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PARSHALL FLUME STAFF GAUGE LOCATION AND ENTRANCE WINGWALL DISCHARGE CALIBRATION CORRECTIONS

by

Bryan J. Heiner

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Civil and Environmental Engineering

Approved:

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Steven L. Barfuss Major Professor	Michael C. Johnson Committee Member
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UTAH STATE UNIVERSITY
Logan, Utah

2009

ABSTRACT

Parshall Flume Staff Gauge Location and Entrance Wingwall

Discharge Calibration Corrections

by

Bryan J. Heiner, Master of Science

Utah State University, 2009

Major Professor: Steven L. Barfuss
Department: Civil and Environmental Engineering

The Utah Water Research Laboratory, in conjunction with the State of Utah, initiated a study to determine the accuracy of a wide variety of flow measurement devices in Utah. The project selected 70 sites with flow measurement devices throughout the state. During the assessment each device had its physical condition and flow measurement accuracy documented.

Although a wide variety of flow measurement devices were tested, the majority were Parshall flumes. Many of the assessed Parshall flumes were not measuring flow to the specified ±5 percent design accuracy. Problems in flow measurement were due to issues with the staff gauge location and incorrect entrance geometry. Laboratory tests were conducted at the Utah Water Research Laboratory in an attempt to provide accurate flow measurement from flumes with these issues. The tests simulated incorrect locations for measuring upstream head with different entrance geometries on a 2-ft-wide Parshall flume.

The flume was tested with three different entrance wingwall configurations, eighteen stilling wells, and two point gauges, allowing water surface profiles to be collected throughout the flume. Corrections for incorrect head measurement locations and entrance geometries were created.

The objective of this thesis is to provide water users and regulators with the information necessary to help improve open-channel flow measurement accuracies. An overview of design accuracies and flow measurement devices is given. In addition, a method to correct for incorrect head readings in Parshall flumes, a widely used flow measurement device in Utah, is presented. It is expected that this information will help water users and regulators monitor their water with the understanding necessary to ensure that water is more accurately measured.

(54 pages)

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LIST OF SYMBOLS AND ABBREVIATIONS

List of Symbols

A	Length of approach wingwall in Parshall flume (ft)
a	Size specific coefficient for Parshall rating equation
b	Size specific coefficient for Parshall rating equation
b	y-intercept of regression line
C_{center}	Correction factor for different centerline locations
C_{sw}	Correction factor for different stilling well location
C_{wall}	Correction factor for different staff gauge locations
H_a	Upstream head measurement (ft)
m	Slope of regression line
Q_a	Actual discharge (cfs)
Q_{cor}	Corrected flow rate (cfs)
Q_i	Indicated discharge (cfs)
Q_{ind}	Flow from the standard Parshall rating curve (cfs)
α	Location ratio

List of Abbreviations

UWRL	Utah Water Research Laboratory
USBR	United States Bureau of Reclamation
ISO	International Organization for Standardization

CHAPTER I

INTRODUCTION

The Utah Water Research Laboratory in conjunction with the State of Utah performed a study between 2007 and 2009 to determine the accuracy of flow measurement below dams in Utah. As requested by the state of Utah, the study investigated flow elements associated with 161 reservoirs throughout the state. Of the total, 21 reservoirs were directly visited, with five using electromagnetic meters, three using ultrasonic meters, and thirteen using Parshall flumes to measure reservoir releases. The accuracy of each reservoir's measuring device was determined using current metering or with a calibrated ultrasonic meter. Of the 21 measurement devices that were tested, three of the five magnetic meters, all three ultrasonic meters, and seven of thirteen Parshall flumes were not measuring flow to the levels of accuracy manufacturer design specifications claim. As results were collected, it was determined that flow measurement design specifications were not always followed when flow measurement devices were put into operation, causing the devices to not meet specified manufacturer design accuracies. Table 1 gives a summary of the specified accuracy for selected devices found through a review of the technical literature.

After being presented with the findings from the first year of the project, the State of Utah encouraged the author to expand the research to determine if flow measurement errors are more widespread than those found just downstream of reservoirs throughout the State. With help from the Division of Water Rights, 49 additional flow measurement sites were located and tested for flow measurement accuracy.

Table 1. Different Flow Measurement Devices and Specified Design Accuracies

Measurement Device	Type	Accuracy
Rated Sections*	Open Channel	±10%
Ramp Flumes	Open Channel	±2%
Parshall Flumes	Open Channel	±3 to 5%
Cutthroat Flumes	Open Channel	±2%
Weirs	Open Channel	±2.5%
Electromagnetic Meter	Pipe	±0.25%
Ultrasonic Meter	Pipe	±1 to 5%

*Refer to Chapter II section *Rated Sections* for the definition of rated sections

The additional devices were widespread throughout Utah to give a representative sample of the many flow measurement devices used in the state. In total, 70 sites were visited and flow measurement devices were tested. The tested devices included fifty Parshall flumes, four ramp flumes, one Cutthroat flume, four weirs, one rated section, five ultrasonic meters, and five electromagnetic meters. One third of the devices that were tested measured flow within their specified design accuracies as indicated in Table 1. Of the two thirds that did not meet the design criteria, 37 percent overestimated the discharge through the devices, meaning that water users were not being supplied with their full water rights. The remaining 63 percent underestimated their water use, resulting in individuals receiving more than their allotment of water.

