Validation of Streamflow Measurements Made with M9 and RiverRay Acoustic Doppler Current Profilers

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Abstract: The USGS Office of Surface Water (OSW) previously validated the use of Teledyne RD Instruments (TRDI) Rio Grande (in 2007), StreamPro (in 2006), and Broadband (in 1996) acoustic Doppler current profilers (ADCPs) for streamflow (discharge) measurements made by the USGS. Two new ADCPs, the SonTek M9 and the TRDI RiverRay, were first used in the USGS Water Mission Area programs in 2009. Since 2009, the OSW and USGS Water Science Centers (WSCs) have been conducting field measurements as part of their stream-gauging program using these ADCPs. The purpose of this paper is to document the results of USGS OSW analyses for validation of M9 and RiverRay ADCP streamflow measurements. The OSW required each participating WSC to make comparison measurements over the range of operating conditions in which the instruments were used until sufficient measurements were available. The performance of these ADCPs was evaluated for validation and to identify any present and potential problems. Statistical analyses of streamflow measurements indicate that measurements made with the SonTek M9 ADCP using firmware 2.00–3.00 or the TRDI RiverRay ADCP using firmware 44.12–44.15 are unbiased and, therefore, can continue to be used to make streamflow measurements in the USGS stream-gauging program. However, for the M9 ADCP, some important issues must be considered in making future measurements. Possible future work may include additional validation of streamflow measurements made with these instruments from other locations in the United States and measurement validation using updated firmware and software. **DOI:** 10.1061/(ASCE)HY.1943-7900.0001087. *© 2015 American Society of Civil Engineers.*

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Introduction

The use of acoustic Doppler current profilers (ADCPs) to measure streamflow (discharge) as part of the USGS stream-gauging program continues to increase. Two new ADCPs for measuring flow in rivers, canals, and estuaries became commercially available in 2009: the SonTek (San Diego, California) RiverSurveyor M9 ADCP [Fig. 1(a)] and the Teledyne RD Instruments (TRDI) (Poway, California) RiverRay ADCP [Fig. 1(b)]. These instruments are used by the USGS and other hydrometric entities, such as other governmental agencies, engineering companies, and academic institutions. In 2013, discharge measurements made with acoustic instruments (including both ADCPs and acoustic Doppler velocimeters) comprised more than 90% of all USGS streamflow measurements. For sites where streams were not wadable, ADCPs were used almost exclusively (>99%) to make streamflow measurements.

During the 12-month period from May 1, 2013, to April 30, 2014, USGS personnel made more than 120,000 streamflow measurements throughout the United States and Puerto Rico, 31% of which were made using an ADCP. The majority (63%) of these ADCP streamflow measurements were made with TRDI 600- and 1,200-kHz Workhorse Rio Grande (18%), 2,000-kHz StreamPro (43%), or other broadband ADCPs (2%). The remaining 37% of these ADCP streamflow measurements were made with SonTek RiverSurveyor M9 (28%) and S5 (1%) ADCPs or TRDI RiverRay (8%) ADCPs. These newer ADCPs (i.e., M9, S5, and RiverRay) were used less than other instruments during this period because the Rio Grande and StreamPro ADCPs have been in use throughout the USGS for over 10 years and because, possibly to a lesser extent, streamflow measurements made with the newer ADCPs have not been completely validated. Nevertheless, use of the M9 ADCP is rapidly increasing because of its compact size, turnkey operation, ease of use, and capacity to measure in a wide range of hydraulic conditions. The number of streamflow measurements made by the USGS using the RiverRay ADCP is also increasing because of similar reasons. To ensure the accuracy, precision, and consistency of USGS streamflow records, it is imperative to determine whether the M9 and RiverRay ADCPs are comparable with proven streamflow measurement instruments and methods such that one instrument may replace other instruments with sufficient accuracy and precision.

Purpose and Scope of Paper

The purpose of this paper is to present the results of field validations of streamflow measurements made with the M9 and RiverRay ADCPs. The S5 ADCP is similar to the M9 ADCP, but it was not validated owing to an insufficient number of measurements. Apart from the physical differences, the M9 and RiverRay ADCPs differ substantially from ADCPs previously tested and used by the USGS in that these newer ADCPs utilize (1) multiple acoustic frequencies (M9) for velocity measurements, (2) a flat-surface, phased-array transducer with larger beam angles (RiverRay), (3) automatic configuration and adaptive measurement methods (M9 and RiverRay) when making velocity measurements, and (4) the application of new (M9) or updated (RiverRay) software for data collection and analysis. Also, little documentation of field validation is available for these new instruments, especially for a wide range of operating conditions. For these reasons, it is necessary to validate that

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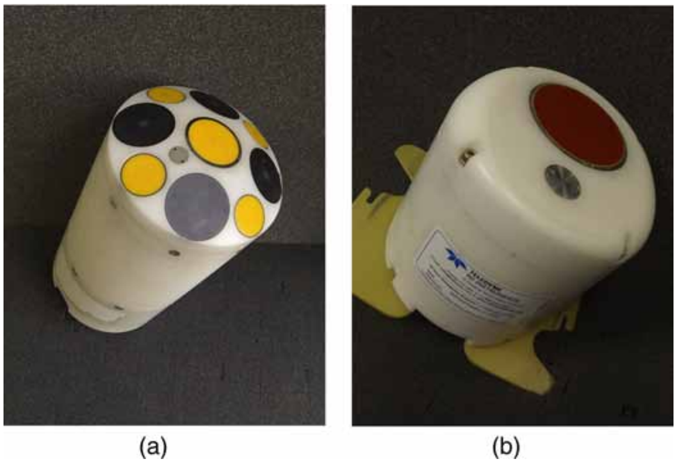

(a) (b)

Fig. 1. (a) M9 ADCP; (b) RiverRay ADCP (images by Justin A. Boldt)

the M9 and RiverRay ADCPs accurately measure discharge to ensure that there are no appreciable changes in long-term streamflow records (usually 30 years or greater) that may be caused by changes in equipment and measurement technology.

A total of 313 validation measurements collected by USGS Water Science Centers (WSCs) and other agencies, including the South Florida Water Measurement District (SFWMD) and New Zealand's National Institute of Water and Atmospheric Research (NIWA), were submitted to an online data depository to be reviewed and analyzed. This number of measurements represents only validation measurements made with the ADCPs described here but includes all firmware versions. Firmware and software control the instrument operation and processing algorithms from inside the ADCP and from an externally connected device, respectively. Changes in firmware or software can affect the discharge computation algorithms, so it is important to analyze each updated firmware/software separately. Updates that do not affect the discharge computation can be included with the previous firmware versions. Here the authors consider only the firmware versions in use at the time of this work.

From this database, 72 M9 measurements (firmware version 2.00–3.00) and 56 RiverRay measurements (firmware version 44.12–44.15) were analyzed. Of the M9 validation measurements, 68 had a navigation reference of bottom track (BT), whereas 49 had a global positioning system (GPS) reference. Bottom tracking is a technique for measuring the velocity of an ADCP (mounted on a moving platform) over the bottom (streambed) by analyzing reflections of sound pulses returned from the streambed (Teledyne RD Instruments 2001a; Simpson 2002). GPS is a space-based satellite navigation system that provides location and time information (Kaplan 1996) and is often used as a navigation reference for ADCP measurements when bottom tracking is unreliable or is biased by sediment transport (Mueller et al. 2013). All 56 of the RiverRay field validation measurements used BT as the navigation reference. The final data sets used in the analysis were collected in the period April 11, 2011–May 8, 2013, by at least 35 different hydrographers using various ADCPs and deployment techniques (e.g., from bridge, cableway, moving boat) at 93 different sites (91 sites in the United States and 2 sites in New Zealand).

Previous Work

The first detailed analyses of ADCP discharge measurements were conducted by Christensen and Herrick (1982) for the USGS and by Simpson and Oltmann (1993). Subsequently, Morlock (1996) documented evaluations of discharge measurements made with 1,200- and 600-kHz versions of a broadband ADCP manufactured by RD Instruments. (RD Instruments became Teledyne RD Instruments in 2005.) In Morlock's study, a total of 31 ADCP streamflow measurements were made at 12 USGS stream-gauging stations and were evaluated by comparison with river discharges determined by conventional USGS methods, such as current meters. The reference discharges used by Morlock (1996) were obtained either from concurrent (or nearly concurrent) current-meter measurements or from stable rating curves at USGS streamflow-gauging stations. Of the 31 ADCP discharge measurements, 25 were within 5% of the reference discharges, and all ADCP-measured discharges were within 8% of the reference discharges. No statistical bias was detected in any of the measurements.

Mueller (2002) performed a field assessment of ADCP discharge measurements at five different sites using instruments manufactured by SonTek (1,500- and 3,000-MHz RiverSurveyor) and TRDI (1,200- and 600-kHz Rio Grande). The mean discharges measured with each ADCP were within 5% of the discharge measured using a Price AA meter or discharge obtained from a stage-discharge rating. A key finding of this work was that the coefficient of variation of the discharge measurements was usually less for the measurements made with TRDI Rio Grande ADCPs than with the SonTek ADCPs tested. The RiverSurveyor ADCPs used narrowband technology, and production of these instruments was discontinued in 2009. Broadband processing is a technique that uses coded pulses to make multiple measurements of the Doppler shift with a single ping, whereas narrowband processing uses a single pulse per ping to measure velocity (Mueller et al. 2013).

Rehmel (2006) found that when the mean channel velocity was greater than 0.25 m/s, discharges measured with the StreamPro ADCP compared well to discharges measured using reference instruments. When the mean channel velocity was less than 0.25 m/s, the individual transect discharges had greater variability but were not biased. Oberg and Mueller (2007) analyzed 100 Rio Grande ADCP field validation discharge measurements and found that streamflow measurements made with these ADCPs were unbiased when compared to a reference discharge regardless of the water-tracking mode used for making the measurement. Water-tracking mode refers to a particular configuration of ADCP pings and processing algorithms that can be changed either manually or automatically to optimize the ADCP performance for the water velocity, turbulence level, and depth being measured (Mueller et al. 2013).

Collection and Analysis of ADCP Validation Measurement Data

Instruments Tested

The M9 ADCP (SonTek 2012) utilizes nine transducers with three acoustic frequencies. This ADCP has dual four-beam 3- and 1-MHz transducers in a Janus configuration (Teledyne RD Instruments 2001a; Simpson 2002), with the 3-MHz beams offset horizontally 45° from the 1-MHz beams. All of the 3- and 1-MHz transducers are fixed at a 25° beam angle in the vertical and are used for velocity and depth measurements. For water depths at or less than 75 cm, the 3-MHz transducers are used for BT. For water depths greater than 75 cm, the 1-MHz transducers are used for BT. The M9 also is equipped with a 500-kHz vertical beam for depth measurement. The M9 ADCP has automatic adaptive sampling (depth-cell size, acoustic frequency, type of signal processing, and ping configuration) based on measured flow conditions (water depth and velocity) to optimize the discharge measurement, and it also has parallel processing capabilities that allow the ADCP system to ping while it is processing the acoustic return from the previous set of pings. The continuous processing allows the ADCP system to optimize the next ping configuration for the hydraulic conditions encountered. Additional details on the M9 ADCP can be found in Mueller et al. (2013, p. 7 and Appendix C).

