream flow manual have been compiled using the guidance provided by operators with extensive experience. Wherever possible, redundant tests have been merged. These tests are designed to support a range of stream flow sensors and operator capabilities. Some well-established programs with the highest standards have implemented very rigorous QC processes (USGS, USACE). Others, with different requirements, may utilize sensors with data streams that cannot support as many QC checks—all have value when used prudently. It is the responsibility of the users to understand and appropriately utilize data of varying quality, and operators must provide support by documenting and publishing their QC processes. A balance must be struck between the time-sensitive needs of real-time observing systems and the degree of rigor that has been applied to non-real-time systems by operators with decades of QC experience.

The nine data QC tests identified in this manual apply to stream flow observations from a variety of sensor types and platforms. Existing programs, such as the USGS, have already developed QC tests that are similar to the U.S. IOOS QARTOD tests in this manual. The QARTOD stream flow committee's objective is for the QC tests of these programs to comply with U.S. IOOS QARTOD requirements and recommendations without being overly prescriptive, by providing meaningful guidance and thresholds that everyone can accomplish within a national framework. The individual tests are described and include codable instructions, output conditions, example thresholds, and exceptions (if any).

Selection of the proper thresholds is critical to a successful QC effort. Thresholds can be based on historical knowledge or statistics derived from more recently acquired data and should not be determined arbitrarily. This manual provides some guidance for selecting thresholds based on input from various operators, but also notes that operators need the subject-matter expertise in selecting the proper thresholds to maximize the value of their QC effort.

Future QARTOD manuals will address standard QC test procedures and best practices for all types of common as well as uncommon platforms and sensors for all the U.S. IOOS core variables. Some test procedures may even take place within the sensor package. Significant components of metadata will reside in the sensor and be transmitted either on demand or automatically along with the data stream. Users may also reference metadata through Uniform Resource Locators to simplify the identification of which QC steps have been applied to data. However, QARTOD QC test procedures in this manual address only real-time, interoperable, in-situ observations made by sensors on fixed platforms. The tests do not include post-processing, which is not conducted in real-time but may be useful for ecosystem-based management, or delayed-mode, which is required for climate studies.

Training and education are of paramount importance to ensuring that both QA and QC practices are in place. The sensor manufacturers can play a huge role in this area. The manufacturers have spent enormous efforts helping customers use these sensors successfully. Most manufacturers provide instructions for best practices, and those practices should be used as a first-order QA for all measurements. The manufacturer-supplied user's manual includes these instructions, and carefully following them is critical to knowing how to use the instruments, understanding their limitations and accuracy, knowing how to interpret output, and then having a meaningful way to validate performance. Validation of sensor performance can be done by taking periodic validation observations, using a known reference instrument that has been properly calibrated and maintained, or performing laboratory tests to a given accuracy. Manufacturers are a key player in training and understanding the equipment, but they must not be relied upon as experts in actually using their equipment in the field. It is wise to develop in-house experts that have access to the manufacturers and have operators and data users work through those experts before seeking assistance from the manufacturers.

Each QC manual is a dynamic document and is posted on the QARTOD website (https://ioos.noaa.gov/project/qartod/) upon completion. This practice allows for updating each U.S. IOOS core variable QC manual as technology development occurs, accommodating not only new sensors, but also the upgrades envisioned for the existing sensors.

This website permits easy access to all QARTOD material and updates as they are identified. It includes code libraries, procedures for testing data, and links to social media—enabling the growing ocean observing community to stay engaged across the enterprise regionally, nationally, and internationally.

This QARTOD project may be one of the best working examples of private-public partnerships, which is a fundamental tenet of U.S. IOOS. As this stream flow manual has exemplified, the sensor manufacturers must be fully involved in the creation of most, if not all, QC manuals for the 34 U.S. IOOS core variables.

It is through this kind of uniform QC process that integration can occur across the national ocean enterprise, capitalizing the *I* in U.S. IOOS. Implementing these procedures will accelerate the research-to-operations process to support a real-time, operational, integrated ocean observing system of defined data quality.

Knowledgeable human involvement
is required to properly understand the conditions within which the stream flow observations are being taken.