Considering that 71 percent of the devices investigated were Parshall flumes, it was determined that finding the cause of inaccuracies of this device would be beneficial to any water user or regulator with Parshall flumes in operation. Chapter II of this thesis describes the process that was undertaken to determine flow measurement accuracies, presents the collected data, and explains some of the possible reasons for flow measurement errors for Parshall flumes.

A major cause for error with Parshall flumes is submergence. If submergence occurs and is not correctly accounted for, errors of up to 60 percent are possible (USBR 2007). Fortunately, Parshall (1936) developed submergence curves with his initial rating calibrations and they are available from many sources (USBR 2001). In addition to the original submergence calibration adjustments, others have provided additional information on the use of Parshall flumes under submerged conditions. Robinson (1965) simplified the correction of submerged discharge in Parshall flumes. Skogerboe et al. (1967a) provided improved submerged-flow calibration curves for 1-in to 50-ft (2.54-cm to 15.24-m) flumes. Bos (1978) concluded that submergence should never exceed 95 percent in Parshall flumes. Peck (1988) found significant discontinuity in submergence relationships previously in use and presented new submergence equations. All of these authors emphasized that the need to provide corrections if a Parshall flumes is used under submerged-flow conditions. However, none of them encouraged the use of the flume when submerged.

Another major contributor to flow measurement errors with Parshall flume flow measurement is structural settlement. Many individuals have investigated the effects of settlement on Parshall flume flow measurement (Skogerboe 1967a; Abt and Staker 1990; Kruse 1992; Genoves et al. 1993; Abt et al. 1989, 1994, 1995, 1998). The results of these studies apply flow measurement corrections to settlement of small flumes, and corrections for a combination of settlement and submergence. Settlement of ±10 percent can amount to 32 percent deviation in flow rate (Abt and Staker 1990; Genoves et al. 1993). When mixed with submergence, errors can be substantially higher (Abt et al. 1995). Corrections to settlement with and without submergence are available and must

be applied in order to achieve accurate flow measurements. Unfortunately, data are only available for small flumes (less than 3 feet throat width). To correct larger flumes, extrapolation must be used, but is not recommended, because the different standard Parshall flume sizes are not geometrically similar.

Two other problems which cause errors in Parshall flumes include incorrect entrance geometry and incorrect staff gauge location. Design specifications call for a radius wingwall, which creates a smooth transition from channel to the converging section of the flume. An alternate design is also given which allows for a 45-degree wingwall to create the transition (USBR 2001). During initial tests, Parshall (1936) noticed that without radius wingwalls a dip or depression made reading staff gauges difficult during "moderately high" flows. This observation raises the question of whether different entrance conditions change standard Parshall rating curves. With regards to the staff gauge location, specifications show the correct placement is at $2A/3$ measured upstream of the crest, where A is the length of the upstream approach section (Figure 1). Standard Parshall flume rating tables were created with the staff gauge in this location. If the gauge is placed anywhere other than $2A/3$, standard calibrations will not provide accurate flow measurements. No literature or work has been found which discusses corrections for either incorrect entrance geometry or staff gauge location. In some cases, if these problems are noticed they can easily be fixed by changing the geometry and location of measurement.

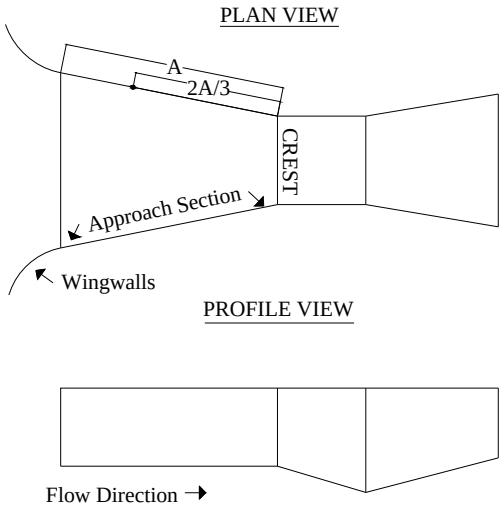


Figure 1. Overview of Parshall flume terminology.

Unfortunately historical records of measurements cannot be easily corrected if the wrong staff gauge location was used when the flows were recorded. For this reason it is advantageous to determine the effects that different entrance geometries and staff gauge locations have on the accuracies of Parshall flumes.

To determine the effects that entrance conditions and staff gauge location have on Parshall flume flow measurement accuracy, a 2-ft model was constructed and tested at the Utah Water Research Laboratory. Chapter III presents the methods and laboratory experiments that were undertaken to determine corrections for different entrance geometries and incorrect staff gauge locations. Unfortunately due to time and space constraints, laboratory experiments only allowed for the collection of data on the 2-ft Parshall flumes. In order to provide water users and regulators with the ability to correct any size Parshall flume that does not meet design specification, it is recommended (in Chapter V) that future research be conducted to extend the current correction factors to other flume sizes.

