COLORADO EXPERIENCE WITH DISCHARGE MEASUREMENTS AT PARSHALL FLUMES AND ASSESSMENT OF PARSHALL FLUME PERFORMANCE


ABSTRACT

The collective experience of the Colorado Division of Water Resources (CDWR) Hydrographic and Satellite Monitoring Branch with operational performance of Parshall flumes installed across Colorado during the last 10-12 years is summarized. Hundreds of discharge measurements have been made at Parshall flumes, ranging in size from 6-inch to 40-ft throat widths during this period. The purpose of these measurements is to continually assess Parshall flume measurement performance in order to provide accurate discharge data for water rights administration. Discharge measurements, along with systematic assessment of flume levelness, flow approach and exit conditions at the flume installation, and other factors, provide quantifiable checks on flume stage-discharge relationship (rating) performance. Causes of any significant departures of measured flow from the flume rating indicated flow and solutions for improved flow accuracy are presented. Several special case studies of flume performance issues are discussed.

BACKGROUND

Colorado water law is based on the concept of “first in time, first in right”. As mining went through its boom and bust cycles in the mid to late 19th century, homesteading and development of agriculture followed closely behind. Prior to Colorado statehood in 1876, territorial laws were enacted allowing water to be taken from streams and rivers to lands “not adjoining the waterway”, as well as recognition of rights of way to transport water across lands not owned by the owners of the water right.

The Colorado Doctrine, or the Doctrine of Prior Appropriation, recognizes: a) those that put the water to use first are entitled to get their water first during periods of water shortage, and b) water is a separate property right that can be sold separately from the land. This is opposed to the Riparian Doctrine that ties water use rights to the ownership of lands adjacent to the river or stream. The codification of fundamental Colorado water law is found in Colorado’s 1876 Constitution, Article XVI, Sections 5, 6 and 7. These basically state: water within the State of Colorado is a public resource belonging to the citizens of the State; the right is recognized to divert unappropriated waters of any natural stream and apply that water to beneficial use with priority of appropriation determining

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who gets water first in times of shortage; and, the right is recognized to convey water across public, private and corporate lands upon payment of just compensation.

In 1879, the Colorado legislature created a part of Colorado’s present water administration system. It provided for the division of the State into ten water districts, nine of these in the South Platte valley and one in the Arkansas. The position of water commissioner was created with this legislation for the express purpose of allocating and distributing water according to the doctrine of prior appropriation. In 1881, the Colorado legislature established the Office of the State Hydraulic Engineer. The purpose of this office was to assist in carrying out the provisions of certain portions of the irrigation laws passed at the same session, and to obtain important information by means of surveys and observations. Primary responsibility was the administration of water rights according to the prior appropriation doctrine, by maintaining a list of water rights, on each stream, in order of priority. The priority of a water right is determined by both when the water was first diverted and put to a beneficial use and when the right was decreed by the district court. Additionally, the State Engineer (among other duties): “shall make, or cause to be made, careful measurements and calculations of the maximum and minimum flow in cubic feet per second, of water in each stream from which water shall be drawn for irrigation, as may be best for affording information for irrigating purposes; commencing with those streams most used for irrigation...”.

These two early pieces of legislation formed the basis of the system of water administration still in use today: measurements of the amount of water in rivers and streams over time provide the data needed and used by water commissioners to administer water rights according to the State’s Constitution. In 1883, Colorado’s second State Engineer, E.S. Nettleton, designed and developed the Colorado Current Meter, cups or vanes rotating in a horizontal plane around a vertical axis, the speed of rotation of which could be directly related to the velocity of water impinging on the vanes. This advance greatly improved the ability to accurately measure stream discharge, and the design is the basis of the Price AA current meter still widely used today. In 1884, Nettleton designed and developed a stream stage recorder for use at stream gage stations to collect continuous records of stream stage, which could be used to compute records of streamflow. The State Engineer’s Office established some of Colorado’s earliest stream gage stations during this period: Cache la Poudre at the Canyon Mouth (1881) and actually the oldest continuous operational streamgage in the US; Arkansas River at Canon City (1888); and, Rio Grande near Del Norte (1889); All are still operated by the CDWR.

More recently, in 1969, the State legislature passed the Colorado Water Rights Determination and Administration Act. This legislation created the Colorado Division of Water Resources (CDWR) as part of the Department of Natural Resources. The State Engineer’s Office was incorporated as the CDWR. CDWR is empowered to administer all surface and ground water rights throughout the state and ensure that water is administered according the State Constitution, court decrees and well permits. CDWR employs approximately 280 professional engineers, geologists, hydrologists, information technology professionals, technicians, and support staff to administer water rights, to evaluate and issue water well permits, monitor stream flow and water use, inspect dams and wells for construction and safety, maintain databases of Colorado water information,
represent Colorado in interstate water compact proceedings, evaluate impacts of and necessary mitigation for various water use activities, educate the public, and numerous other responsibilities.