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Supporting Documents Found on the QARTOD Website:

https://ioos.noaa.gov/ioos-in-action/stream-flow

U.S. Geological Survey Continuous Monitoring Workshop—Workshop Summary Report

A History of the Water Resources Branch, U.S. Geological Survey: Volume I From Predecessor Surveys to June 30, 1919

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Appendix B. Quality Assurance

A major pre-requisite for establishing data quality for stream flow observations is having strong QA practices that address all actions related to the sensor during pre-deployment, deployment, and post-deployment. The consensus that emerged from past QARTOD meetings was that good quality data requires good QA, and good QA requires good scientists, engineers, and technicians applying consistent practices. Generally, QA practices relate to observing systems' sensors (the hardware) and include things like appropriate sensor selection, calibration, sensor handling and service, and evaluation of sensor performance.

B.1 Sensor Calibration Considerations

Observations must be traceable to one or more accepted standards such as NIST through a calibration performed by the manufacturer and/or the operator. If the calibration is conducted by the manufacturer, the operator must also conduct some form of an acceptable calibration check.

An often-overlooked calibration or calibration check can be performed by choosing a consensus standard. For example, deriving the same answer (within acceptable levels of data precision or data uncertainty) from four different sensors of four different manufacturers, preferably utilizing several different technologies, constitutes an acceptable check. Because of the trend toward corporate conglomeration, those wishing to employ a consensus standard should ensure that the different manufacturers are truly independent.

Wet chemical sensors also have defined reagent stability and storage considerations that should be accounted for. For example, if reagents are beyond a "best-by date" the data are likely suspect. If reagents drift (NH4 or NO3 reagent degradation), that drift must be known or monitored.

B.2 Sensor Comparison

An effective QA effort continually strives to ensure that end data products are of high value and to prove they are free of error. Operators should seek out partnering opportunities to inter-compare systems by co-locating differing sensors, thereby demonstrating high quality by both to the extent that there is agreement and providing a robust measure of observation data uncertainty by the level of disagreement. If possible, operators should retain an alternate sensor or technology from a second manufacturer for similar in-house checks. For resource-constrained operators, however, it may not be possible to spend the time and funds needed to procure and maintain two systems. For those who do so and get two different results, the use of alternate sensors or technologies provide several important messages: a) a measure of corporate capabilities; b) a reason to investigate, understand the different results, and take corrective action; and c) increased understanding that, when variables are measured with different technologies, different answers can be correct; they must be understood in order to properly report results. For those who succeed in obtaining similar results, the additional sensors provide a highly robust demonstration of capability. Such efforts form the basis of a strong QA/QC effort. Further, sensor comparison provides the operator with an expanded supply source, permitting less reliance upon a single manufacturer and providing competition that is often required by procurement offices.

Users often take validation observations during deployment, recovery, or service. These times are risky for ensuring quality sensor data—often due to initial stabilization, sensor/environment disturbance, or high fouling near the end of the deployment. At least one observation should be obtained mid-deployment without disturbing the sensor.

B.3 Bio-fouling and Corrosion Prevention Strategies

Bio-fouling is a frequent cause of SF sensor failure, so the following strategies may be useful for ameliorating the problem:

- Use anti-fouling paint with the highest copper content available (up to 75%) when possible (but not on aluminum).
- Tributyltin oxide (TBTO) anti-foulant systems, often used in conjunction with a pumped system, are highly effective (e.g., Sea-Bird SBE 43)
- To help with post-deployment clean-up (but not as an anti-foulant), wrap the body of the sensor with clear packing tape for a small probe or plastic wrap for a large instrument, followed by PVC pipe wrap tape. (This keeps the PVC tape from leaving a residue on the sensor.) Wrap the sensor body with copper tape (again, beware of aluminum).
- Coat with zinc oxide (Desitin ointment).
- Use brass door/window screen around opening to sensor. The combination of copper and zinc is a great anti-foulant and is significantly cheaper than copper screen.
- Remember that growth is sensor, depth, location, and season dependent.
- Flush out with chlorine gas pumped through the system. This technique requires a lot of battery power.
- Plan for routine changing or cleaning of sensor as necessary.
- Check with calibration facility on which anti-foulants will be handled (allowed) by the calibrators.
- Avoid or isolate dissimilar metals.
- Maintain sacrificial anodes and ensure they are properly installed (good electrical contact).
- Maximize the use of non-metallic components.
- Use UV-stabilized components that are not subject to sunlight degradation.
- Where applicable, maintain sensor surfaces by gentle cleaning (e.g., using a baby toothbrush).
- Use petroleum-based lubricants as biocides
- Carefully maintain and clean filters.
- Obtain mid-deployment validation field samples.