CHAPTER II

CONDITIONAL ASSESSMENT OF FLOW MEASUREMENT ACCURACY THROUGHOUT THE STATE OF UTAH[1]

ABSTRACT

A study conducted by the Utah Water Research Laboratory assessed the accuracies of flow measurement devices throughout the State of Utah. During the study, a wide variety of flow measurement devices were evaluated including flumes, weirs and rated sections in open channel systems and magnetic and ultrasonic meters in closed conduit systems. The specified design accuracies for each device are presented as found through literature review. Actual flow measurements were determined at 70 sites throughout the State of Utah. Actual flow measurements were determined by current metering or using a Fuji ultrasonic flow meter. Actual flow measurements were recorded and compared to the theoretical discharges of each device. Comparison between actual and theoretical flow indicated that only 33 percent of the measurement devices tested currently measure flow within manufacturer design specifications. The remaining 67 percent of the flow measurement devices contain measurement errors of some kind. Field data is presented and a detailed analysis of the flow measurement accuracy throughout Utah is given. In addition, possible reasons for the flow measurement errors and their corrections are also discussed.

[1]Coauthored by Bryan Heiner, Steven L. Barfuss, P.E., and Michael C. Johnson, Ph.D., P.E.

INTRODUCTION

Limited and depleted water resources have become an issue of increased concern especially in dry and arid regions of the world. As a result, public and private water distribution systems have realized the importance of accurately measuring water used in their systems. Unfortunately, even though many systems currently have measurement devices and methods in place throughout their systems, effective water management is still challenged by inaccurate flow measurements. Understanding the available methods and measurement devices and their specified accuracies is vital to ensuring that the best achievable distribution and use of water is occurring.

A study conducted through the Utah Water Research Laboratory set out to assess the accuracy of flow measurement devices through the State of Utah. The intent of this study was to provide a generalized overview to water users and regulators on how effective water is being measured throughout the state. Many different flow measurement devices were assessed during the study including rated sections, ramp, Parshall and Cutthroat flumes, weirs, magnetic and ultrasonic meters. Brief descriptions of these devices are presented below followed by a summary of their specified design measurement accuracies in Table 2.

Rated Sections consist of stage height vs. discharge charts or graphs. These site specific charts and graphs are created using the velocity-area principle (USBR 2001; ISO 2007). Velocity measurements are taken by the appropriate means and multiplied by the cross sectional area of the stream. This is done at several stages and then combined to form a rating curve for the specific site. Rated sections can be accurate to ±10 percent,

but this accuracy often decreases over time unless consistent ratings and verifications are performed (USBR 2001).

Ramp Flumes have simple shapes and are easy to install (Bos 1978). Ramp flumes are only one type of long-throated flumes that can be purchased commercially or designed for a specific site based on channel geometries and design discharges. Long-throated flumes often consist of a ramp placed into the bottom of a channel with a staff gauge or stilling well installed a specified distance upstream to measure head. When properly calibrated with accurate upstream and downstream head measurements, long-throated flumes can be accurate to ±2 percent to up to 90 percent submergence (USBR 2001).

Parshall Flumes were developed between 1915 and 1922, and have been widely used in the western United States (USBR 2001) as a simple way to measure discharge in open channels (Cone 1917; Parshall 1926; Merkley 2008). Parshall Flumes can be purchased commercially or built to design specifications given by Parshall (1926) (USBR 2001; Bos 1978). Because Parshall flumes are not geometrically similar, each specified flume size has its own calibration and corresponding rating curve. Parshall flumes can be accurate to ±3 to 5 percent up to 50 percent submergence on flumes with 3-inch throats or less; and ±3 to 5 percent up to 80 percent submergence on flumes with throats greater than 8 ft (USBR 2001).

Cutthroat Flumes are similar to Parshall flumes except they do not contain a throat section and have a flat level floor throughout the entirety of the flume (USBR 2001). The lack of a throat section and flat floor, along with the same 3:1converging and

6:1 diverging sections on all throat widths, makes construction simple (USBR 2001; Bos 1978). Cutthroat flumes can be as accurate as ±2 percent (Merkley 2008).

Weirs come in a variety of shapes and sizes including sharp crested, broad crested, v-notch, and Cipolletti. Weirs are overflow structures placed perpendicular to flow that measure head upstream of the structure's crest to calculate a theoretical flow (USBR 2001; Bos 1978). Weirs can be as accurate as +/- 2.5 percent (USBR 2001).

Electromagnetic Meters use the principle of Faraday's law of induction to calculate a flow passing through an applied magnetic field (Repas 2007). Magnetic Flux meters contain no moving parts and can be used with pipes varying in size from 0.1 to 72 inch in diameter. When properly installed and calibrated, magnetic flow meters can be accurate up to ±0.25 percent of the upper range flow boundary (Miller 1996).

Ultrasonic Meters emit sounds waves that propagate through the fluid and measure the flow by either monitoring frequency change or travel time of the emitted sound (Miller 1996). Ultrasonic meters can be used on pipes from 1 to 108 inch in diameter depending on transducers and meter type. Typical accuracies are from 1 to 5 percent of the upper flow boundary (Miller 1996).

RESEARCH APPROACH

Over a two-year period, seventy field sites with flow measurement structures were identified and assessed. Before the sites were visited, the type of measurement device, maximum and minimum flows and typical operation procedure were gathered for each device. These details enabled field crews to arrange site visits that allowed further information to be collected during the device's regular operation.