Significant development has transpired over the 137 years since Colorado became a State, including development of major urban centers (particularly on the Front Range), economic development, and agricultural development. Interstate compacts and agreements were developed describing how water, which has its source in Colorado, would be shared with downstream States. By the later decades of the 20th century, heavy stress on Colorado’s limited water supply and on administration of that water supply was being experienced. Population growth has resulted in greater domestic demand for both surface and ground water. Increasingly complex water court decrees, augmentation plans, exchanges, etc. have been developed and executed. Colorado water administrators are experiencing greater and greater need for timely and accurate water resources data at more and more locations statewide.

THE CDWR HYDROGRAPHY AND SATELLITE MONITORING BRANCH

The Colorado State Engineer has general supervisory control over measurement, record-keeping, and distribution of the public waters of the State. Within CDWR, the State Engineer charges the Hydrography and Satellite Monitoring Branch with streamflow measurement and monitoring responsibility. This involves the collection and dissemination of accurate, high quality ‘real-time’ surface water (stream and reservoir) data to support the water rights administration mission of the agency. The Branch currently operates and maintains over 530 satellite-telemetered gage stations throughout Colorado, and coordinates with the USGS, and other State and Federal agencies that operate approximately an additional 390 gage stations in the State. Primary objectives of this work are: 1) to conduct streamflow measurements at streamgaging sites along the State’s natural rivers and creeks, and at major ditch and canal diversions, and, 2) to operate and maintain a water resources data collection (at key gage stations) and telemetry system to provide accurate near real-time water supply data to water administration decision makers. This latter effort is known as the Colorado Satellite-Linked Water Resources Monitoring System (SMS) and is fully described by Ley et al. (2010). Water level (stage) sensing and satellite telemetry equipment at gages on the network are visited on a regular basis. Stage sensor calibration checks are made to ensure accurate data, and equipment is checked to help minimize operational downtime and missing data. Flow measurements are performed on rivers, streams, creeks, major ditch and canal diversions to maintain accurate stage-discharge relationships at the gage station sites.

The CDWR Hydrographic Program employs standard operating procedures used for streamflow measurement; gage station design, construction, operation and maintenance; and streamflow record development that are directly attributable to US Geological Survey standards and protocols (Rantz et al., 1982; Sauer and Turnipseed, 2010; Turnipseed and Sauer, 2010). Discharge measurements are made using conventional vertical axis Price AA and pygmy current meters, and hydroacoustics technology
Maintaining accurate real-time data requires expenditure of considerable manpower resources to ensure that remote gage station hardware and sensors remain in calibration, and the stage-discharge relationships accurately reflect current channel/control conditions. Since important real-time water administration decisions are made based on the available data, the Hydrographic Branch’s calibration efforts are rigorous. State hydrographers are located in each of the 7 major river basins in Colorado. They visit gage stations as frequently as every week, but generally at two to four week intervals. Over 4,000 discharge measurements are made and saved in a digital database annually.

Raw and processed gage station data are available to users at the Colorado Surface Water Conditions web site (www.dwr.state.co.us). This website provides users with current surface water conditions (streamflow and reservoir storage), and provisional, historical data in graphic and tabular formats. A touch tone telephone-based application called WaterTalk, an automated water information phone line is also available to users to access streamflow data at user selected stream gages.

WATER MEASUREMENT AT PRIMARY DIVERSION STRUCTURES

The majority of the large, senior water rights in Colorado belong to irrigation companies. These rights are also often the calling right in the administration of a water district. These diversion rights can significantly affect mainstem and tributary stream flows. Dozens of major irrigation diversions are monitored by the SMS, and in large part these diversions are measured using Parshall flumes.

Trans-basin diversions (from one river basin drainage to another) and transmountain diversions (from one side of the Continental Divide to the other) must be carefully measured and monitored. Such diversions are obviously of major interest to water users in the source basin as well as to water right holders exercising the diversion rights in the receiving basin. Over 40 such transmountain diversions and trans-basin diversions are monitored by the SMS, and again, in large part these diversions are measured using Parshall flumes.

Parshall Flumes

The Parshall flume was developed in the early 20th century by Ralph Parshall and others at (then) Colorado A&M College (Parshall, 1936; Parshall, 1953). Parshall flumes have been employed extensively throughout Colorado to measure irrigation water diversions and deliveries, and are one of the most widely used water measurement devices in the world. The Parshall flume is characterized as a short-throated, critical depth flume. Flow control is achieved in a converging section from the flume entrance to the throat, in which flow accelerates from tranquil, sub-critical velocity to critical velocity at the flume throat. The accelerating, curvilinear flow to the flume throat and the non-geometric similitude among sizes required a unique stage-discharge relationship to be empirically developed for each flume size. Under free flow conditions, a single upstream head measurement at a specific location in the converging flume section is used to compute
flow. Parshall conducted a large number of flume calibration studies to develop free flow ratings for various flume sizes at the Colorado State College Hydraulics lab in Ft Collins Colorado and at an outdoor lab near Bellevue about 8 miles northwest of Ft Collins.