The RiverRay ADCP (Teledyne RD Instruments 2009, 2012) has a flat-surface, phased-array transducer that forms four beams in a Janus configuration with 30° beam angles in the vertical. This ADCP also has automatic adaptive sampling based on measured flow conditions to optimize the collection and processing of the discharge measurement. This autoadaptive configuration algorithm varies the standard depth-cell size, standard depth-cell ping configuration, and the number of surface depth cells based on depth and hydraulic conditions. Additional details regarding the RiverRay characteristics and configuration can be found in Mueller et al. (2013, p. 9–10 and Appendix C).

Data Collection and Processing Methods

All field streamflow measurements are based on some assumptions and are subject to error. For this and other reasons, presently (2015) there is no method for measuring discharge that provides the true flow value at any instant in time. For many years, the USGS has used the Price AA or Pygmy current mechanical meter to make streamflow measurements in accordance with methods defined in Rantz et al. (1982). Oberg and Mueller (2007) and other researchers have shown that streamflow measurements made with a broadband ADCP were equivalent to streamflow measurements made with these mechanical meters and other commonly used instruments and techniques.

For the present work, the acceptable types of reference streamflow allowed in this study (ranked from most ideal to least ideal) include (1) simultaneous acoustic measurement, (2) simultaneous current-meter measurement, (3) stable rating curve (stage-discharge relation), and (4) sequential acoustic measurement. A stable rating curve is one that has not experienced a recent shift or is not frequently shifted. Simultaneous measurements are always better than sequential measurements because the measured flow is more likely to be the same, and acoustic measurements are preferred because they are most similar to the instruments being tested. If the reference and comparison measurements were not concurrent, the hydrographer was required to provide stage data or some other documentation to show that the measured flow was not changing substantially during the time that the streamflow measurements were being made. The reference measurements were typically made using a 1,200-kHz Rio Grande ADCP using BT as the navigation reference but also included 600-kHz Rio Grande ADCP, 2,000-kHz StreamPro ADCP, FlowTracker acoustic Doppler velocimeter, Price AA mechanical meter, or gauge (stable stage-discharge relation) measurements. All of these instruments and methods were previously validated or are accepted methods for measuring streamflow in the USGS. In some cases, the ADCPs used for reference measurements were also equipped with differential GPS.

In this study, the hydrographer was asked to process the measurements submitted using established USGS procedures (Mueller et al. 2013). These procedures included, but were not limited to, evaluation of moving-bed test results, evaluation of the quality of BT and GPS data (where available), any data screening that was necessary, an evaluation of the extrapolation methods to be used, and a qualitative assessment of streamflow measurement quality. When this work was accomplished, the validation data set and supporting documentation were submitted to an online data depository established and maintained by the USGS Office of Surface Water (OSW). This database provides an effective and efficient way to compile and share hydroacoustic instrument evaluation data. Using numerous hydrographers (rather than a single hydrographer) reduces the amount of time needed to collect a sufficient number of validation measurements for statistical analyses and, thus, enables more timely analysis of field validation testing to evaluate the performance of acoustic instruments in a wide variety of hydraulic conditions and identify potential data-collection and analysis problems or ADCP bias. Every validation data submission contained not only the comparison measurement data files for each instrument but also hydrographer contact information, a description of the data files, and other documentation, such as measurement comments, field notes, and photographs.

Rather than conducting all M9 or RiverRay comparisons using a single ADCP, all hydrographers used their own instruments and equipment. Consequently, comparison measurements were made using many different ADCPs for each type of ADCP tested, minimizing any potential bias from use of a single instrument. To ensure consistency and adequate processing and review of the validation measurements submitted, the authors also thoroughly reviewed and reprocessed each data set following the procedures outlined in Mueller et al. (2013) and Oberg et al. (2005). Field notes and other available information were also reviewed to help provide an indication of adherence to USGS measurement policies and procedures. These additional data—hydrographer contact information, description of files, comments, field notes, and photographs—proved valuable in ensuring quality comparisons.

The manufacturers made numerous changes in firmware and software over time after the introduction of these ADCPs in 2009. Many of these firmware and software changes were made in response to issues identified during preliminary USGS evaluations. Because most of the issues identified by the testing could bias or otherwise adversely affect the quality of measured discharges, comparison measurements using this outdated firmware/software could not be included in the subsequent analysis. Therefore, only M9 validation measurements collected using firmware 2.00–3.00 (2.00, 2.31, and 3.00) and RiverRay validation measurements collected using firmware 44.12–44.15 (44.12, 44.13, 44.14, and 44.15) were used for the analyses described in this paper. For most of the M9 validation measurements, GPS data were simultaneously collected with BT data when possible. Two independent GPS navigation references were available—GGA, a position-based GPS reference, and VTG, a Doppler-based GPS reference velocity (National Marine Electronics Association 2002). The number of accepted validation measurements for each firmware group according to ADCP navigation reference is shown in Table 1. The firmware groupings presented in this paper were also justified because firmware changes incorporated into these versions should not result

Table 1. Number of Field Validation Measurements Available for Analysis for Each ADCP Firmware Group

ADCP navigation	M9 ADCP firmware				RiverRay ADCP firmware
reference	0.80–0.84	1.00–1.05	1.50–1.71	2.00–3.00	44.12–44.15
BT	46	27	45	68	56
GPS-GGA	21	13	29	47	N/A
GPS-VTG	21	13	30	49	N/A

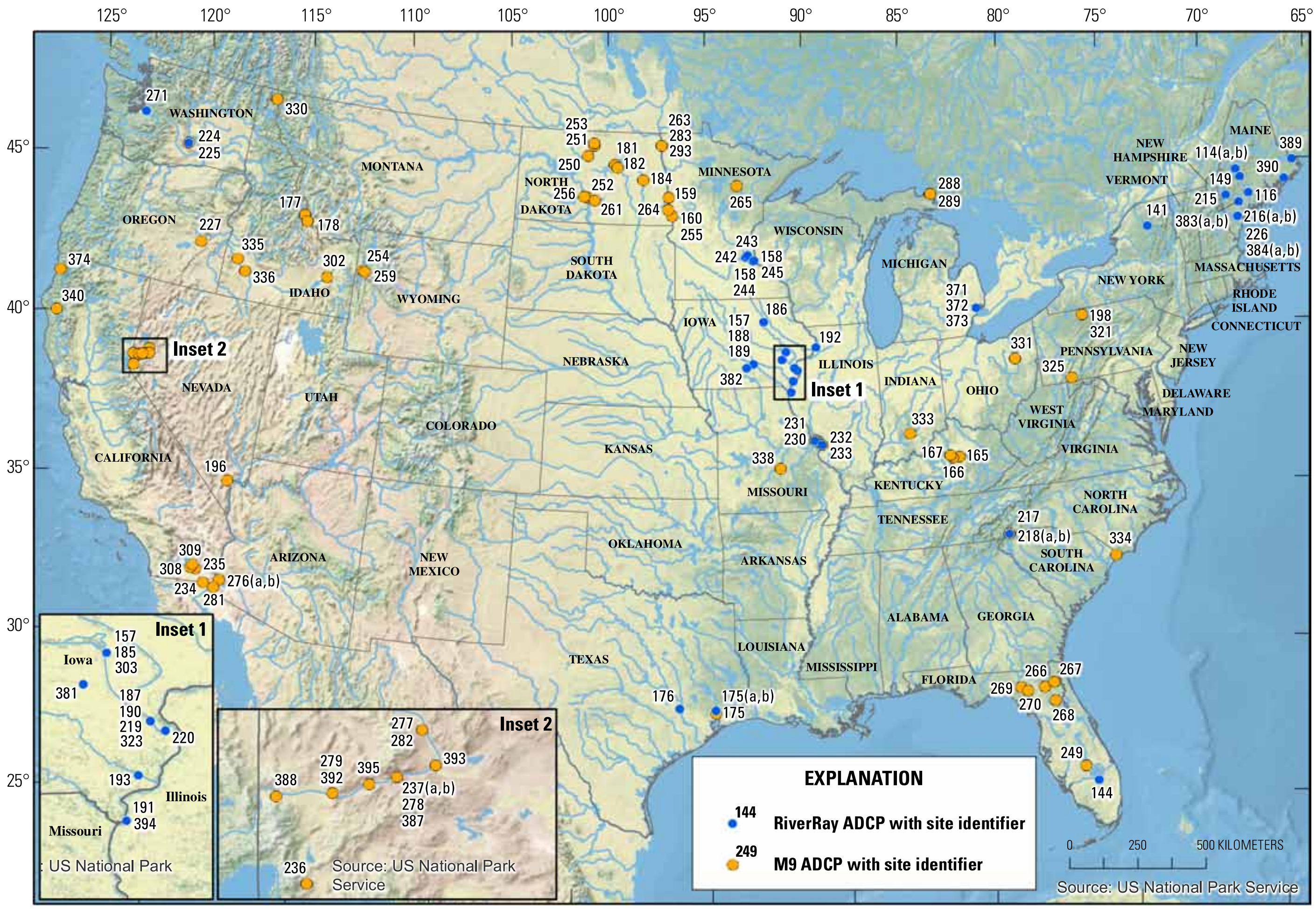
Note: ADCP = acoustic Doppler current profiler; BT = bottom track; GGA = position-based GPS; VTG = vector-based GPS.

in substantive changes in measured discharge. In contrast, M9 firmware version 1.00 introduced the SmartPulseHD adaptive acoustic pulse scheme algorithm (SonTek 2012), and M9 firmware version 2.00 had an improved BT algorithm, both of which resulted in substantial changes in measured discharge or measurement quality. Although prior M9 firmware groups are not presented in this paper, preliminary analyses indicate that discharge measurements made using these firmware groups may be biased low, which is what in part motivated this study.

Comparison measurements were never excluded from analysis just because the measured discharges did not compare well (e.g., more than 5% difference between measurements); however, some measurements had to be excluded because of serious quality issues (approximately 15% of submitted measurements). In some cases, it was determined that the quality of the reference measurement was such that a valid comparison could not be made. Serious quality issues included measurements with invalid BT, invalid moving-bed test, invalid/poor-quality GPS, improper/invalid compass calibration, poor measurement technique (e.g., rapid changes in boat heading, pitch, roll, or speed; low exposure time; air entrainment; unsuitable cross section; poor instrument choice), or water velocities outside the ADCP operating range. Consequently, measurements with a poor reference or serious quality issues were removed from subsequent analyses. These quality issues could have been avoided by good site selection and proper techniques and equipment, which can be controlled by the hydrographer. In contrast, comparison measurements may not compare well with the reference measurement because of deficiencies in the ADCP design, physical components, or processing algorithms. These are deficiencies in the ADCP and are beyond the user's control. M9 ADCP data were processed using SonTek's *RiverSurveyor Live* software version 3.50 (SonTek 2012), and RiverRay ADCP data were processed using TRDI's *WinRiver II* software version 2.08 (Teledyne RD Instruments 2011b).