Table 2. Flow Measurement Devices and Specified Design Accuracies

Measurement Device	Type	Accuracy
Rated Sections	Open Channel	+/- 10%
Long Throated Flumes	Open Channel	+/- 2%
Parshall Flumes	Open Channel	+/- 3 to 5%
Cutthroat Flumes	Open Channel	+/- 2%
Weirs	Open Channel	+/- 2.5%
Electromagnetic Meters	Pipe	+/- 0.25%
Ultrasonic Meter	Pipe	+/- 1 to 5%

Field crews visited each site and carefully collected a variety of information to determine the state of the flow measurement device. The devices were visually inspected based on thirteen criteria listed in Table 2 that include physical integrity, approach conditions and proper installation. In addition to a visual inspection of each device, design dimensions were taken with a tape measure. A level and rod were also used to determine the elevation of critical surfaces on the open channel flow measurement devices. This data allowed the field crew to determine if design specifications were met and to what degree the device had settled.

Once the visual inspection, dimensions and elevations were recorded the field crew determined what actual flow rate was passing through the device. For open-channel measurements current metering was performed according to the International Organization for Standardization document 748. Field crews used a Pygmy meter, SonTek FlowTracker ADV, or a RDI StreamPro to determine velocity and depth measurements. The methods and instrumentation used for open channel measurements were calibrated by the authors to ±3 percent. Closed conduit measurements were determined with a Fuji portable ultrasonic meter which was calibrated by the authors on a

variety of pipe sizes. The Fuji was found to be capable of measuring flows to +/- 3 percent without calibration and ±1 percent with calibration. Simultaneous flow measurements were taken with the measurement device in question and the method chosen by the field crew. The indicated measurement device flow rate and the actual flow rate were documented and compared.

RESEARCH APPROACH

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RESULTS

Seventy measurement devices were assessed including 50 Parshall flumes, four ramp flumes, one Cutthroat flume, four weirs, one rated section, five ultrasonic meters, and five electromagnetic meters. Of the measurement devices assessed, 271 potential issues were documented. Table 3 gives 13 criteria and the number of documented findings for each. Only 29 percent of the structures were considered in acceptable condition and these coincided with structures that were recently installed or maintained.

In addition to the visual inspection, the structures were assessed based on the accuracies of their flow measurement. Figure 2 shows the measurement errors for each device tested. The solid lines in the figure represent the specified design accuracy for each device as given in Table 2. Many of the devices were evaluated at more than one flow rate, and as a result, each tested flow was plotted in Figure 2 with the same number.

Table 3. Assessment Criteria and Results

Assessment Criteria	Number of Documented Findings*
Acceptable condition	20
Bent, broken or caving in	13
Blockage	6
Bypassing flow	5
Cavitation	2
Corrosion, rust or worn concrete	25
Improper approach	26
Improper installation or parameters	5
Incorrect geometry	20
Incorrect or no H_a measurement	35
Incorrect or no H_b measurement	52
Settlement	34
Vegetation or debris in entrance	28

*Structures can exhibit more than one criteria

Twenty three of the tested devices measured flow within the design specifications given in Table 2 at all flow rates tested. The remaining 47 sites contained one or more flow rate that had flow measurement errors in excess of the design specifications. Of the devices with flow measurement errors 63 percent underestimate and 37 percent overestimate the actual flow through the devices (Figure 3). This means that 37 percent of the structures were releasing less water than their theoretical measurements calculate, preventing water users from receiving their true allotment of water.