The flume stage-discharge relationships or rating equations (Parshall, 1936 and 1953; USBR, 2001 and elsewhere) are reported to be accurate to within ±3-5% of the true flow only under several stringent design, construction, installation, and operating conditions. These include:

- careful fabrication or construction to given structural dimensions for each flume size
- approach channel design and maintenance such that:
  - length of straight and unobstructed channel upstream, with mild slope, is at least 10 times the channel width
  - channel upstream of the structure should be both wider and deeper than the flume entrance cross section
  - stilling pool should be created and maintained in this upstream section (15-18 inches deeper than the flume crest) so that water flow is tranquil (smooth surface) and slow
  - transition from upstream channel bed to flume floor (no shallower than 1:4 slope) should be provided
  - wing walls from channel section to flume entry no shallower than 45° transition
  - upstream pool should be kept free of weeds and trash; sediment should be routinely removed
- flume floor in the converging section to the flume throat must be installed and maintained level laterally and longitudinally
- free outfall flow conditions meaning the flume crest elevation is designed and installed based on engineering analysis of channel geometry, slope, and design flow; and maintenance of downstream flow channel conditions to ensure no more than 70% submergence for flumes from 1 to 8 feet in size and no more than 80% submergence for flume sizes of 10 feet and larger
- head measurement (staff gage or stilling well intakes) must be correctly positioned vertically (staff reads zero and stilling well intake invert at the flume floor), and longitudinally along the flume converging section wall (⅔A upstream from the flume crest, where A is the converging section sidewall length, as measured along the wall and not axially in the flume)
- maintenance of the integrity of the flume (corrosion of metal, concrete spalling, etc.) to minimize deviations in cross sectional flow area and roughness from design conditions
- maintenance of the integrity of the flume installation to eliminate leaks past sidewalls or under the flume
- attention to transient maintenance issues such as moss and other aquatic vegetative growth in the flume, debris in the flume, and debris/vegetation in the up- and downstream channel, all of which can affect cross-sectional flow area and roughness deviations from design conditions, or cause backwater into the flume throat and flume submergence greater than specified for free flow conditions.
Several laboratory and field studies have been conducted to evaluate Parshall flume performance when these conditions are not met. Effects of longitudinal and lateral flume settlement, with and without submerged outfall conditions, on measured flume discharge versus indicated (i.e., determined from rating) flume discharge for flumes up to 2-foot throat widths were studied in the Hydraulics Lab at Colorado State University (Genovez et al., 1993; Abt et al., 1994; Abt et al.,1995). Correction and adjustment procedures were developed.

Abt and Ruth (1997) presented and discussed field assessments of 66 Parshall flumes ranging in size from 9-inch to 6-foot throat widths (there was one 12-ft flume in the study) installed around Colorado. Integrity of the flume construction and installation, including levelness, and operating conditions, such as approach and outfall conditions were assessed. Flume submergence and flow rate were also determined. A wide variety of issues were found. Rated discharge was compared with corrected discharge, where flow corrections were applied for lateral and longitudinal settlement and submergence based on Genovez et al (1993), Abt et al (1994), Abt et al (1995). In 59 percent of the flumes assessed, the rating indicated discharge was less than corrected discharge, i.e., more water delivered than indicated. Abt and Ruth (1997) also report 41 percent of the flumes assessed were measuring flow beyond ±5 percent of the corrected flow. Independent measurements of actual flow at the sites studied were apparently not made.

Heiner et al. (2011) reported results of an assessment of 70 Utah flow measurement structures, 50 of which were Parshall flumes ranging in size from 2 ft to 12 ft throat widths. Again, a wide variety of issues were found ranging from settling to poor approach flow to improper stage measurement to vegetation/debris and sediment problems. Only 15 of the 50 Parshall flumes were found to measure flow within ±5 percent of the indicated flow.

In this paper, we report on the field operational performance of over 220 Parshall flume installations across Colorado used for measuring mainstem river, tributary, and creek diversions; and trans-basin and transmountain diversions. Flume size ranges from 6-inch to 40-ft throat widths. Flume performance is assessed by on-site inspection of the flume installation, settling (as determined by differential leveling), improper approach conditions, and independent discharge measurements of stream flow.

**METHODS**

Discharge measurement summary data were obtained from the CDWR discharge measurement database for all measurements made at Parshall flume gage stations by CDWR hydrographers over approximately the last 12 years. In a few cases, measurement summaries dating back to the 1980’s have been hand entered, and were also included in this analysis. Stage-discharge relationships (rating curves) used at these gages, whether the standard Parshall flume rating for the given flume size, or a custom rating based in part on the standard Parshall flume rating, were also obtained. The discharge measurements were categorized by flume size. The measurement shift and percent difference from the rating were computed for each measurement:
Shift (ft) = Rating GH for Measured Q – Observed GH

% difference = \[\frac{(\text{Measured Q} - \text{Rating Q})}{\text{Rating Q}}\] x 100

where GH is gage height (ft), Measured Q is independent measurement of discharge (cfs), and Rating Q is the indicated discharge (cfs) from the flume rating at the observed gage height.

All measurements for a given flume size were plotted against the standard flume rating curve for that flume size. Note that while discharge is the dependent variable, the standard convention of plotting discharge as the abscissa and stage as the ordinate is used here. Measurements with positive (+) shifts, indicating the actual flow is greater than the rated flow at the measured gage height, plot to the right of the rating curve, while measurements with negative (-) shifts, indicating the actual flow is less than the rated flow at the measured gage height, plot to the left of the rating curve.