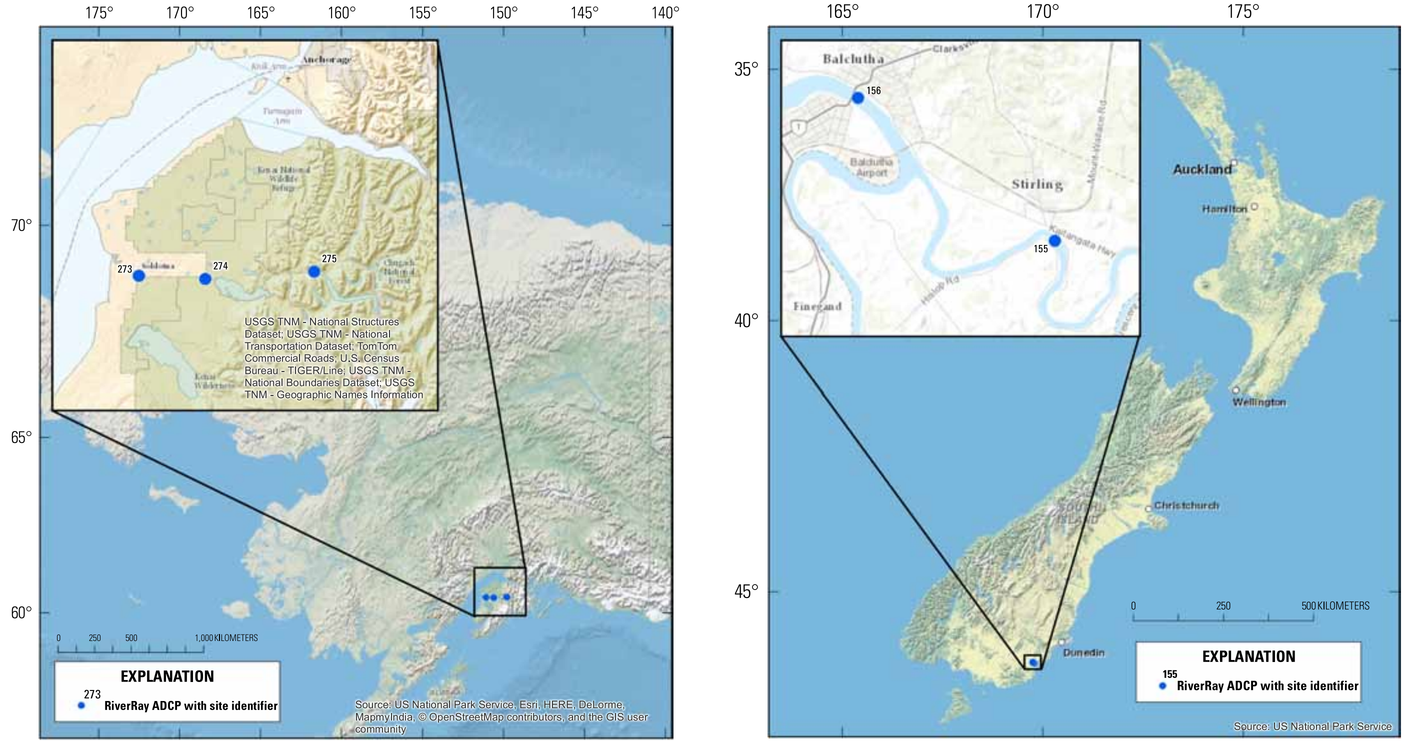
Description of Sites and Flow Characteristics

After the submitted measurements were screened, 128 comparison measurements (72 of M9 and 56 of RiverRay) from a total of 93 different sites were available for analysis. The location of the evaluation sites used in this study are shown in Fig. 2. Almost all of these sites are located at or near continuous-record streamflow-gauging stations. The drainage area for the sites used for validation ranged



(a)

Fig. 2. Measurement location sites for the M9 and RiverRay ADCP validation data sets in (a) the continental United States (source: U.S. National Park Service); (b) Alaska (source: U.S. Park Service, Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, the GIS user community; Inset Source: USGS TNMNational structures data set; USGS TNMNational transportation data set; TomTom commercial roads; U.S. Census BureauTIGER/Line; USGS TNMNational boundaries data set; USGS TNMGeographic names information); (c) New Zealand (source: U.S. National Park Service)



(b) (c)

Fig. 2. (*Continued.*)

from 10 to 1,800,000 km^2. Detailed station and location information is presented in the Appendix.

Site and channel characteristics for these validation measurements varied greatly because this analysis was based on user-submitted data from hydrographers at sites throughout the United States and at two sites in New Zealand (Fig. 2). Measurement site cross sections ranged from concrete trapezoidal canals to small streams to large rivers. Care was taken to ensure that the final, screened data cover the range of operating conditions to avoid any bias in the statistical results. The distribution of measured discharge, mean velocity, mean depth, and mean width for M9 and RiverRay validation measurements are shown in Fig. 3. The RiverRay measurements comprised slightly larger flows (and, thus, higher mean velocities, mean depths, and mean widths) than the M9 measurements (Fig. 3), which could be expected because the conditions for which these two instruments were designed do not exactly overlap.

Statistical Analysis

A percentage-difference value, Per diff, was computed for each reference and comparison measurement pair to normalize the data sets and is given by

$$\text{Per diff} = \frac{Q_{\text{comparison}} - Q_{\text{reference}}}{Q_{\text{reference}}} \times 100\% \tag{1}$$

where $Q_{\text{comparison}}$ is the comparison instrument discharge (M9 or RiverRay) and $Q_{\text{reference}}$ is the reference discharge. Four different tests for normality [probability plot correlation coefficient (PPCC) test (Helsel and Hirsch 2002), Shapiro–Wilk test (Shapiro and Wilk 1965), Lilliefors test (Lilliefors 1967), and Jarque–Bera test (Jarque and Bera 1987)] were used to determine whether the percentage-difference values for each data set group (M9 2.00–3.00 BT, M9 2.00–3.00 GGA, M9 2.00–3.00 VTG, and RiverRay 44.12–44.15 BT) were from a nonnormal distribution as shown in Table 2. Testing for normality ensures that the most appropriate statistical test is used. The PPCC test at a 0.10 significance level (Helsel and Hirsch 2002) was the primary test for normality, and the other three tests were used to verify the PPCC test results.

For the PPCC test, the table of critical values (r^*) for the correlation coefficient was obtained from Looney and Gulledge (1985) and was developed using the Blom (1958) plotting position. For the M9 2.00–3.00 BT group, the PPCC test (along with both the Shapiro–Wilk and Lilliefors tests) rejects the null hypothesis that the data are from a normal distribution because the correlation coefficient ($r = 0.945$) was less than the critical r^* value of 0.986. A log-transform of the percentage-difference data best improved the distribution of the data, but results from the normality tests still indicated nonnormality of the data. Therefore, a Wilcoxon signed-rank test was used for the statistical analysis of the M9 2.00–3.00 BT data. The Wilcoxon signed-rank test is a nonparametric hypothesis test that is equivalent to a t-test but is valid for a nonnormal population (Helsel and Hirsch 2002). For each of the M9 2.00–3.00 GGA, M9 2.00–3.00 VTG, and RiverRay 44.12–44.15 BT groups, the PPCC test (along with the Shapiro–Wilk, Lilliefors, and Jarque–Bera tests) fails to reject the null hypothesis that the data are from a normal distribution. Therefore, a t-test was used for the statistical analyses of these three data groups.

For the t-test, the null hypothesis is that the mean of the percentage-difference values is equal to zero, and the alternative hypothesis is that the mean of the percentage-difference values is not equal to zero. For the Wilcoxon signed-rank test, the null hypothesis is that the median of the percentage-difference values is equal to zero, and the alternative hypothesis is that the median of the percentage-difference values is not equal to zero (Ott and Longnecker 2010). All hypothesis tests were performed at a 0.05

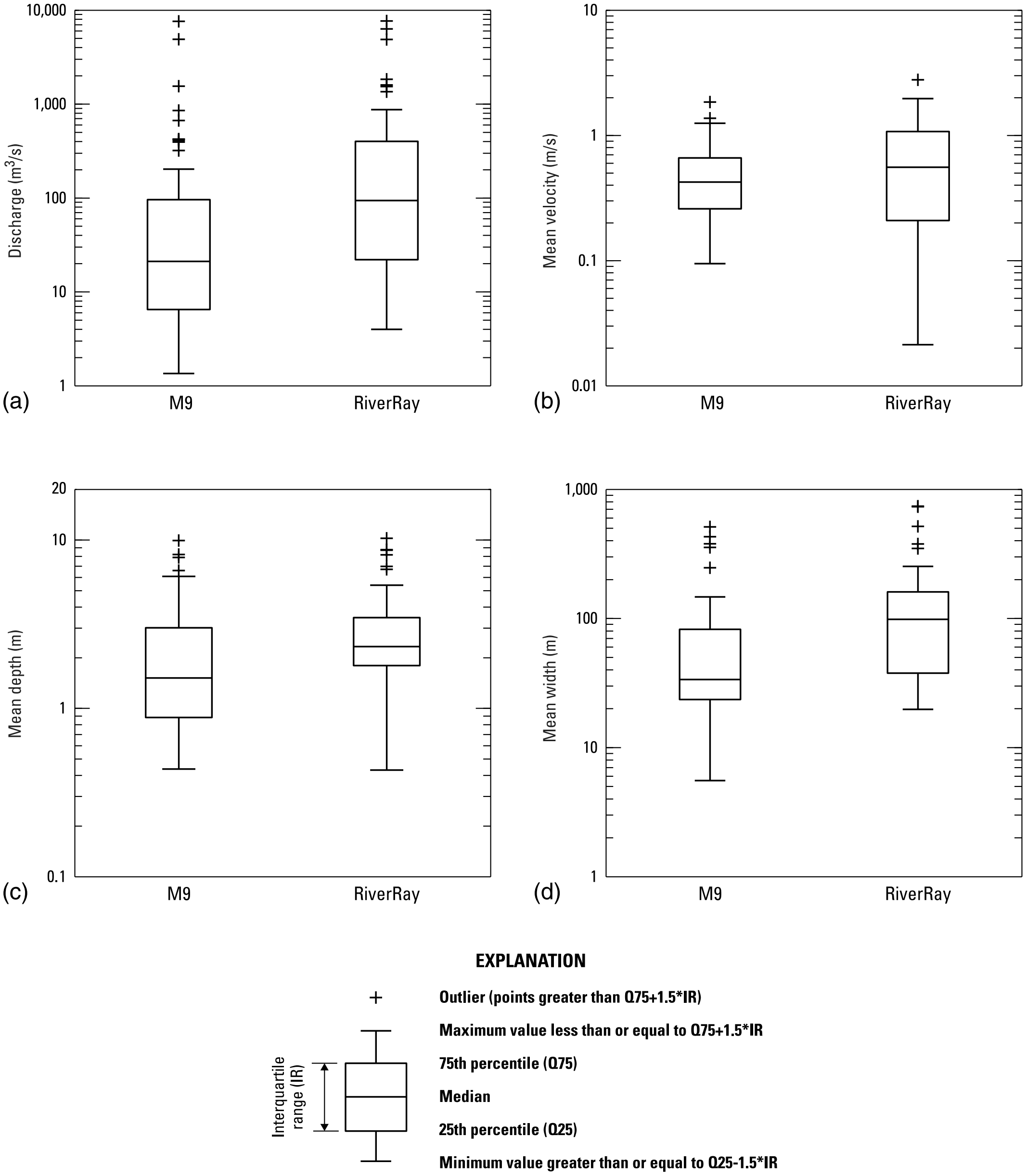


Fig. 3. Ranges of (a) discharge; (b) mean velocity; (c) mean depth; (d) mean width for the M9 and RiverRay ADCP validation data sets