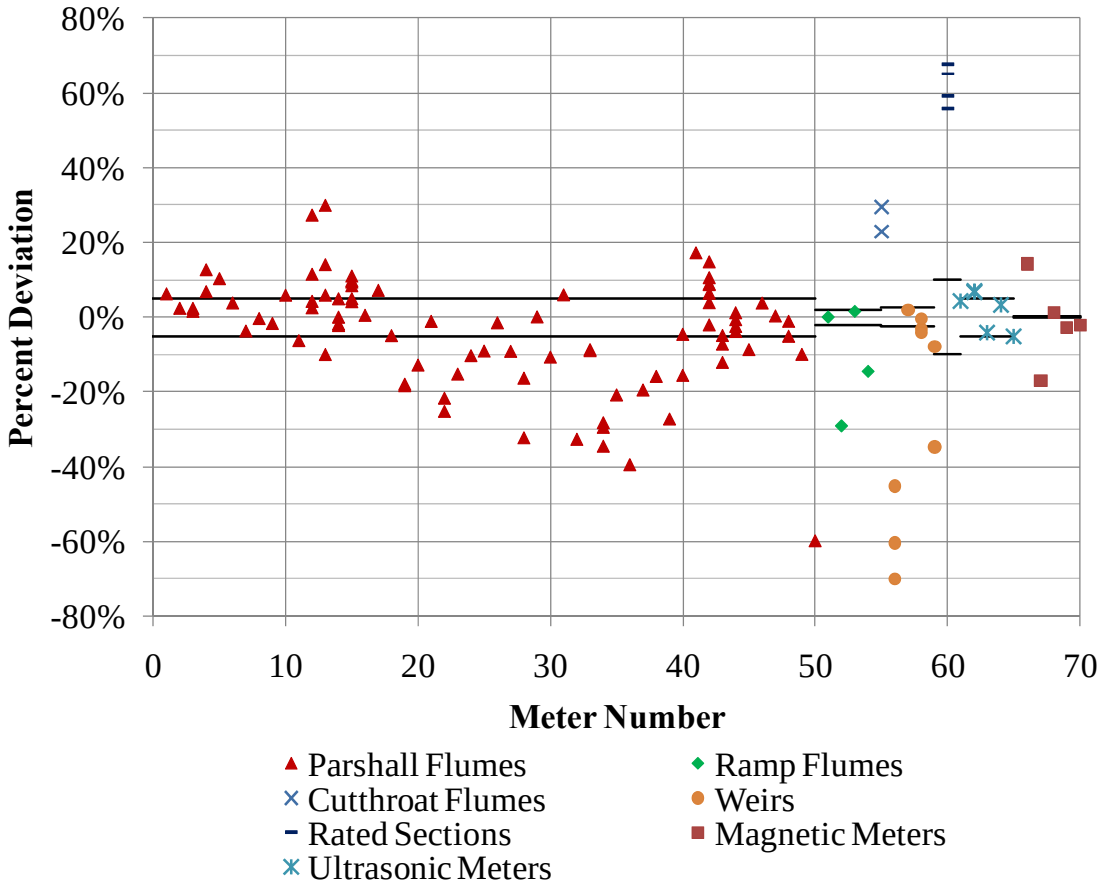


Figure 2. Flow measurement accuracies for all tested measurement devices.

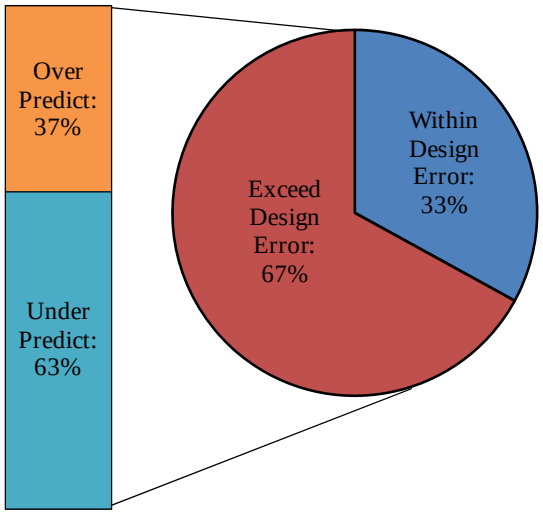


Figure 3. Errors in flow measurement for all assessed devices.

ANALYSIS

Many problems were observed during the study. Unfortunately, there is a large range of possible problems that could occur, so only a few will be discussed in detail herein. Due to the fact that the majority of the sites assessed were Parshall flumes, the remainder of the analysis will mainly focus on these measurement devices. A review of the 50 Parshall flumes tested revealed some of the major causes of flow measurement errors. Figure 4 shows that problems associated with staff gauge placement, settlement, vegetation and debris, improper approach and corrosion were present on about half the Parshall flumes investigated.