B.4 Common QA Considerations

The following lists suggest ways to ensure QA by using specific procedures and techniques:

- Perform pre-deployment calibrations on every sensor.
- Perform post-deployment calibrations on every sensor, plus in-situ comparison before recovery.
- Calibrate ready-to-use spares periodically.
- Monitor with redundant sensors whenever possible.
- Collect in-situ water samples to compare with the sensor.
- Take photos of sensor fouling for records.
- Record all actions related to sensors – calibration, cleaning, deployment, etc.
- Compare the first day or less of readings from newly deployed sensor to last sensor deployed. Large shifts in median values can indicate a problem with one of the sensors. A post calibration of a previously deployed sensor may help to determine if it is the source of the discontinuity in readings.
- Monitor battery voltage and watch for unexpected fluctuations.

When evaluating which instrument to use, consider these factors:

- Selection of a reliable and supportive manufacturer and appropriate model
- Measurable data concentration range (including detection limit)
  - Lowest and highest possible readings
- Operating range (i.e., some instruments won't operate at certain temperatures)
  - Could be depth or pressure range
  - Salinity correction
- Resolution/precision required
- Sampling frequency – how fast the sensor can take measurements
- Reporting frequency – how often the sensor reports the data
- Response time of the sensor – sensor lag – time response
- Power source limitations
- Clock stability and timing issues
- Internal fault detection and error reporting capabilities

When evaluating which specifications must be met:

- State the expected accuracy.
- Determine how the sensor compared to the design specifications.
- Determine if sensor met those specifications.
- Determine whether the result is good enough (fit for purpose: data are adequate for nominal use as preliminary data).

General comments regarding QA procedures:

- A diagram (http://www.ldeo.columbia.edu/~dale/dataflow/), contributed by Dale Chayes (LDEO) provides a visual representation of proper QA procedures.
- Require serial numbers and model ID from the supplier.
- Develop useful checklists and update them as needed.
- Do not assume the calibration is perfect (could be a calibration problem rather than a sensor problem).
- Keep good records of all related sensor calibrations and checks (e.g., conductivity and temperature).
- Use NIST-traceable standards when conducting calibrations or calibration checks.

- Keep good maintenance records. Favor sensors that maintain an internal file of past calibration constants, which is very useful since it can be downloaded instead of transcribed manually, thus introducing human error.
- Plot calibration constants or deviations from a standard over time to determine if the sensor has a drift in one direction or another. A sudden change can indicate a problem with the sensor or the last calibration.
- Don't presume that anomalous values are always problems with a sensor. Compare measurements with other sensors to help determine if the reading is real; then examine the possibility of problems with a sensor.
- Follow the manufacturer's recommendations and best practices established by knowledgeable users to ensure proper sampling techniques. For example, in a non-pumped sensor in a turbulent environment, bubbles can adhere to the surface of a sensor resulting in anomalous readings. Cycle the wipers or shutter before the reading to brush off the bubbles from the face of the instrument. For a pumped system in a turbulent environment, a degassing "Y" may limit bubbles adhering to the face of the sensor.

B.5 QA Levels for Best Practices

A wide variety of techniques are used by operators to assure that SF sensors are properly calibrated and operating within specifications. While all operators must conduct some form of validation, there is no need to force operators to adhere to one single method. A balance exists between available resources, level of proficiency of the operator, and accuracy. The various techniques span a range of validation levels and form a natural hierarchy that can be used to establish levels of certification for operators (table B-1). The lists in the following sections suggest ways to ensure QA by using specific procedures and techniques.

Table B-1. Best practices indicator for QA

QA Best Practices Indicator	Description
Good Process	SF sensors are swapped and/or serviced at sufficiently regular intervals so as to avoid data steps (unexpected offsets) upon swap/service. Pre- and post-deployment calibration checks are conducted on each sensor.
Better Process	The good processes are employed, plus pre- and post-deployment calibration checks are conducted using alternative sensors to confirm performance.
Best Process	The better processes are employed, following a well-documented protocol, or alternative sensors are used to validate in-situ deployments. Or, pre- and post-calibrations are conducted by the manufacturer.