At artificial controls such as Parshall flumes, shifts to the rating may be caused by all of the factors discussed in the previous section. The sign of the shift, (+) or (-), is a result of whether the affecting factor causes observed gage height to be greater or less than the rating gage height for the measured flow. For example, moss or other aquatic vegetative growth on the flume floor in the converging section effectively causes increased gage height for a given discharge and thus results in a negative shift. Conversely, upstream approach conditions which result in excess approach velocities (no provision for stilling of flow to tranquil conditions) typically result in positive shifts since flow velocity through the flume is faster than conditions under which flume ratings were developed. Shift adjustments to the rating, essentially a new or “re-calibrated” rating, may be applied temporarily, such as for the conditions of transient aquatic vegetation growth. Or, the shifts may be consistent to one side of the standard rating, and relatively stable, such as in the case of some poor approach channel designs, in which case, a semi-permanent variable stage-shift relationship is developed and applied. In such cases, this essentially becomes a custom rating for the flume.

Measurement percent difference from the standard rating is an indicator of whether the flume is measuring within expected accuracy (±3-5%) and whether remedial procedures need to be implemented ranging from complete physical refurbishment of the installation to development and application of a variable stage-shift relationship to improve measurement accuracy. Discharge measurement accuracy ratings used by CDWR are based on USGS methods (Turnipseed and Sauer, 2010). Measurements are rated good (within 5% of the true flow), fair (within from 5% to 8% of the true flow), and poor (greater than 8% from the true flow).

**DISCUSSION OF RESULTS**

A total of 4,228 independent discharge measurements at 223 flume installations across Colorado are summarized in Table 1. The results in Table 1 are broken down by number of sites and number of measurements analyzed for each flume size. The range of
observed gage heights and measured discharges represented by the independent measurements is given. The last three columns of Table 1 break the number of measurements into measurement percent difference categories: good (<5% from true flow), fair (5% to 8%), and poor (more than 8%).

Table 1 shows that for 45% of the discharge measurements, the flumes were found to be operating within 5% of the rating indicated flow. In such instances, unless there is a consistent trend in the shift from the rating, typically no shift adjustment is considered necessary nor applied. If, however, there is a consistent trend in the sign and magnitude of the shift as determined by calibration measurements, then a shift will be developed and applied to improve overall flume measurement accuracy. For approximately 16% of the measurements, flumes were found to be operating within 5% to 8% of the standard rating. And, in 39% of the measurements, the flume was operating more than 8% from the standard rating. In these last two categories, shifts will typically be applied and further calibration measurements are often scheduled and flume inspections undertaken to determine the root causes of the flume measurement deviations.

Summary results shown in the last three columns of Table 1 indicate the smaller flume sizes included in this summary (up to 6 ft throat widths) tended to operate with greater deviation from the standard rating, and thus greater potential for compromised measurement accuracy. For the smaller flume sizes (up to 6-ft throat widths), an average of approximately 56% of discharge measurements show the flumes are operating greater than 8% from the standard rating. For the larger flumes in this summary (8 ft and larger throats) better measurement accuracy was found. An average of approximately 60% of the discharge measurements show these flumes are operating within 5% of the standard rating. Several factors contribute to this result, including for example: random discharge measurement errors will be a larger percentage of the smaller flows measured at the smaller flume sites, smaller flumes tend to be lighter (smaller mass) installations and potentially more prone to frost heaving and settling, discharge errors in small flumes due to even small lateral or longitudinal settling will be a larger percentage of measured flows than for the same amount of settling in a large flume.

Discharge measurements included in this analysis are plotted with the standard Parshall flume rating curve in Figures 1-16 for each flume size (with the exception of the 6-inch, 7-ft and 40-ft flumes, for which there were only a few available measurements). A quick visual assessment of these rating curve plots reveals:

- In Figures 1 through 9, for flume sizes up to 6-ft throats, the larger measurement deviation from the standard rating (as discussed above regarding Table 1) is readily apparent when compared to Figures 11-16 for the larger flume sizes, which illustrate much less measurement variability from the standard rating.
- Documented submerged flow measurements are readily apparent in Figures 2, 7, 8, and 10 (blue symbols circled in a blue oval) and illustrate the large measurement error that occurs when the flume is under submergence and only a single upstream head
Table 1. Summary of discharge measurements made by CDWR Hydrographers during approximately 1999 to present at various size Parshall flumes across Colorado.