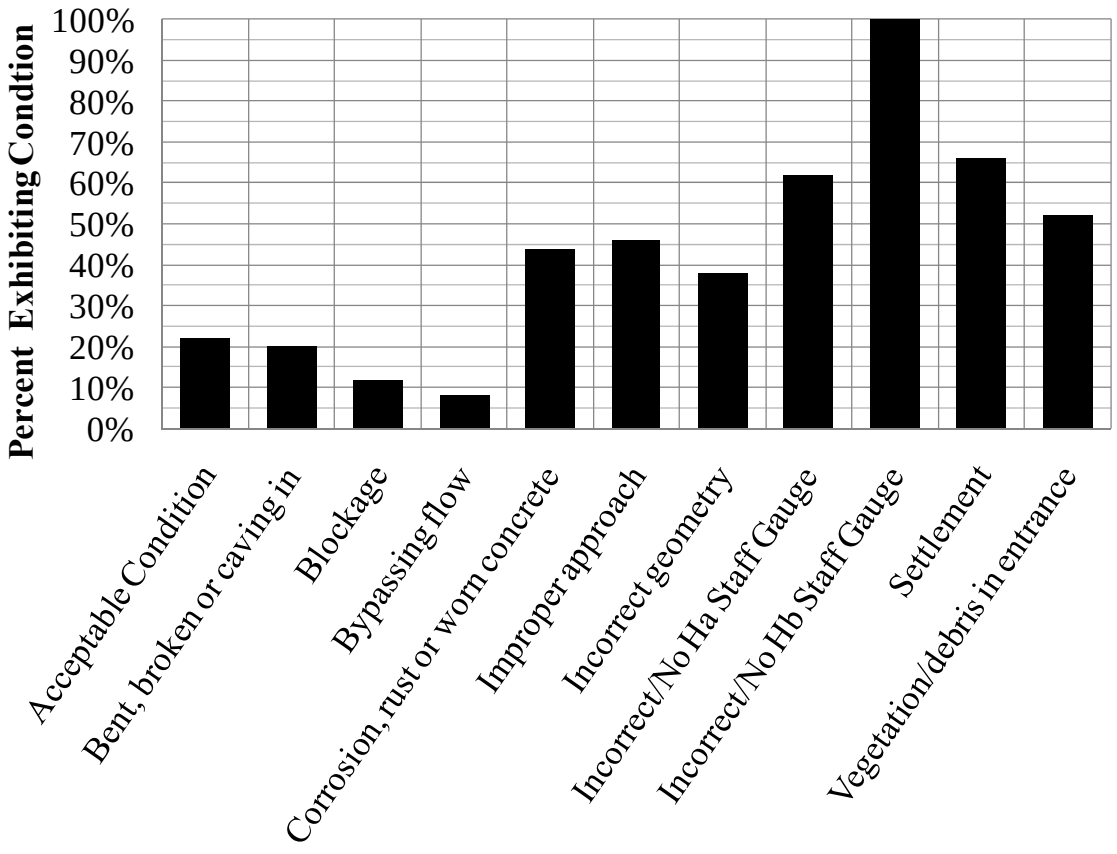


Figure 4. Parshall flume assessment criteria.

Correct Placement of the Staff Gauge is essential for all open-channel flow measurement devices that require head readings to determine the flow rate. Of the 50 assessed Parshall flumes, 62 percent were either not measuring the head in the right place or had no method to measure the head at all. Parshall (1936) created standard ratings based on head measurements taken at 2*A*/3 upstream of the crest measured adjacent to the converging wall, where *A* is the length of the approach wall. This specified distance is unique to all flumes and unless the upstream head is determined in this location the standard rating will not provide accurate flow measurements. An unpublished but under review study from the authors showed that errors of up to 60 percent can occur when staff gauges are misplaced in Parshall flumes. In addition to the upstream head being measured incorrectly, none of the 50 Parshall flumes that were assessed had the ability to measure the downstream head when submergence occurred. This is problematic because if submergence corrections are not applied, errors of up to 60 percent are possible (USBR 2007). Simply ensuring that upstream and downstream head measurements are taken at the correct location and appropriately utilizing these measurements in either the free- or submerged-flow equation will improve the accuracy of flow measurement.

Settlement has been a concern and, therefore, a focus of many researchers throughout the years (Skogerboe 1967b; Abt and Staker 1990; Kruse 1992; Genoves et al. 1993; Apt et al. 1989, 1994, 1995; 1998). Particular studies show that settlement of ±10 percent can amount to up to 32 percent deviation in flow rate in Parshall flumes (Abt and Staker 1990; Genoves et al. 1993). When mixed with submergence, errors can be substantially higher (Abt et al. 1995). When Parshall flumes settle they must be corrected by either re-calibration or being leveled to provide accurate flow measurements. An easy

way to re-level a settled flume is to elevate the floor of the flume by pouring a level concrete slab throughout the length of the flume.

Vegetation and Debris were documented in 52 percent of the Parshall flumes assessed. Although the Parshall flume was originally designed to maintain high velocities so that debris would not collect in the device (Parshall 1936), over time it has proven difficult to prevent debris and vegetation from collecting near and within the flume. As sediment is deposited and vegetation grows in the approach section of the flume, cross sectional areas change causing the standard ratings to become invalid. Often sediment is hard to see and gradually accumulates over time, and the changes in flow rate seem minimal. Large flow measurement errors are possible when sediment accumulates. To prevent sediment and vegetation from reducing flow measurement accuracies, any accumulated debris should be regularly removed from the flume.

Approach Conditions allowing uniform inflow to the measurement device is essential for accurate flow measurements. Forty six percent of the Parshall flumes assessed did not meet design approach conditions. For Parshall flumes, it is required that the appropriate wingwalls be attached to the approach and that the velocities be low upstream of the device. When these criteria are not met standing waves form in the device that prevent accurate flow measurement (Parshall 1936; Blaisdell 1994). For open-channel measurements in general it is recommended that if the control width is greater than 50 percent of the approach channel, then 10 average approach flow widths of straight unobstructed approach are required. If the control width is less than 50 percent, then 20 control widths of straight unobstructed approach are required (Bos 1978; USBR 2001).

Corrosion in the form of rust or worn concrete was highly evident with many Parshall flumes and may be a significant reason for the high number of flumes that did not measure within expected accuracies. When corrosion is present in measurement devices it changes the dimensional accuracies of the device. To ensure that the standard ratings can be used, tight dimensional tolerances are expected by Parshall (1936). When corrosion changes the geometry of the flume standard ratings will not provide accurate flow measurements. Unfortunately, corrosion is difficult to remedy, so most flumes with excessive corrosion should be replaced.

Other Issues including incorrect geometry, bent, broken or misshaped flumes and flows that bypass the flumes can contribute to large amounts of flow measurement errors. Even though a relatively small number of other devices were tested during this assessment it is important to realize that similar problems to those found and discussed in Parshall flumes are possible for all types of open channel measurement devices. Closed-conduit measurement devices, on the other hand, can be difficult to assess. Careful consideration should be given to the installation of closed conduit measurement devices, ensuring that the manufacturer's specified upstream and downstream unobstructed straight pipe diameters exist and that input parameters are correctly entered into the meter's computer.