Table 2. Selection of Hypothesis Test for Each Data Group Based on Normality Test Results; Null Hypothesis: Data Are from a Normal Distribution

Data group	PPCC test[a]	Shapiro–Wilk test[b]	Lilliefors test[b]	Jarque–Bera test[b]	Hypothesis test
M9 2.00–3.00 BT	Reject	Reject	Reject	Fail to reject	Wilcoxon signed-rank
M9 2.00–3.00 GGA	Fail to reject	Fail to reject	Fail to reject	Fail to reject	*t*-test
M9 2.00–3.00 VTG	Fail to reject	Fail to reject	Fail to reject	Fail to reject	*t*-test
RiverRay 44.12–44.15 BT	Fail to reject	Fail to reject	Fail to reject	Fail to reject	*t*-test

Note: BT = bottom track; GGA = position-based GPS; PPCC = probability plot correlation coefficient; VTG = vector-based GPS.
[a] Primary test for normality.
[b] Secondary tests for normality.

significance level with a two-sided *p*-value because the ADCP comparison measurement could be greater or less than the reference streamflow measurement.

The ADCP validation data sets were characterized and examined by means of exploratory data analysis based on one-to-one and residual plots. Exploratory data analysis refers to the visualization of data sets in order to identify any trends, patterns, or outliers. Summary statistics (median, mean, and standard deviation) are reported, and bootstrap methods (Moore et al. 2010) were employed using *MATLAB* software (*MATLAB version 8.1*) to obtain a 95% confidence interval for the mean percentage-difference values. Bootstrap methods (bootstrapping) are beneficial because they allow for the computation of confidence intervals without the need for a data set with a normal distribution or containing a large number of samples. The percentage differences are assumed to be a random sample and are resampled with replacement thousands of times. With adequate resamples, the bootstrap distribution of a statistic represents the sampling distribution of the statistic. The bootstrap estimate of bias is the difference between the mean of the bootstrap distribution and the value of the statistic in the original data sample. If the bootstrap distribution is approximately normal with a small bias, then a confidence interval for the parameter can be calculated using the bootstrap standard error (Moore et al. 2010).

Validation of SonTek M9 Streamflow Measurements

M9 Validation Measurement Data

Sixty-eight M9 validation measurements using BT navigation reference with firmware 2.00–3.00 were available for analysis. Additionally, 47 GGA-referenced and 49 VTG-referenced validation measurements were also available for analysis (Table 3). The number of BT validation measurements is greater because GPS data (i.e., GGA and VTG) were not collected for all validation measurements. The number of GPS-referenced measurements is not necessarily the same because certain issues affecting measurement quality, such as multipath, affect one GPS reference but not the other. Four of the 68 M9 validation measurements with BT reference had moving-bed conditions and were corrected with an appropriate moving-bed correction method (Mueller et al. 2013). A summary of the validation streamflow measurements and the flow characteristics for the M9 data set can be found in the appendix.

Selected plots used in exploratory data analysis for the M9 data set are shown in Fig. 4. Measured discharge ranges over four orders of magnitude, and no bias is evident from examination of the one-to-one plots [Figs. 4(a, c, e)]. Residual plots [Figs. 4(b, d, f)] indicate that scatter is greater at lower discharges for the BT-, GGA-, and VTG-referenced discharges. Additional plots of percentage difference versus various hydraulic parameters (stream width, mean depth, and mean velocity) were also examined (Fig. 5). The variability of the residuals shown in Fig. 5 appears to decrease as the mean depth increases. This is not altogether unexpected. The percentage unmeasured area for ADCP discharge measurements will be greater when the mean depth is shallower. Moreover, as the velocity decreases, the relative contribution of instrument noise (García et al. 2012) becomes greater. Similarly, as the mean width of the stream decreases, the unmeasured (estimated) flow near the edges becomes proportionally larger. All of these factors may contribute to the increased variability observed for shallower depths (<3 m). No trends between stream width or mean velocity and percentage differences were evident.

Table 3. Number of M9 Validation Measurements by Firmware Version

ADCP navigation reference	n	M9 ADCP firmware 2.00	2.31	3.00
BT	68	44	6	18
GPS-GGA	47	31	3	13
GPS-VTG	49	33	3	13

Note: ADCP = acoustic Doppler current profiler; BT = bottom track; GGA = position-based GPS; n = number of measurements; VTG = vector-based GPS.

M9 Validation Results

The p-values from the hypothesis tests (on the percentage-difference values) and the median, mean, and standard deviation of the percentage differences between the M9-measured discharges and the reference discharges are shown in Table 4. A Wilcoxon signed-rank test was used to analyze the BT data, and a t-test was used to analyze the GGA and VTG data. Statistical analyses indicate that there is no significant difference between the M9-measured discharges and the reference discharge at the 0.05 significance level. The mean and median percentage-difference values are all negative but close to zero. The standard deviation of the percentage differences is smallest for the BT-referenced discharges.

Bootstrapping with 100,000 resamples was performed on the mean percentage differences for each data group (BT, GGA, and VTG). The mean percentage difference from the bootstrap distribution is the same as the mean percentage difference of the validation data, indicating that the mean of the bootstrap distribution has no bias as an estimator of the mean of the original sample. The 95% confidence intervals for the mean percentage differences from the bootstrap method are shown in Table 5. Graphical analysis of the percentage differences, along with a hypothesis test and bootstrap methods on the percentage differences, indicate that the BT-, GGA-, and VTG-referenced M9 data are not biased relative to the reference measurements.

Validation of TRDI RiverRay Streamflow Measurements

RiverRay Validation Measurement Data

Fifty-six RiverRay validation measurements using BT navigation reference with firmware 44.12–44.15 were available for analysis (41 measurements with firmware 44.12, 1 with firmware 44.13, 8 with firmware 44.14, and 6 with firmware 44.15). GPS-referenced data were not collected. Of the 56 RiverRay validation measurements, 9 had moving-bed conditions and were corrected with an appropriate moving-bed correction method (Mueller et al. 2013). A summary of the validation streamflow measurements and the flow characteristics for the RiverRay data set can be found in the appendix.

Selected plots used in exploratory data analysis for the available RiverRay 44.12–44.15 data set are shown in Fig. 6. Measured discharge ranges over four orders of magnitude, and no bias is evident from examination of the one-to-one plots [Fig. 6(a)]. A residual plot [Fig. 6(b)] indicates that the percentage-difference values are homoscedastic with no trends. Additional plots of percentage difference versus various hydraulic parameters (stream width, mean depth, and mean velocity) are shown in Fig. 7. No trends between these parameters and percentage differences are evident.

RiverRay Validation Results

The p-values from the hypothesis test (on the percentage-difference values) and the median, mean, and standard deviation of the percentage differences between the RiverRay-measured discharges and the reference discharges are shown in Table 4. A t-test was used on the RiverRay data. Statistical analysis indicates that there is no significant difference between RiverRay-measured discharges and the reference discharge at the 0.05 significance level. The percentage-difference values and variability are comparable between the RiverRay measurements and the M9 measurements.

Bootstrapping with 100,000 resamples was performed on the mean percentage differences. The mean percentage difference from

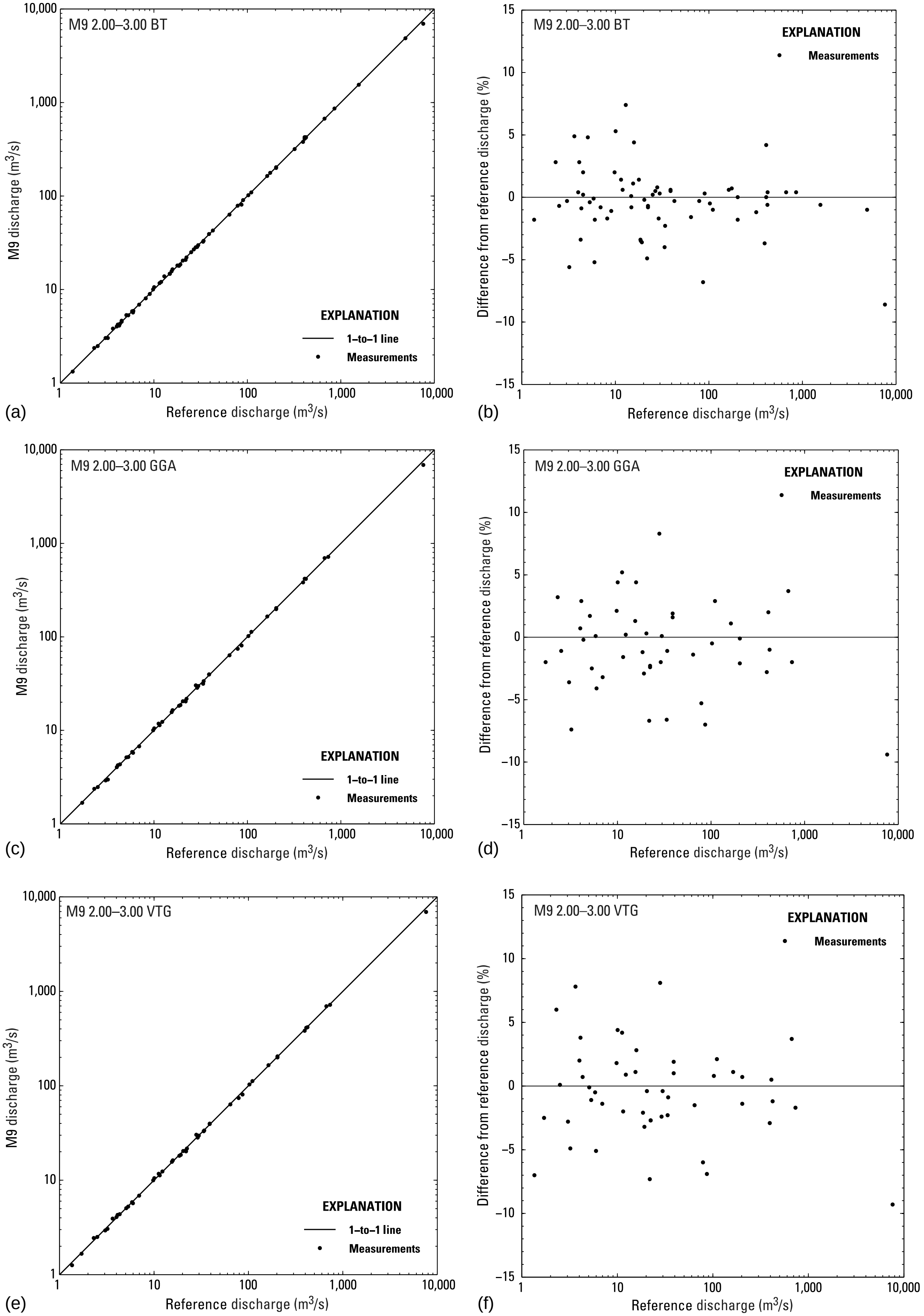


Fig. 4. (a, c, e) One-to-one plots and (b, d, f) residual plots for M9 2.00–3.00 (BT, GGA, and VTG) groups