<table>
<thead>
<tr>
<th>Flume Size</th>
<th>No. of Sites</th>
<th>Measurements</th>
<th>% Difference from Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number</td>
<td>Gage Height Range (ft)</td>
<td>Discharge Range (cfs)</td>
</tr>
<tr>
<td>6-inch</td>
<td>2</td>
<td>0.37-0.89</td>
<td>0.47-1.76</td>
</tr>
<tr>
<td>9-inch</td>
<td>2</td>
<td>0.17-1.04</td>
<td>0.18-3.23</td>
</tr>
<tr>
<td>1-ft</td>
<td>6</td>
<td>0.13-1.04</td>
<td>0.14-4.75</td>
</tr>
<tr>
<td>18-inch</td>
<td>6</td>
<td>0.39-1.14</td>
<td>1.17-5.48</td>
</tr>
<tr>
<td>2-ft</td>
<td>23</td>
<td>0.01-1.32</td>
<td>0.05-12.9</td>
</tr>
<tr>
<td>30-inch</td>
<td>7</td>
<td>0.01-1.08</td>
<td>0.03-11.3</td>
</tr>
<tr>
<td>3-ft</td>
<td>24</td>
<td>0.04-1.87</td>
<td>0.15-27.7</td>
</tr>
<tr>
<td>4-ft</td>
<td>32</td>
<td>0.15-2.28</td>
<td>0.87-60.6</td>
</tr>
<tr>
<td>5-ft</td>
<td>23</td>
<td>0.13-2.78</td>
<td>0.62-96.6</td>
</tr>
<tr>
<td>6-ft</td>
<td>19</td>
<td>0.03-2.90</td>
<td>0.05-131</td>
</tr>
<tr>
<td>7-ft</td>
<td>2</td>
<td>0.70-1.47</td>
<td>14.4-46.8</td>
</tr>
<tr>
<td>8-ft</td>
<td>20</td>
<td>0.21-4.65</td>
<td>3.53-412</td>
</tr>
<tr>
<td>10-ft</td>
<td>11</td>
<td>0.02-2.71</td>
<td>0.24-192</td>
</tr>
<tr>
<td>12-ft</td>
<td>19</td>
<td>0.20-5.01</td>
<td>2.57-627</td>
</tr>
<tr>
<td>15-ft</td>
<td>15</td>
<td>0.15-5.51</td>
<td>3.15-976</td>
</tr>
<tr>
<td>20-ft</td>
<td>4</td>
<td>0.16-3.10</td>
<td>2.95-487</td>
</tr>
<tr>
<td>25-ft</td>
<td>4</td>
<td>0.20-3.01</td>
<td>6.07-572</td>
</tr>
<tr>
<td>30-ft</td>
<td>3</td>
<td>0.24-4.82</td>
<td>12.0-1610</td>
</tr>
<tr>
<td>40-ft</td>
<td>1</td>
<td>1.03-1.82</td>
<td>161-386</td>
</tr>
<tr>
<td>Total</td>
<td>223</td>
<td>4228</td>
<td>1924</td>
</tr>
</tbody>
</table>
settling, spalling, etc., which, for the measured gage height results in a larger flow than indicated by the standard rating.

- Less apparent, but still evident in a few cases, is the opposite effect, where heaving of the flume or some other factor (increased surface roughness, aquatic vegetative growth, etc.) have caused in increase in the effective point of zero flow and measurements plot with a curvilinear (concave up) trend versus the standard rating.
- In a several instances of the larger flumes, some discharge measurements show a curvilinear (concave down) trend plotting to the right of the standard rating (positive shifts) at higher discharges and gage heights. This result is typically caused by high approach velocities in the upstream approach channel and in the flume entrance section.

CASE STUDIES

The CDWR Hydrography and Satellite Monitoring Branch performs discharge measurements and systematic assessments of flume installation and operating conditions to document quantifiable checks on flume measurement performance. As data are gathered and evaluated, causes of departures of measured flow from the flow indicated by the flume rating, whether these departures are ephemeral or long term, and solutions for improved flow accuracy are formulated. Often, flume installations must be physically refurbished to improve measurement accuracy to desired levels. In other cases, shifts to the rating may be temporary in nature and measurement accuracy is improved by application of measurement shifts to the rating (temporary ratings) over identified periods of time when the flume performance was affected. In yet other cases, the data and evaluations may suggest the flume performance has been altered in some semi-permanent way and a custom rating is developed and maintained to provide improved measurement accuracy. Following are several brief example case studies illustrating flume performance issues and solutions implemented.

Effects of Aquatic Vegetation Growth in the Flume

Figure 16 shows discharge measurements made at 3 different 30-ft Parshall flumes. The measurements for Site No. 1-30 are highlighted with gold symbols. This flume is subject to considerable moss growth in the flume converging section and crest, particularly at lower gage heights (<1.00 ft) and flows. Such flow conditions typically occur in mid to late summer at this site, under high air temperature and warmer water temperature conditions. The consistent plotting of the measurements above and to the left of the standard rating illustrates the small negative shifts which occur due to the moss growth. Real time measurement accuracy of the flume is improved by applying small negative shift adjustments to the real time gage height data prior to computing flow. Such adjustments are applied and removed as site conditions change, i.e., cleaning of the moss from the flume floor, subsequent re-growth, etc. This is obviously a very dynamic situation and requires considerable attention in order to maintain measurement accuracy. Flume owners (and of the water diverted) are typically keen to keep such affected structures clean to avoid getting reduced credit and less water diverted.
High Approach Velocities/Poor Approach Conditions