CONCLUSIONS

The earth's limited water resources have forced managers of water distribution systems in both public and private arenas to consider the increasing importance of accurately measuring water flow rates and volumes. Even though many systems

currently have measurement devices and methods in place throughout their systems, effective management is still challenged due to inaccuracies in these measurements. A study conducted at the Utah Water Research Laboratory assessed 70 water measurement devices throughout the State of Utah in an attempt to provide water users and regulators an overview of measurement device accuracy. Visual inspections across 13 categories documented 271 issues from the 70 sites visited. In addition to the visual inspections, actual flow measurements were taken and compared to the theoretical flows provided from each device. Two thirds of all the devices that were tested indicated flow measurements that exceeded manufacturer design specifications, with 37 percent of those over estimating the discharge through the structure. It was determined that errors in flow measurement were caused by a variety of reasons, including; incorrect measurement of upstream head, settlement, vegetation and debris, improper approach and corrosion. As water users and operators understand potential issues that compromise accurate flow measurements, simple steps can be taken to remedy the problems and improve the management and distribution of our water resource.

CHAPTER III

FLOW RATE SENSITIVITY DUE TO PARSHALL FLUME STAFF GAUGE LOCATION AND ENTRANCE WINGWALL CONFIGURATION[2]

ABSTRACT

Parshall flume tests were conducted to determine the sensitivity on indicated flow rate resulting from improperly located staff gauges and differing entrance conditions to the flume. An acrylic 2-ft (61-cm) Parshall flume was constructed to specified design dimensions and installed level in an 8-ft (243.8-cm) wide testing flume at the Utah Water Research Laboratory. Multiple stilling wells and two sliding point gauges were used to determine the head measurements from stilling well ports and water surface elevations along the wall and down the center of the converging approach section of the flume for multiple flow rates. The recommended radius wingwall, a 45-degree wingwall and no wingwall were also tested with and without offsets at the entrance to the flume. The laboratory tests indicated that head measurements taken at locations other than the location specified by Parshall (2*A*/3) can produce up to 60 percent errors in the flow measurement. Additionally, the lack of wingwalls and the incorrect design and installation of wingwalls cause standing waves to form in the throat of the flume which also affects flow measurement accuracies.

[2] Coauthored by Bryan Heiner, Steven L. Barfuss, P.E., and Michael C. Johnson, Ph.D., P.E.

INTRODUCTION

The Parshall flume was named after the primary contributor to its design. Ralph L. Parshall began with work from Cone (1917), which was then extended and adapted to become what it is now. This inexpensive, but simple flume has a converging approach section and a flat floor that leads to a throat of defined width with a downward sloped floor and ending with a diverging exit section with an upward slope (Parshall 1926, 1936; Parshall and Rohwer 1921). The Parshall flume is intended to provide accurate flow measurement (+/-2 to 5 percent) in a wide variety of open channels (Parshall 1926, 1936). After its development, the Parshall flume has been widely used in irrigation projects throughout the western United States (USBR 2001). Even though the use of the Parshall flume was intended primarily to meet general field conditions where extreme measurement accuracy is not required (Parshall 1936), it has also been installed in arid water distribution systems where source water is becoming a more valuable and increased accuracy is required.

To help ensure that a Parshall flume provides accurate flow measurement, many individuals and entities have investigated and provided specific information regarding its use and operation. Some of the previous work on Parshall flumes has been chronologically summarized as follows:

Parshall (1953) discovered that when the free flow equation for 1- to 8-ft (30.48- to 243.84-cm) flumes was used to estimate the discharge in flumes of larger size (8- to 40-ft (2.44- to 12.19-m)), the discharge was overestimated. Parshall presented a new rating equation and construction guidelines for free flow operation of larger flumes.

Robinson (1965) suggested a simplified approach to the correction of submerged discharge in Parshall flumes where the percent submergence is used to look up corresponding correction factor.

Skogerboe et al. (1967a) used momentum relationships, dimensional analysis and empirical testing to describe flow in Parshall flumes and provide submerged flow calibration curves for flumes sized 1-in to 50-ft (2.54-cm to 15.24-m).

Bos (1978) conducted an extensive review of the design specifications and application of Parshall flumes recommending that each flume be constructed to exact design dimensions, carefully leveled both longitudinally and laterally and that submergence should never exceed 95 percent.

Davis and Deutsch (1980) created a three-dimensional finite difference code to simulate the flow through Parshall flumes to determine the effects that velocity profile, flume slope, and flume geometry have on standard Parshall ratings. Results of the model were compared with a 6-in (15.24-cm) Parshall flume and were reported as good. Davis and Deutsch (1980) believed that the model would be able to predict flow ratings in "non-standard" conditions given adequate computing power.

Peck (1988) experimented on a 1-ft (30.5-cm) Parshall flume and found significant discontinuity in submergence/discharge relationships previously in use. Errors of up to 12 percent from actual can occur at the same submergence and upstream head. New submergence equations were presented and the suggestion to not operate 1-ft (30.5-cm) Parshall flumes above 60 percent submergence was given.

Abt et al. (1989) installed a 3-in (7.62 cm) Parshall flume in a channel and determined that during free flow conditions flow errors of up to ±32 percent can occur at

longitudinal slopes of ±10 percent. A method to correct for longitudinal settlement in a 3-in (7.62-cm) Parshall flume was suggested.