B.6 Additional Sources of QA Information

Operators using SF sensors also have access to other sources of QA practices and information about a variety of instruments. For example, the Alliance for Coastal Technologies (ACT) serves as an unbiased, third party testbed for evaluating sensors and platforms for use in coastal and ocean environments. ACT conducts instrument performance demonstrations and verifications so that effective existing technologies can be recognized, and promising new technologies can become available to support coastal science, resource management, and ocean observing systems. The NOAA Ocean Systems Test and Evaluation Program (OSTEP) also conducts independent tests and evaluations on emerging technology as well as new sensor models. Both ACT and OSTEP publish findings that can provide information about QA, calibration, and other aspects of sensor functionality. The following list provides links to additional resources on QA practices.

- Manufacturer specifications and supporting Web pages/documents
- QARTOD - https://ioos.noaa.gov/project/qartod/
- ACT - http://www.act-us.info/
- OSTEP - https://tidesandcurrents.noaa.gov/ostep.html
- USGS - http://water.usgs.gov/owq/quality.html
- USGS - http://pubs.usgs.gov/tm/2006/tm1D3/
- USGS - http://or.water.usgs.gov/pubs/WRIR01-4273/wri014273.pdf
- WOCE - https://www.nodc.noaa.gov/woce/
- NWQMC - http://acwi.gov/monitoring/

B.7 Sample Checklists

The following samples provide hints for development of deployment checklists taken from QARTOD IV:

General QA Checklist:

- ❒ Read the manual.
- ❒ Establish, use, and submit (with a reference and version #) a documented sensor preparation procedure (protocol). Should include cleaning sensor according to the manufacturer's procedures.
- ❒ Calibrate sensor against an accepted standard and document (with a reference and version #).
- ❒ Compare the sensor with an identical, calibrated sensor measuring the same thing in the same area (in a calibration lab).
- ❒ View calibration specifications with a critical eye (don't presume the calibration is infallible). Execute detailed review of calibrated data.
- ❒ Check the sensor history for past calibrations, including a plot over time of deviations from the standard for <u>each</u> (this will help identify trends such a progressively poorer performance). Check the sensor history for past repairs, maintenance, and calibration.
- ❒ Consider storing and shipping information before deploying.
    - Heat, cold, vibration, etc.
- ❒ Record operator/user experiences with this sensor.
- ❒ Search the literature for information on your particular sensor(s) to see what experiences other researchers may have had with the sensor(s).
- ❒ Establish and use a formal pre-deployment checklist.

- ❒ Ensure that technicians are well-trained. Use a tracking system to identify those technicians who are highly trained and then pair them with inexperienced technicians for training purposes.

Deployment Checklist

- ❒ Scrape bio-fouling off platform.
- ❒ Verify sensor serial numbers.
- ❒ Perform visual inspection; take photos if possible (verify position of sensors, connectors, fouling, and cable problems).
- ❒ Verify instrument function at deployment site just prior to site departure. Monitor sensors for issues (freezing, fouling).
- ❒ Use established processes to confirm that the sensor is properly functioning, before departing the deployment site.
- ❒ Specify date/time for all recorded events. Use GMT or UTC.
- ❒ Check software to ensure that the sensor configuration and calibration coefficients are correct. Also check sampling rates and other timed events, like wiping and time averaging.
- ❒ Visually inspect data stream to ensure reasonable values.
- ❒ Compare up and down casts and/or dual sensors (if available).
- ❒ Note weather conditions and members of field crew.

Post-deployment Checklist

- ❒ Take pictures of recovered sensor prior to cleaning.
- ❒ Check to make sure all clocks agree or, if they do not agree, record all times and compare with NIST.
- ❒ Post-calibrate sensor before and after cleaning, if possible. Perform in-situ side by side check using another sensor, if possible
- ❒ Use standard procedures to provide feedback about possible data problems and/or sensor diagnostics.
- ❒ Clean and store the sensor properly or redeploy.
- ❒ Visually inspect physical state of instrument.
- ❒ Verify sensor performance by:
  - Checking nearby stations;
  - Making historical data comparisons (e.g., long-term time-series plots, which are particularly useful for identifying long-term bio-fouling or calibration drift.)