Site 12-15 is a transmountain diversion gage at the downstream end of a tunnel under the Continental Divide through which water is diverted from the Colorado River drainage basin to the Arkansas River drainage basin. The measurement structure can be described as a standard, concrete, 15 foot Parshall flume and is located approximately 90 feet downstream of the mouth of the tunnel. The approach channel from the mouth of the tunnel to the flume is a concrete rectangular section. The channel section gradually increases in width from the width of the tunnel mouth to a width of approximately 25 feet over a distance of about 70 feet. This is followed by approximately 20 feet of channel having a constant 25-foot width. This constant width section ends at the flume entrance. The floor of the approach channel is flat. There is no provision over this 90-foot reach for a deeper channel section prior to the flume entrance, or any other channel modifications to help still the flow to the recommended tranquil flow conditions. Approach velocities to the flume above a stage of 3.00 ft are high, exceeding an average of 4 ft/s at the flume entrance. Previous experiences with such poor, high velocity approach flow conditions at other flumes have shown such flumes operate with a positive shift to the standard flume rating, i.e., at higher flows the flume passes more water than the standard flume rating suggests for the given gage height. Parshall (1936) reported results of limited tests conducted at the Bellevue lab in which the approach velocity to a 2 ft flume was varied. He found that discharge through the 2-ft flume was not significantly affected when approach velocities were nearly 3 times the approach velocity for standard conditions of about 1 ft/s.

A series of high flow (650-950 cfs) measurements have been made over the past 10 years at Site 12-15. These measurements show a consistent departure from the rating. A high velocity “thread” of water in the center section of the approach channel at the flume entrance and shaped like the tunnel is evident (Figure 17) for these high flows. The high flow measurements have been used to build and further refine a variable stage-shift relationship (for stages above about 2.70 ft), which, when applied to the standard flume rating results in a custom rating for the flume. The custom flume rating is shown in Figure 18. For gage heights above 2.70 ft, 19 measurements showed a percent difference from the standard 15 ft Parshall flume rating ranging from 3.2% to 10% and averaging 7.2%. Against the custom rating, these same 19 measurements showed a percent difference ranging from -3.5 to 4.7% and averaging 0.93%. Calibration efforts continue in order to better define the range of stage where the flume departs significantly from the standard rating.

Apparent Changes to Flume Effective Point of Zero Flow

Sites 2-4 and 17-6 are transmountain diversion gages. Water is diverted from the Colorado River drainage basin and carried by open ditch to the Arkansas River drainage basin. The measurement structure at Site 2-4 is a standard, steel 4 foot Parshall flume, while at Site 17-6 it is a standard, concrete 6 foot Parshall flume. Approach and outfall channel conditions are good at both locations.
A series of discharge measurements made over the past 13 years at Site 2-4 have shown (and continue to show) that the flume operates with a nearly constant negative shift of -0.03 ft over the range of stage measured. These discharge measurements have been used to build variable stage-shift relationship or custom rating for the flume. Measurements, the custom flume rating (blue line), and the standard 4-ft flume rating (red line) are plotted in Figure 19. Measurements showed a percent difference from the standard 4 ft Parshall flume rating ranging from -3.6% to -24% and averaging -11%. Against the custom rating, these same measurements showed a percent difference ranging from -3.8 to 2.7% and averaging 0.19%. The negative shift from the standard rating to the custom rating is attributed to an effective increase in the flume’s point of zero flow caused by corrosion and deposits on the steel floor resulting in increased roughness and water surface elevation.

The opposite is the case at Site 17-6, where a series of discharge measurements made over the past 14 years at the site have shown (and continue to show) that the flume operates with a nearly constant positive shift of 0.04 ft over the range of stage measured. These discharge measurements have been used to build variable stage-shift relationship or custom rating for the flume. Measurements, the custom flume rating (blue line), and the standard 6-ft flume rating (red line) are plotted in Figure 20. Measurements showed a percent difference from the standard 6 ft Parshall flume rating ranging from 3.3% to 40.2% and averaging 14.1%. Against the custom rating, these same measurements showed a percent difference ranging from -2.7 to 1.5% and averaging -0.14%. The positive shift from the standard rating to the custom rating is attributed to an effective decrease in the flume’s point of zero flow caused by some spalling and erosion on the flume floor resulting in an effective decrease in water surface at the same flow level compared to the standard rating.

Site 21-2 is a 2 foot steel Parshall flume on a small creek. The flume is not level laterally. At the staff gage-stilling well intake transect, the floor at the right side (stilling well side) is approximately 0.06 ft lower than the flume floor at the left side (staff gage side). There is also a small downward tilt from flume entrance to throat. Backwater is not an issue, but approach conditions vary due to scour in the channel above the flume due to higher flows during snowmelt runoff, and aquatic vegetation growth during low flow periods causing slow water and deposition in the approach. The site requires continuous work on the approach channel. The gage is operated using the staff gage as the primary reference gage, and combined with the lateral slope in the flume, this results in a small additional unaccounted area of flow relative to the flume’s standard condition, resulting in positive shifts to the rating. Discharge measurements made at Site 21-2 are plotted with a standard 2-ft Parshall rating in Figure 21. The concave downward trend in the measurements is consistent with the additional unaccounted flow area and the fact that this additional area essentially means the point of zero flow for this structure has effectively dropped to a slightly lower stage. The extra unaccounted flow area can be used to develop a geometrically (area) corrected custom rating. The corrected rating is plotted as a blue line in Figure 21. The geometric correction in this case is equivalent to a +0.02 ft shift to the standard rating, or, an effective reduction of the point of zero flow by 0.02 ft. Measurements plotted in Figure 21 show the flume operating at an average of
30.2% difference from the standard 2-ft Parshall rating. Against the custom (geometrically corrected) rating, the flume is now operating at an average 7.4% difference from the custom rating. Variable approach channel conditions, measurement errors and variability due to shallow depths and slow velocities at low flows, and the slight longitudinal tilt are remaining factors causing deviations from the custom rating.