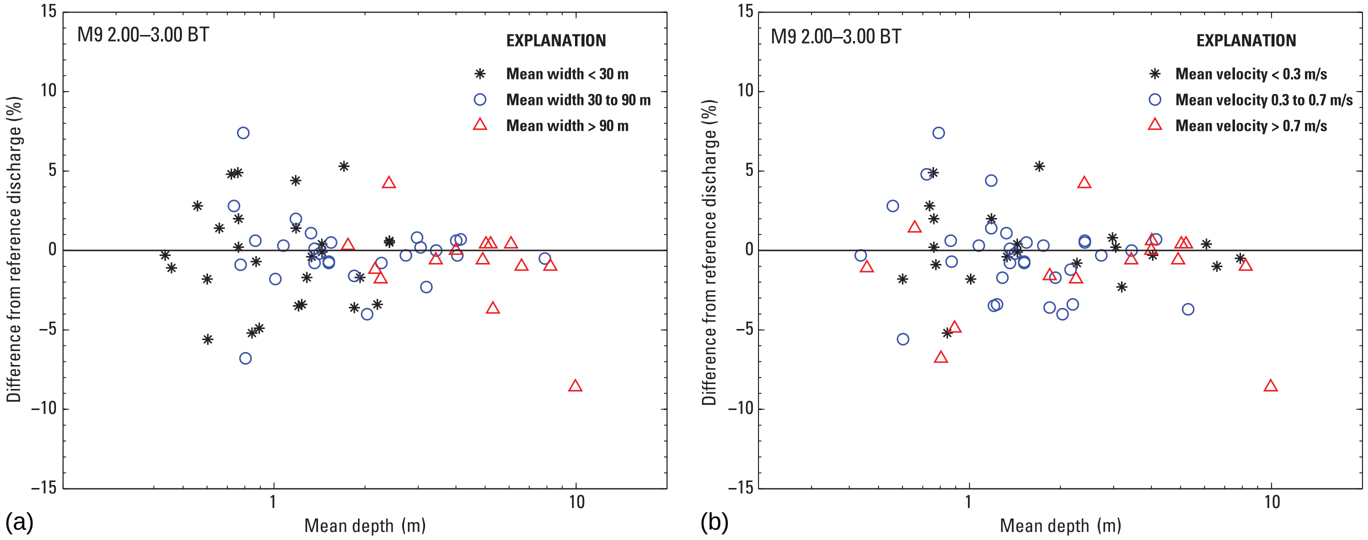


Fig. 5. Residual plots versus mean depth [grouped by (a) mean width and (b) mean velocity]

Table 4. Summary of Test Statistics for M9 2.00–3.00 and RiverRay 44.12–44.15 Data Groups

			Percentage difference		
ADCP	ADCP navigation reference	p-value	Median	Mean	Standard deviation
SonTek M9	BT	0.16	−0.3	−0.4	2.7
SonTek M9	GPS-GGA	0.16	−1.0	−0.7	3.5
SonTek M9	GPS-VTG	0.29	−0.5	−0.6	3.7
TRDI RiverRay	BT	0.12	0.3	0.7	3.4

Note: ADCP = acoustic Doppler current profiler; BT = bottom track; GGA = position-based GPS; VTG = vector-based GPS; and negative values for the median and mean denote that the comparison streamflow measurement (M9 or RiverRay) was less than the reference streamflow measurement, and vice versa.

Table 5. Mean Percentage Differences for M9 2.00–3.00 and RiverRay 44.12–44.15 Validation Measurements with Corresponding 95% Confidence Intervals from Bootstrapping

		Percentage difference		
ADCP	ADCP navigation reference	Sample mean	Bootstrap mean	95% confidence interval
SonTek M9	BT	−0.4	−0.4	−1.0–0.3
SonTek M9	GPS-GGA	−0.7	−0.7	−1.8–0.3
SonTek M9	GPS-VTG	−0.6	−0.6	−1.6–0.5
TRDI RiverRay	BT	0.7	0.7	−0.2–1.6

Note: ADCP = acoustic Doppler current profiler; BT = bottom track; GGA = position-based GPS; VTG = vector-based GPS; and negative values for the percentage difference statistics denote that the comparison streamflow measurement (M9 or RiverRay) was less than the reference streamflow measurement, and vice versa.

the bootstrap distribution is the same as the mean percentage difference of the validation data, indicating that the mean of the bootstrap distribution has no bias as an estimator of the mean of the original sample data. The 95% confidence interval for the mean percentage difference from the bootstrap method is shown in Table 5. Graphical analysis of the percentage differences, along with a hypothesis test and bootstrap methods on the percentage differences, indicate that the BT-referenced RiverRay data are not biased relative to the reference streamflow measurements.

Discussion

The ADCP validation data sets and statistical analyses indicate that measurements made with the SonTek M9 ADCP using firmware 2.00–3.00 or the TRDI RiverRay ADCP using firmware 44.12–44.15 are unbiased. The uncertainty associated with SonTek M9 and TRDI RiverRay ADCP measurements with BT navigation reference using the data and analysis presented here are ±5.4 and ±6.8%, respectively. The uncertainty associated with SonTek M9 ADCP measurements with GGA and VTG navigation reference are ±7.0 and ±7.4%, respectively. These uncertainty values are at the 95% confidence level (two standard deviations). Traditional current-meter measurements performed under ideal conditions with the two-point method have an uncertainty at two standard deviations of ±5.6–6.1% (Pelletier 1988). Oberg and Mueller (2007) calculated an uncertainty of ±4.4% for a set of ADCP measurements with measurement durations of 500 to 1,000 s. Sources of variability come from the reference instrument and the comparison instrument, and the results presented here are comparable with previous studies. Therefore, the M9 and RiverRay ADCPs (with the proper firmware/software) can be used to make streamflow measurements in the USGS stream-gauging program. However, for the M9 ADCP, some important quality issues must be considered in making future measurements in the stream-gauging program.

Of the M9 validation measurements submitted with a BT reference, 15% had serious quality issues and, therefore, were excluded from the final analysis. Serious quality issues included measurements with invalid BT, invalid moving-bed test, invalid/poor-quality GPS, improper/invalid compass calibration, poor measurement technique, or water velocities outside the ADCP operating range. Because these quality issues were not documented in the data submission, it is likely that many of these issues were not noticed by the hydrographers submitting them. This result indicates that the aforementioned quality issues were not readily apparent in the ADCP data collection and processing software. For example, depending on how the hydrographer configures the software (e.g., composite tracks and track reference code), it is relatively common for the

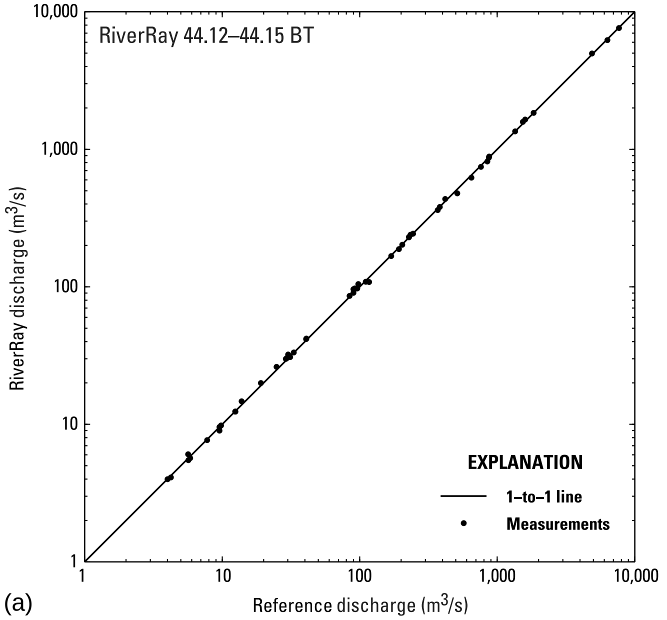


Fig. 6. (a) One-to-one plot; (b) residual plot for RiverRay 44.12–44.15 group

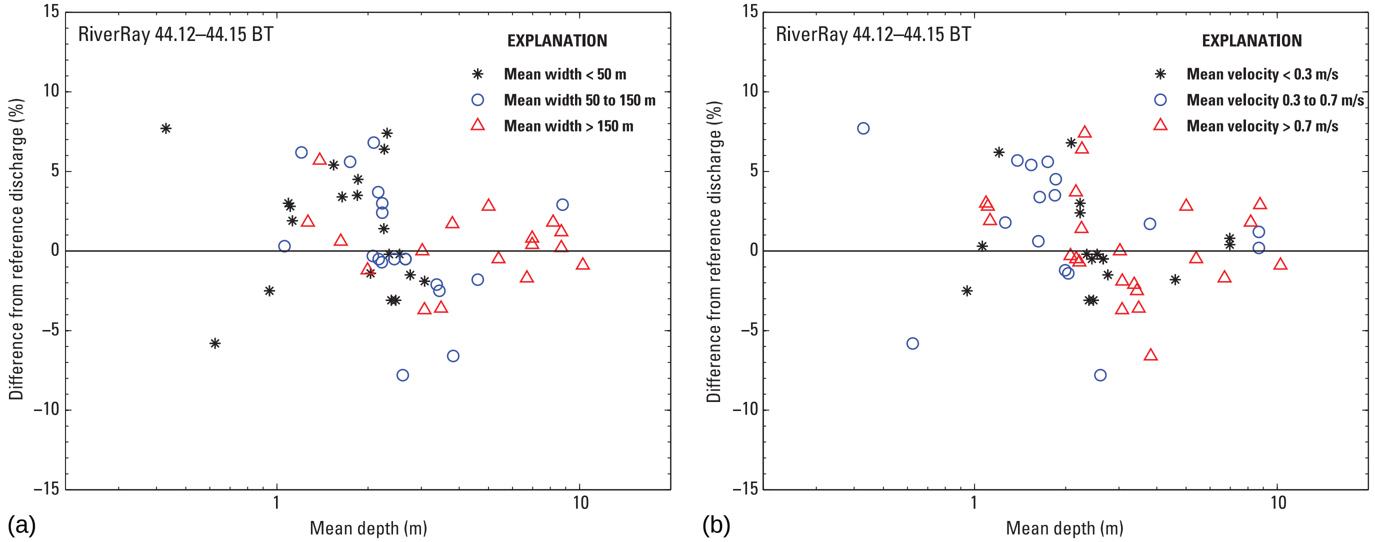


Fig. 7. Residual plots versus mean depth [grouped by (a) mean width and (b) mean velocity]

hydrographer to be unaware of any resulting BT issues. In addition, since the time that these data were collected and analyzed, the USGS has modified its data-analysis software (loop and stationary moving-bed tests; see Mueller et al. 2013) to help identify potential invalid moving-bed tests so that the hydrographer could be so informed of some of these issues while in the field. If the streamflow measurements with these serious quality issues had not been excluded, statistical analysis indicates that the M9-measured discharges would be biased low relative to the reference measurements. The implication is that M9 BT-referenced streamflow measurements may be biased low if these measurements have the same serious quality issues. In contrast, no RiverRay BT validation measurements were excluded from analysis owing to serious quality issues.