**Abnormal Vertical Velocity Profile**

Site 2-15 is another transmountain diversion gage which measures waters diverted from the Colorado River basin to the South Platte River basin. The measurement structure is a concrete 15 foot Parshall flume in good condition. Water exiting the transmission tunnel enters a 0.5 acre stilling reservoir before entering the Parshall flume on the opposite side of this reservoir, some 300 feet away. The stilling reservoir provides tranquil, laminar approach flow conditions. The immediate approach channel is devoid of accumulated sediment and has a greater than 1:4 slope. Geometric and differential level analysis of the flume did not show any significant deviations nor lateral or longitudinal levelness issues.

Discharge measurements at this site are made using a bridge crane above the standard \( H_s \) location. Both standard and individually rated Price AA current meters have been used. They are suspended on either a C50-lb or C75-lb Columbus weight. Section depths are obtained using a sectional rod, reducing systematic depth measurement errors resulting from downstream drift of the current meter and weight. Discharge measurements have consistently shown a positive shift from the standard rating with larger deviations at higher stages. These observations are consistent with mass balance computations made on the reservoirs associated with this gage. The positive shifts to the rating are attributed to two factors that result in a vertical velocity profile at the measurement section that is nearly uniform with depth compared to the standard 1/6 power law vertical velocity profile: 1) an abnormal wing wall configuration where the wing walls from the channel section to the flume section, upstream of segment D (Parshall, 1953), are at a shallower than 45° angle with respect to the flume mouth and the wing wall tapers from an approximate 60° slope at its extreme upstream end to vertical at the flume entrance section, and 2) the floor of the flume has been coated with an epoxy paint-like coating that greatly reduces roughness and reduces adherence of aquatic vegetation. The combined effect of these two factors is an overall higher average velocity with reduced floor and sidewall friction effects as water enters the flume. The typical vertical and lateral velocity distribution measured at a higher flow and stage at Site 2-15 is shown in Figure 22. Note the range in velocities, and then compare to Figure 17 where floor and sidewall effects are apparent and a much wider range of velocities was measured. Discharge measurements continue to be made periodically, as well as at targeted stages, to better map deviations away from the rating with the ultimate goal of developing a custom rating for this site. Due to operational practices, duplicative measurements throughout the full range in stage experienced are difficult to obtain at this site.
High Approach Velocities: Approach Channel and Flume Degradation

Site 11-15 is a stream delivery quantification point for a large irrigation water conveyance system distributing waters across several sub-basins tributary to the South Platte River. The flume is a concrete 15 foot Parshall flume in fair condition. In the upstream channel, flow exits from a tunnel approximately 0.25 miles upstream from the flume, higher up on a hillside. From this point, the channel drops down a steep gradient chute into the flume’s forebay, which includes a stilling basin section, that is deeper and wider (transitioning from 10 feet to 25 feet wide over 50 linear feet) than the flume. However, the volume of the stilling basin is insufficient to effectively dissipate energy in the high velocity, surging flow produced by the drop chute. The flume has also been coated with an anti-spall paint, reducing friction losses through the flume, adding to the high approach velocity condition.

A custom rating accounting for high approach velocities was developed and had been used at this site for better than 30 years. Measurements made over the last several years, and especially those made from 2010 to present, have shown a negative shift or shift to the left of the custom rating of -1.6% to -5.4%. This denotes a reduction in the water delivered for a given stage. Visual inspection of the flume floor and walls showed areas were the anti-spall coating has been worn off, areas of rough concrete, and some areas of spalled concrete. These visual observations are consistent with the discharge measurement results indicating increased friction losses along the degrading concrete bottom and walls. Differential levels run on the Parshall flume in 2012 showed the flume is level and the primary reference gage is correct. A new rating has been developed. It plots to the left of the custom rating but still to the right of the standard 15 foot Parshall flume rating.