For the reasons described earlier, M9 ADCP users should exercise appropriate caution with this instrument in making streamflow measurements. Preliminary analyses indicate that early firmware/software versions of the M9 (firmware less than 2.00) may have resulted in discharge measurements that were biased low, but the statistical analyses of data collected with more recent firmware versions (2.00–3.00) presented here indicate that the null hypothesis—that the discharges are unbiased—cannot be rejected. Nevertheless, it is suggested that users of these instruments periodically make comparison measurements, review the measurement files carefully, and stay current on testing being conducted by the USGS and other hydrometric entities. One source for such information are the USGS Hydroacoustics Web pages (http://hydroacoustics.usgs.gov/).

At least three factors may have affected the results of this study, including (1) the possibility of regional trends or hydrographer bias, (2) the effect of the reference instrument used, and (3) the assumption that the comparison measurements analyzed are a random sample of the streamflow-measurement data population. The first factor concerns trends or differences in results based on the geographic region where the comparison measurements were obtained. Because hydrographers tended to make measurements within their own geographic region, this result is related to the issue of hydrographer bias. Although the comparison measurement data came from a variety of hydrographers throughout the United States, the number of comparison measurements was greater in some geographic regions and by some hydrographers. The concern here is that an individual hydrographer could have equipment or an ADCP operation technique that causes a measurement bias, which could then have biased the results of this study if a large number of validation measurements were submitted by that hydrographer. Each hydrographer submitted an average of three to four comparison measurements. Only one comparison measurement each was submitted by 13 different hydrographers, whereas the greatest number of comparison measurements (14 measurements) was submitted by a single hydrographer. For the final data set used in the statistical analyses, 52% of comparisons were submitted by 20% of hydrographers. None of these numbers of measurements were deemed excessive, and an examination of the differences between comparison and reference streamflow measurements indicated no substantial trends causing measurement bias by geographic region or hydrographer.

The effect of the instrument used to obtain the reference discharge measurement was also examined because not all reference discharge measurements were made with the same type of instrument. Fifty-six percent of the comparisons made use of a 1,200 kHz RioGrande ADCP to measure the reference discharge, and 22% of the comparisons made use of a StreamPro ADCP to measure the reference discharge. Although the remaining reference instrument types composed a small percentage of the total discharges measured, no trends were seen, as shown in Table 6. The mean percentage differences ranged from −0.5 to 1.6%, and all but the FlowTracker comparisons were within ±0.5%. This result is encouraging because all of these instruments are either considered a standard or were previously validated as unbiased compared to a standard reference.

Finally, a key assumption in the bootstrap methods analysis was that the validation measurement data represented a random sample of the streamflow data population. Moore et al. (2010) state that bootstrap confidence intervals can be affected by two sources of random variability: (1) the resamples are chosen at random from the sample and (2) the original sample is chosen at random from the population. The variation due to resampling can be decreased by increasing the number of resamples. The number of resamples used in this analysis (100,000) is high enough to make the variation due to resampling effectively zero. Thus, the remaining question concerns the randomness of the original sample (i.e., the validation measurement data). Although it is difficult to prove that this assumption is correct, great care was taken to avoid this issue. As stated previously, 35 different hydrographers submitted the 128 validation measurements, and this was a large and diverse group of hydrographers with varying levels of expertise in making streamflow measurements. The same set of written instructions was provided to all USGS WSCs. Based on the number of measurements submitted with serious quality issues or poor comparisons, it is clear that hydrographers were not just submitting measurements for which they obtained favorable comparisons. Finally, the sample sizes were large (>50) in order to increase the chance of finding a significant difference and to more reliably represent the streamflow data population.

Table 6. Effect of the Reference Instrument on Statistical Analyses

Reference instrument	*n*	Percentage of total	Mean difference (%)
Rio Grande 1,200 kHz	72	56.3	0.2
StreamPro	28	21.9	−0.2
Rio Grande 600 kHz	10	7.8	−0.5
FlowTracker	7	5.5	1.6
Gauge	6	4.7	−0.4
Price AA	5	3.9	0.5
Total	128	—	—

Note: Gauge = stage–discharge relation (rating curve); and positive values for the mean difference statistic denote that the comparison streamflow measurement was greater than the reference streamflow measurement, and vice versa; *n* = number of measurements.

Summary and Conclusions

Field validation streamflow measurements made with SonTek M9 and TRDI RiverRay ADCPs were analyzed to determine whether discharges measured with these instruments were equivalent to those of other standard methods for measuring discharge. A total of 313 validation measurements collected by USGS WSCs and other agencies were submitted to an online data depository to be reviewed and analyzed. From this database, 72 M9 comparison streamflow measurements (firmware version 2.00–3.00) and 56 RiverRay comparison streamflow measurements (firmware version 44.12–44.15) were analyzed. The final data sets used in the analysis were collected from April 11, 2011, to May 8, 2013, by at least 35 different hydrographers using various ADCPs and deployment techniques (e.g., from bridge, cableway, moving-boat) at 93 different sites.

Analysis of the streamflow measurements was accomplished by means of exploratory data analysis, statistical hypothesis testing, and bootstrap methods. Graphical analyses of the percentage differences of the comparison measurements compared to a reference measurement, along with hypothesis testing and bootstrap methods on the percentage differences, indicate that measurements made with a BT-, GGA-, or VTG-referenced M9 ADCP using firmware 2.00–3.00 or a BT-referenced RiverRay ADCP using firmware 44.12–44.15 were not biased relative to the reference measurements. Moreover, the uncertainties associated with M9 and RiverRay streamflow measurements are comparable to current-meter measurement uncertainties. Therefore, the M9 and RiverRay ADCPs can continue to be used to make streamflow measurements in the USGS stream-gauging program.

Of the M9 ADCP validation streamflow measurements submitted for analysis, 15% had undetected quality issues that rendered them unusable in this analysis. It is suggested that M9 ADCP users make periodic comparison measurements, diligently review M9 measurement data, and stay current on developments with regard to these ADCPs. However, these quality-assurance practices should be followed when using any new ADCP. No RiverRay validation streamflow measurements were excluded from analysis owing to serious quality issues.

Field testing of ADCPs is important in order to cover the full range of instrument operating conditions. Few organizations have the resources and the institutional commitment to conduct systematic quality assurance of these instruments. The USGS OSW continues to work with ADCP manufacturers to improve ADCP firmware and software, add enhancements, and resolve deficiencies and quality issues identified in testing. Possible future work may include additional validation of streamflow measurements made with these instruments from other locations in the United States and measurement validation using updated firmware and software.