SUMMARY AND CONCLUSIONS

The CDWR Hydrography and Satellite Monitoring Branch operates and maintains over 530 stream gages around Colorado to provide accurate real-time stream flow data in support of the water rights administration mission of the agency. Included among these gages are hundreds of Parshall flumes used for water measurement at diversions. Over 4200 discharge measurements made at 223 Parshall flumes across Colorado, ranging in size from 6-inch to 40-ft throat widths, were compared to standard flume stage discharge relationships. CDWR Hydrographers proactively inspect, assess physical conditions, and perform discharge measurements at flume sites. The results are used to design interventions for improving and maintaining flume measurement accuracy. Interventions range from complete removal and replacement of the measurement structure, to channel and/or flume floor modifications to eliminate submergence, to temporary and permanent custom rating development and implementation, to increased discharge measurement frequency. This program provides quantifiable checks on short and long term adequacy of standard and custom flume stage-discharge relationships. Several case studies of flume performance issues illustrating causes of departures of measured flow from the flume rating indicated flow and solutions for improved flow accuracy were presented and discussed.
This proactive program vividly shows that one cannot just simply install and walk away from an open channel water measurement structure such as a Parshall flume and expect accurate flow measurement. The following conclusions are made:

- Care needs to be taken when designing, installing, or constructing Parshall flumes. Strict adherence to standard Parshall flume dimensions is required for standard ratings to apply.

- Upstream approach channel conditions, in which smooth, tranquil flow into the flume entrance is developed and maintained, are required for standard ratings to apply. Deviations from standard installation considerations can have varied and significant effects on Parshall flume measurement accuracy.

- Elevation setting of the flume crest must be carefully designed and downstream exit channel conditions must be maintained to eliminate flume submergence (or keep within allowable limits). Flow measurement error using a single upstream head measurement when a flume is operating submerged is significant.

- Physical problems and deficiencies may develop over time, such as flume floor levelness, increased surface roughness, development of abnormal velocity profiles, etc., and can significantly affect flume performance.

- Site evaluations and visual observations taking into consideration overall installation conditions and specific installation deficiencies are good predictors of the direction of Parshall flume measurement bias (under or over measurement). The magnitude of the bias can only be determined with a systematic program of independent discharge measurements.

- Development and application of custom Parshall flume ratings (temporary or permanent) is often warranted as a result of flume inspections and independent measurement. Such interventions were shown to improve flume measurement accuracy.

Although not explicitly included in this paper, CDWR staff have similar inspection, evaluation and measurement experience at other types of water measurement structures, including Cipoletti, rectangular, v-notch and other sharp crested weirs, broad crested weirs, long-throated flumes, cutthroat flumes, and submerged orifices with similar results and conclusions. All open channel water measurement structures require frequent maintenance, physical inspection and evaluation, and periodic independent discharge measurements to verify the structure is operating within design parameters and that expected measurement accuracies are being achieved.

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The authors, all current staff members of the CDWR Hydrography and Satellite Monitoring Branch, have each been involved with Parshall flume operational performance assessment in Colorado for several years. They hereby wish to acknowledge the contributions and efforts of many other past and present CDWR staff who have measured and evaluated Parshall flumes in Colorado.
REFERENCES


Figure 1. Discharge measurements (n=6) at standard 9-inch Parshall flume plotted with standard rating.

Figure 2. Discharge measurements (n=32) at standard 1-foot Parshall flume plotted with standard rating.

Figure 3. Discharge measurements (n=15) at standard 1.5-foot Parshall flume plotted with standard rating.
Figure 4. Discharge measurements (n=434) at standard 2-foot Parshall flume plotted with standard rating.

Figure 5. Discharge measurements (n=131) at standard 2.5-foot Parshall flume plotted with standard rating.

Figure 6. Discharge measurements (n=168) at standard 3-foot Parshall flume plotted with standard rating.
Figure 7. Discharge measurements (n=540) at standard 4-foot Parshall flume plotted with standard rating.

Figure 8. Discharge measurements (n=363) at standard 5-foot Parshall flume plotted with standard rating.

Figure 9. Discharge measurements (n=254) at standard 6-foot Parshall flume plotted with standard rating.
Figure 10. Discharge measurements (n=325) at standard 8-foot Parshall flume plotted with standard rating.

Figure 11. Discharge measurements (n=89) at standard 10-foot Parshall flume plotted with standard rating.

Figure 12. Discharge measurements (n=487) at standard 12-foot Parshall flume plotted with standard rating.
Figure 13. Discharge measurements at (n=790) standard 15-foot Parshall flume plotted with standard rating.

Figure 14. Discharge measurements (n=59) at standard 20-foot Parshall flume plotted with standard rating.

Figure 15. Discharge measurements (n=253) at standard 25-foot Parshall flume plotted with standard rating.
Figure 16. Discharge measurements (n=275) at standard 30-foot Parshall flume plotted with standard rating.

Figure 17a. Velocity distribution for measurement 60 (335 cfs) at Site 12-15.

Figure 17b. Velocity distribution for measurement 69 (976 cfs) at Site 12-15.
Figure 18. Custom (shift-adjusted) rating at Site 12-15 as defined by discharge measurements compared to standard 15-foot Parshall flume rating.

Figure 19. Custom (shift-adjusted) rating at Site 2-4 as defined by discharge measurements compared to standard 4-ft Parshall flume rating.

Figure 20. Custom (shift-adjusted) rating at Site 17-6 as defined by discharge measurements compared to standard 6-ft Parshall flume rating.
Figure 21. Custom (geometrically corrected) rating at Site 21-2 as defined by discharge measurements compared to standard 2-ft Parshall flume rating.

Figure 22. Velocity distribution for measurement 399 (558 cfs) at Site 2-15 showing little sidewall and floor friction effects on velocity.