Table 7. Summary of M9 2.00–3.00 ADCP Validation Data Set

					Reference measurement				M9 comparison measurement						Measurement characteristics			
Site identifier	Station number	Latitude (degrees)	Longitude (degrees)	Drainage area (km^2)	Instrument type	Freq (kHz)	Firmware	Q (m^3/s)	BT Q (m^3/s)	Per diff (%)	GGA Q (m^3/s)	Per diff (%)	VTG Q (m^3/s)	Per diff (%)	Duration (s)	Width (m)	Mean depth (m)	Q/Area (m/s)
302	14314500	43.244	−112.286	108	Price AA	—	—	1.4	1.3	−1.8	—	—	1.3	−7.0	828	8.5	0.6	0.26
261	06349280	46.699	−100.291	—	Rio Grande	1,200	10.16	1.7	—	—	1.7	−2.0	1.7	−2.5	814	16.8	1.1	0.10
181	05055300	47.908	−99.416	4,302	FlowTracker	—	3.70	2.3	2.4	2.8	2.4	3.2	2.4	6.0	1,235	11.0	0.6	0.38
281	09522900	32.618	−114.621	—	StreamPro	2,000	31.11	2.5	2.5	−0.7	2.5	−1.1	2.5	0.1	969	5.6	0.9	0.52
250	05120000	48.160	−100.729	29,267	FlowTracker	—	3.70	3.0	3.0	−0.3	2.9	−3.6	2.9	−2.8	987	20.7	0.4	0.34
253	05123400	48.589	−100.442	3,004	FlowTracker	—	3.70	3.2	3.0	−5.6	3.0	−7.4	3.1	−4.9	957	8.2	0.6	0.65
278	10351600	39.585	−119.440	4,341	StreamPro	2,000	31.11	3.6	3.8	4.9	—	—	3.9	7.8	800	25.1	0.8	0.19
252	06349500	46.794	−100.657	4,351	Rio Grande	1,200	10.16	4.0	4.0	0.4	4.0	0.7	4.1	2.0	863	9.8	1.4	0.29
282	10351700	39.777	−119.338	4,732	StreamPro	2,000	31.11	4.1	4.2	2.8	4.2	2.9	4.3	3.8	1,547	35.0	0.7	0.16
268	02243000	29.509	−81.946	2,898	Rio Grande	1,200	10.16	4.2	4.1	−3.4	—	—	—	—	823	10.1	1.2	0.34
277	10351700	39.777	−119.338	4,732	Gauge	—	—	4.3	4.3	−0.9	4.3	−0.2	4.4	0.7	1,108	33.3	0.8	0.16
218a	03439000	35.143	−82.825	176	StreamPro	2,000	31.11	4.5	4.5	0.2	—	—	—	—	968	23.2	0.8	0.26
218b	03439000	35.143	−82.825	176	StreamPro	2,000	31.11	4.5	4.6	2.0	—	—	—	—	1,042	23.2	0.8	0.26
196	09419800	36.122	−114.904	5,680	FlowTracker	—	3.50	5.1	5.3	4.8	5.2	1.7	5.1	−0.1	855	18.3	0.7	0.38
264	05053000	46.468	−96.783	5,387	Price AA	—	—	5.3	5.3	−0.4	5.2	−2.5	5.3	−1.1	1,011	21.3	1.3	0.23
182	05055400	47.821	−99.276	4,444	Rio Grande	1,200	10.17	5.9	5.9	−0.1	5.9	0.1	5.8	−0.5	961	16.6	1.4	0.24
387	10351600	39.585	−119.440	4,341	StreamPro	2,000	31.12	6.0	5.7	−5.2	5.7	−4.1	5.7	−5.1	1,471	26.1	0.8	0.27
393	10351650	39.632	−119.282	4,475	StreamPro	2,000	31.12	6.0	5.9	−1.8	—	—	—	—	1,694	31.3	1.0	0.19
251	05122000	48.506	−100.434	31,857	Rio Grande	1,200	10.16	7.0	6.9	−0.8	6.7	−3.2	6.9	−1.4	876	32.7	2.3	0.09
267	02246000	30.113	−81.907	458	Rio Grande	1,200	10.16	8.2	8.1	−1.7	—	—	—	—	868	12.3	1.3	0.52
178	13305000	44.940	−113.639	2,323	StreamPro	2,000	31.12	9.1	9.0	−1.1	—	—	—	—	1,133	17.9	0.5	1.11
279	10350000	39.521	−119.700	3,706	Gauge	—	—	9.8	10.0	2.0	10.0	2.1	10.0	1.8	1,793	31.2	1.2	0.27
184	05057000	47.433	−98.027	16,757	Rio Grande	1,200	10.17	10.1	10.6	5.3	10.5	4.4	10.5	4.4	946	23.7	1.7	0.25
227	13215000	43.574	−118.210	2,849	StreamPro	2,000	31.12	11.2	—	—	11.8	5.2	11.7	4.2	924	20.3	1.1	0.51
177	13305310	45.133	−113.799	3,149	StreamPro	2,000	31.12	11.5	11.7	1.4	11.3	−1.6	11.3	−2.0	988	16.3	0.7	1.08
325	03079000	39.860	−79.229	989	StreamPro	2,000	31.12	12.0	12.1	0.6	—	—	—	—	839	40.3	0.9	0.34
236	10311100	39.154	−119.807	11	StreamPro	2,000	31.11	12.3	—	—	12.3	0.2	12.4	0.9	1,061	36.5	0.8	0.41
331	03117000	40.770	−81.524	1,342	FlowTracker	—	3.70	12.9	13.9	7.4	—	—	—	—	931	34.0	0.8	0.48
198	03007800	41.819	−78.293	642	StreamPro	2,000	31.12	14.8	14.8	0.1	—	—	—	—	792	34.7	1.4	0.31
321	03007800	41.819	−78.293	642	StreamPro	2,000	31.12	14.8	14.7	−0.8	—	—	—	—	792	34.7	1.4	0.31
392	10350000	39.521	−119.700	3,706	StreamPro	2,000	31.11	15.5	15.7	1.1	15.7	1.3	15.7	1.1	1,277	32.0	1.3	0.37
308	10255550	33.105	−115.664	—	Price AA	—	—	15.8	16.5	4.4	16.5	4.4	16.3	2.8	1,188	24.4	1.2	0.55
237a	10351600	39.585	−119.440	4,341	Rio Grande	1,200	10.17	17.8	18.0	1.4	—	—	—	—	1,040	27.1	1.2	0.55
235	09527594	33.091	−115.449	—	Rio Grande	1,200	10.17	18.6	17.9	−3.4	18.3	−1.2	18.2	−2.1	858	14.9	2.2	0.57
237b	10351600	39.585	−119.440	4,341	StreamPro	2,000	31.12	18.7	18.0	−3.5	—	—	—	—	1,040	27.7	1.2	0.56
175	08067070	29.961	−94.810	—	StreamPro	2,000	31.11	19.2	18.5	−3.6	18.7	−2.9	18.6	−3.2	1,432	27.1	1.8	0.38
388	10347460	39.507	−119.931	2,681	StreamPro	2,000	31.12	20.5	20.4	−0.2	20.5	0.3	20.4	−0.4	1,291	33.2	1.4	0.44
259	13014500	43.621	−110.623	1,611	StreamPro	2,000	31.11	21.8	20.8	−4.9	20.4	−6.7	20.2	−7.3	791	26.5	0.9	0.92
255	05051500	46.266	−96.598	10,386	Rio Grande	1,200	10.17	22.3	22.1	−0.7	21.8	−2.3	21.7	−2.7	825	44.3	1.5	0.33
160	05051500	46.266	−96.598	10,386	Rio Grande	1,200	10.17	22.3	22.1	−0.8	21.8	−2.4	21.7	−2.7	825	44.3	1.5	0.33
283	05092000	48.572	−97.147	90,131	Rio Grande	1,200	10.17	25.1	25.1	0.2	—	—	—	—	955	80.6	3.1	0.10
395	10350340	39.557	−119.552	4,092	Rio Grande	1,200	10.17	26.8	26.9	0.5	—	—	—	—	1,599	42.3	1.5	0.41
159	05054000	46.861	−96.783	17,612	Rio Grande	1,200	10.16	28.0	28.3	0.8	30.4	8.3	30.3	8.1	788	49.6	3.0	0.19
309	10254730	33.199	−115.596	—	Price AA	—	—	29.0	28.5	−1.7	28.5	−2.0	28.3	−2.4	1,176	23.5	1.9	0.66
340	11475000	40.218	−123.631	5,457	Rio Grande	1,200	10.16	29.7	29.8	0.3	29.7	0.1	29.6	−0.4	958	49.0	1.1	0.56
334	02110500	33.913	−78.715	2,875	Rio Grande	1,200	10.16	33.7	32.4	−4.0	31.5	−6.6	33.0	−2.3	2,114	50.6	2.0	0.32

Table 7. (*Continued.*)

					Reference measurement				M9 comparison measurement						Measurement characteristics			
Site identifier	Station number	Latitude (degrees)	Longitude (degrees)	Drainage area (km^2)	Instrument type	Freq (kHz)	Firmware	Q (m^3/s)	BT Q (m^3/s)	Per diff (%)	GGA Q (m^3/s)	Per diff (%)	VTG Q (m^3/s)	Per diff (%)	Duration (s)	Width (m)	Mean depth (m)	Q/Area (m/s)
293	05092000	48.572	−97.147	90,131	Rio Grande	1,200	10.17	34.0	33.2	−2.3	33.6	−1.1	33.7	−0.9	786	80.1	3.2	0.13
276a	09522500	32.876	−114.455	—	Rio Grande	1,200	10.17	39.0	39.2	0.5	39.8	1.9	39.7	1.9	871	24.5	2.4	0.66
276b	09522500	32.876	−114.455	—	Rio Grande	1,200	10.17	39.0	39.2	0.6	39.6	1.6	39.4	1.0	769	24.5	2.4	0.66
249	02273230	27.214	−81.202	—	Rio Grande	600	10.17	42.8	42.7	−0.3	—	—	—	—	971	33.1	2.7	0.47
265	05211000	47.232	−93.530	8,728	StreamPro	2,000	31.12	64.4	63.3	−1.6	63.5	−1.4	63.4	−1.5	948	37.1	1.8	0.94
165	03284230	37.843	−84.441	10,621	Rio Grande	1,200	10.16	78.8	78.6	−0.3	74.6	−5.3	74.1	−6.0	1,048	78.7	4.0	0.25
254	13013650	43.654	−110.715	4,343	StreamPro	2,000	31.11	86.7	80.8	−6.8	80.6	−7.0	80.7	−6.9	755	78.5	0.8	1.37
338	06933500	37.930	−91.977	7,356	StreamPro	2,000	31.12	90.0	90.3	0.3	—	—	—	—	900	109.3	1.8	0.47
166	03286500	37.829	−84.724	13,043	Rio Grande	1,200	10.16	102.4	101.9	−0.5	101.8	−0.5	103.2	0.8	1,118	89.0	7.9	0.15
167	03287000	37.926	−84.821	13,214	Rio Grande	1,200	10.16	110.1	109.0	−1.0	113.3	2.9	112.4	2.1	922	108.6	6.6	0.15
234	09527700	32.704	−115.048	—	Rio Grande	1,200	10.16	163.4	164.4	0.6	165.2	1.1	165.2	1.1	713	39.5	4.0	1.03
263	05092000	48.572	−97.147	90,131	Rio Grande	1,200	10.17	175.8	176.9	0.7	—	—	—	—	1,266	85.1	4.2	0.50
336	13171620	42.946	−115.979	105,671	Rio Grande	1,200	10.17	202.9	199.2	−1.8	198.6	−2.1	199.9	−1.4	875	95.4	2.3	0.94
335	—	43.287	−116.416	105,671	Rio Grande	1,200	10.17	203.3	203.4	0	203.2	−0.1	204.7	0.7	983	84.5	3.4	0.70
266	02321000	29.998	−82.274	495	Rio Grande	1,200	10.16	321.0	317.1	−1.2	—	—	—	—	2,079	246.9	2.2	0.60
270	02320500	29.956	−82.928	20,409	Rio Grande	1,200	10.16	394.2	379.6	−3.7	383.1	−2.8	382.7	−2.9	873	125.6	5.3	0.59
374	11530500	41.511	−123.978	31,339	Rio Grande	1,200	10.16	409.6	426.6	4.2	—	—	—	—	930	146.9	2.4	1.16
333	03371500	38.770	−86.410	10,000	Rio Grande	1,200	10.17	410.2	410.0	0	418.6	2.0	412.1	0.5	941	122.6	4.0	0.84
288	—	46.506	−84.346	—	Rio Grande	600	10.17	422.3	419.6	−0.6	417.9	−1.0	417.4	−1.2	1,003	103.9	3.4	1.18
269	02320000	30.100	−83.172	18,855	Rio Grande	1,200	10.16	423.9	425.8	0.4	—	—	—	—	823	107.0	5.0	0.79
289	—	46.498	−84.332	—	Rio Grande	600	10.17	669.6	672.5	0.4	694.4	3.7	694.3	3.7	425	430.5	6.1	0.26
256	06342500	46.814	−100.821	482,771	Rio Grande	1,200	10.16	731.5	—	—	716.9	−2.0	719.3	−1.7	599	203.9	3.6	1.01
330	12308000	48.701	−116.197	—	Rio Grande	1,200	10.17	855.6	859.3	0.4	—	—	—	—	968	131.3	5.2	1.25
230	06935965	38.789	−90.471	1,357,147	Rio Grande	1,200	10.16	1553.3	1544.4	−0.6	—	—	—	—	2,649	355.3	4.9	0.89
233	07010000	38.629	−90.180	1,805,213	Rio Grande	1,200	10.16	4899.2	4851.0	−1.0	—	—	—	—	886	511.8	8.2	1.16
225	12472800	46.629	−119.864	248,638	Gauge	—	—	7617.2	6961.5	−8.6	6898.1	−9.4	6906.3	−9.3	743	379.1	9.9	1.85
Min	—	—	—	—	—	—	—	1.4	1.3	−8.6	1.7	−9.4	1.3	−9.3	425	5.6	0.4	0.09
Mean	—	—	—	—	—	—	—	287.6	282.8	−0.4	234.6	−0.7	225.3	−0.6	1,040	71.0	2.3	0.53
Max	—	—	—	—	—	—	—	7617.2	6961.5	7.4	6898.1	8.3	6906.3	8.1	2,649	511.8	9.9	1.85

Note: — = data not available; BT = bottom track; Duration = duration of M9 comparison streamflow measurement; Freq = frequency; Gauge = stage-discharge relation (rating curve); GGA = position-based GPS; Latitude = decimal degrees (positive value indicates North and vice versa); Longitude = decimal degrees (negative value indicates West and vice versa); Max = maximum; Min = minimum; Per diff = percentage difference from reference measurement (positive value means M9 streamflow measurement was greater than the reference streamflow measurement, and vice versa); Q = discharge; Q/Area = mean velocity; Station number = USGS gauging-station number; VTG = vector-based GPS.

Table 8. Summary of RiverRay 44.12–44.15 ADCP Validation Data Set

Site identifier	Station number	Latitude (degrees)	Longitude (degrees)	Drainage area (km^2)	Reference measurement				RiverRay comparison measurement		Measurement characteristics			
					Instrument type	Freq (kHz)	Firmware	Q (m^3/s)	BT Q (m^3/s)	Per diff (%)	Duration (s)	Width (m)	Mean depth (m)	Q/Area (m/s)
303	05453520	41.715	−91.530	8,068	Rio Grande	1,200	10.17	4.0	4.0	−0.5	914	79.5	2.4	0.02
217	03439000	35.143	−82.825	176	StreamPro	2,000	31.11	4.2	4.1	−2.5	730	20.9	0.9	0.21
381	05455500	41.470	−91.714	1,487	FlowTracker	—	3.70	5.6	6.1	7.7	811	32.2	0.4	0.41
216b	01064000	43.818	−70.450	1,142	StreamPro	2,000	31.12	5.7	5.5	−3.1	1,196	23.0	2.5	0.10
216a	01064000	43.818	−70.450	1,142	Rio Grande	1,200	10.17	5.9	5.7	−3.1	992	23.5	2.4	0.10
226	01064000	43.818	−70.450	1,142	Rio Grande	1,200	10.17	7.8	7.7	−1.5	836	20.3	2.8	0.14
382	05487980	41.247	−93.290	862	FlowTracker	—	3.70	9.5	9.0	−5.8	659	22.4	0.6	0.68
384b	01064000	43.818	−70.450	1,142	Rio Grande	1,200	10.17	9.6	9.6	−0.2	1,069	21.3	2.3	0.19
384a	01064000	43.818	−70.450	1,142	Rio Grande	1,200	10.17	9.8	9.8	−0.2	1,040	19.8	2.5	0.20
185	05453520	41.715	−91.530	8,068	Rio Grande	1,200	10.17	12.4	12.4	−0.5	649	73.7	2.7	0.06
157a	05453520	41.715	−91.530	8,068	Rio Grande	600	10.17	12.4	12.4	−0.5	649	73.8	2.7	0.06
186	05458300	42.737	−92.470	4,007	Rio Grande	1,200	10.17	13.8	14.7	6.2	2,406	127.2	1.2	0.09
175b	08067070	29.961	−94.810	—	StreamPro	2,000	31.11	19.1	20.0	4.5	682	28.3	1.9	0.37
175a	08067070	29.961	−94.810	—	StreamPro	2,000	31.11	19.2	19.9	3.5	1,326	27.1	1.8	0.38
390	01022500	44.608	−67.935	588	Rio Grande	1,200	10.17	24.8	26.2	5.4	905	29.6	1.5	0.55
383a	01055500	44.269	−70.230	438	Gauge	—	—	29.0	29.9	3.0	989	26.4	1.1	1.04
383b	01055500	44.269	−70.230	438	Gauge	—	—	29.5	30.3	2.8	905	25.8	1.1	1.06
189	05488110	41.361	−92.973	31,934	Rio Grande	1,200	10.17	30.2	32.2	6.8	749	120.5	2.1	0.12
144	—	26.697	−80.807	—	Rio Grande	600	10.17	30.6	31.6	3.4	1,966	43.8	1.6	0.43
215	01054300	44.593	−70.733	337	StreamPro	2,000	31.12	31.3	30.9	−1.4	670	25.7	2.0	0.60
323	05465500	41.178	−91.182	32,375	Rio Grande	1,200	10.17	33.2	33.3	0.3	934	125.7	1.1	0.25
188	05488110	41.361	−92.973	31,934	Rio Grande	1,200	10.17	40.8	41.8	2.4	1,008	126.2	2.2	0.15
157b	05488110	41.361	−92.973	31,934	Rio Grande	1,200	10.17	40.9	42.1	3.0	1,008	126.2	2.2	0.15
271	12100490	47.275	−122.207	1,228	Price AA	—	—	84.4	86.0	1.9	504	47.5	1.1	1.83
371	04165500	42.596	−82.909	1,901	Rio Grande	1,200	10.16	90.0	95.8	6.4	850	43.9	2.3	0.91
187	05465500	41.178	−91.182	32,375	Rio Grande	1,200	10.17	90.0	90.6	0.6	856	169.2	1.6	0.33
220	05465700	41.103	−91.064	32,711	Rio Grande	1,200	10.17	91.4	96.6	5.7	1,162	154.1	1.4	0.43
389	01021000	45.137	−67.318	3,559	StreamPro	2,000	31.12	92.2	97.4	5.6	1,075	78.2	1.7	0.67
373	04165500	42.596	−82.909	1,901	Rio Grande	1,200	10.16	96.1	97.5	1.4	732	44.3	2.3	0.96
219	05465500	41.178	−91.182	32,375	Rio Grande	1,200	10.17	96.3	98.0	1.8	886	181.1	1.3	0.42
372	04165500	42.596	−82.909	1,901	Rio Grande	1,200	12.16	97.5	104.7	7.4	879	44.3	2.3	0.95
242	05330920	44.870	−93.192	43,771	Rio Grande	1,200	10.17	110.8	108.8	−1.8	1,643	96.1	4.6	0.25
149	01046500	45.052	−69.886	7,032	Rio Grande	1,200	10.17	117.3	108.1	−7.8	985	97.3	2.6	0.46
190	05465500	41.178	−91.182	32,375	Rio Grande	1,200	10.17	169.1	167.1	−1.2	1,163	174.3	2.0	0.49
141	04266500	44.235	−74.572	1,867	Rio Grande	1,200	10.16	192.5	187.7	−2.5	878	63.4	3.4	0.88
155	NIWA752	−46.255	169.784	21,963	Rio Grande	1,200	10.16	203.4	202.4	−0.5	933	85.0	2.2	1.10
245	05344490	44.749	−92.804	19,813	Rio Grande	1,200	10.17	228.4	230.3	0.8	1,637	160.2	7.0	0.20
158b	05344490	44.749	−92.804	19,813	Rio Grande	1,200	10.17	228.4	229.3	0.4	1,637	160.2	7.0	0.20
192	05420460	41.827	−90.190	221,702	Rio Grande	600	10.17	234.5	238.5	1.7	879	160.9	3.8	0.38
275	15258000	60.493	−149.808	1,642	Rio Grande	1,200	10.16	244.4	243.8	−0.3	764	108.5	2.1	1.09
114a	01042500	45.340	−69.962	4,118	Rio Grande	1,200	10.17	369.4	362.4	−1.9	736	43.2	3.1	2.78
274	15266110	60.467	−150.599	3,124	Rio Grande	1,200	10.16	383.3	380.7	−0.7	801	121.2	2.2	1.43
273	15266300	60.478	−151.079	5,053	Rio Grande	1,200	10.16	419.2	434.9	3.7	731	124.5	2.2	1.56
193	05474000	40.754	−91.277	11,168	Rio Grande	600	10.17	512.3	478.7	−6.6	897	100.0	3.8	1.34
156	NIWA75207	−46.236	169.746	21,963	Rio Grande	1,200	10.16	648.1	624.0	−3.7	1,058	169.9	3.1	1.24
114b	01042500	45.340	−69.962	4,118	Rio Grande	1,200	10.17	760.9	744.9	−2.1	826	123.6	3.4	1.83

Table 8. (*Continued.*)

Site identifier	Station number	Latitude (degrees)	Longitude (degrees)	Drainage area (km^2)	Reference measurement				RiverRay comparison measurement		Measurement characteristics			
					Instrument type	Freq (kHz)	Firmware	Q (m^3/s)	BT Q (m^3/s)	Per diff (%)	Duration (s)	Width (m)	Mean depth (m)	Q/Area (m/s)
116	01049265	44.472	−69.684	13,994	Rio Grande	600	10.17	847.3	816.5	−3.6	952	217.2	3.5	1.12
158a	05331580	44.746	−92.848	96,088	Rio Grande	1,200	10.17	869.9	871.5	0.2	785	176.5	8.7	0.57
244	05331580	44.746	−92.848	96,088	Rio Grande	1,200	10.17	874.7	885.5	1.2	785	176.5	8.7	0.57
243	05331000	44.944	−93.088	95,311	Rio Grande	1,200	10.17	1353.2	1346.2	−0.5	913	253.5	5.4	0.99
231	06935965	38.789	−90.471	1,357,147	Rio Grande	1,200	10.16	1538.2	1581.4	2.8	1,263	348.5	5.0	0.88
176	08111500	30.129	−96.188	113,648	Rio Grande	600	10.17	1596.1	1642.5	2.9	1,035	117.7	8.8	1.55
191	05474500	40.394	−91.374	308,207	Rio Grande	1,200	10.17	1841.7	1841.6	0.0	1,036	734.5	3.0	0.83
232	07010000	38.629	−90.180	1,805,213	Rio Grande	1,200	10.16	4885.7	4973.9	1.8	1,355	517.3	8.2	1.16
394	05474500	40.394	−91.374	308,207	Rio Grande	600	10.17	6333.6	6225.3	−1.7	1,006	741.8	6.7	1.27
224	12472800	46.629	−119.864	248,638	Gauge	—	—	7688.0	7619.7	−0.9	690	378.3	10.3	1.97
Min	—	—	—	—	—	—	—	4.0	4.0	−7.8	504	19.8	0.4	0.02
Mean	—	—	—	—	—	—	—	603.9	602.7	0.7	990	133.1	3.2	0.71
Max	—	—	—	—	—	—	—	7688.0	7619.7	7.7	2,406	741.8	10.3	2.78

Note: — = data not available; BT = bottom track; Duration = duration of RiverRay comparison streamflow measurement; Freq = frequency; Gauge = stage–discharge relation (rating curve); GGA = position-based GPS; Latitude = decimal degrees (positive value indicates north and vice versa); Longitude = decimal degrees (negative value indicates west and vice versa); Max = maximum; Min = minimum; Per diff = percentage difference from reference measurement (positive value means RiverRay streamflow measurement was greater than the reference streamflow measurement, and vice versa); Q = discharge; Q/Area = mean velocity; Station number = USGS gauging-station number; VTG = vector-based GPS.

Appendix. M9 and RiverRay ADCP Validation Data Sets

Collecting a large ADCP validation data set is such a colossal task that it was deemed important and valuable to make these data available. Tables 7 and 8 show a summary of the location and station information, the reference and comparison streamflow measurements, and the flow characteristics for the M9 2.00–3.00 and RiverRay 44.12–44.15 ADCP validation data sets, respectively. The first column refers to the site identifiers shown in Fig. 2. The tables are sorted in ascending order by reference streamflow.

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