Abt and Staker (1990) installed a 3-in (7.62-cm) Parshall flume in a recirculating channel and determined that during free flow conditions, flow errors of up to +/- 7 percent occur at lateral flume slopes of +/- 10 percent, with the errors being dependent on which side of the flume H_a measurements are taken. A method to correct for lateral settlement in a 3-in (7.62-cm) Parshall flume was suggested.

Wright and Taheri (1990, 1991) showed that a 1-ft (30.5-cm) Parshall flume, when calibrated in a laboratory environment, had flows that deviated from standard ratings up to 25 percent higher in the range of recommended flows. It was determined that the existing rating for a 1-ft (30.5-cm) Parshall flume is only valid to a minimum flow of 1.5 cfs (0.0425 m^3/s). An alternative rating equation was presented to estimate 1-ft (30.5-cm) Parshall flume flows from 0.03 cfs (0.00085 m^3/s) to 4 cfs (0.113 m^3/s).

Kruse (1992) recommended that the work by Abt and Staker (1990) be re-evaluated to correct the lateral settlement of a 3-in (7.62-cm) Parshall flume by averaging the right and left side head readings or by adjusting the head readings to reference the average crest elevation. Using the methods suggested by Kruse, 52 of 60 calculated discharges fell within +/- 3 percent of measured discharges.

Abt and Staker (1992) discovered that of four pre-manufactured 3-in (7.62-cm) Parshall flumes none had the same apron, wall height or throat dimensions. When presenting test results (Abt and Staker 1990), the exact rating equation was not presented because it deviated from the standard rating equation created by Parshall (1936).

Abt et al. (1992) validated previous work (Abt and Staker 1990; Abt et al. 1989) on the correction of settlement in 3-in (7.62-cm) Parshall flumes and proved that the correction factors can be applied to other small flumes (1-3 in. (2.54-7.62 cm)). In addition Abt et al. (1992) developed a procedure for correcting lateral and longitudinal settlement simultaneously.

Genoves et al. (1993) tested a 1-ft (30.5-cm) and 2-ft (61.0-cm) Parshall flume and extended previous work for the correction of lateral, longitudinal and combined settlement. Results showed that for +/- 5 percent longitudinal and lateral slopes, 28 percent and 10 percent errors in rating occur, respectively. Genoves presented correction factors as a function of the flume slope, the flow depth (H_a), and the throat width.

Wright et al. (1994) developed a theoretical model that takes into account the effect of fluid viscosity on the flow in the approach section of Parshall flumes. The model was compared and calibrated with flume tests on 3-in (7.62-cm), 6-in (15.24-cm) and 1-ft (30.5-cm) Parshall flumes. Wright et al. (1994) determined that the rating equations developed by Parshall (1926, 1936) over predict the discharge at flows less than 15 percent of the maximum rated flow.

Blaisdell (1994) re-analyzed the original Parshall flume data obtained in 1926 using the least-squares method. Small differences were found, but both Blaisdell and Parshall claim the accuracy of the flume to be +/- 5 percent. Tests on scaled and full size Parshall flumes were used to validate ratings of the 6-, 10- and 15-ft (182.88-, 304.8- and 457.2-cm) flumes. At high flows, depressions and surface waves were documented that adversely affected the rating equations (Blaisdell 1994). Blaisdell (1994) recommended

the use of radius wingwalls as Parshall depicts graphically in his 1950 and 1953 papers and the USBR (2001) depict in the design specifications for Parshall flumes.

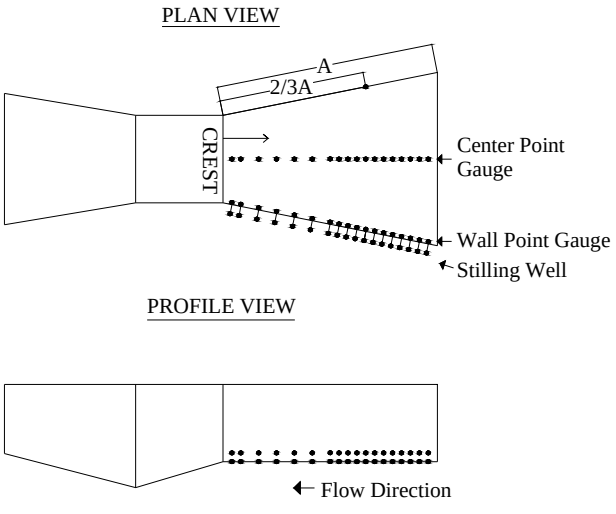
Abt et al. (1994) conducted a series of tests on a 1-ft (30.5-cm) Parshall flume to determine the effects of lateral settlement on flow ratings when submergence is present. The flume tested was found to be in error 3 percent, 5 percent, and 11 percent for lateral settlement of +/-2 percent with a submergence of 70 percent, 80 percent, and 90 percent respectively. A procedure for correcting the flow for lateral settlement and submergence was also presented.

Abt et al. (1995) performed a series of 383 experiments on Parshall flumes ranging from 1-in to 2-ft (2.54-cm to 61.0-cm) in size to determine the effects of lateral and longitudinal settlement combined with different levels of submergence. Lateral slopes were tested from -11.6 percent to +11.6 percent and longitudinal slopes ranged from -10.5 percent to +10.5 percent with submergence being tested from 70 percent to above 90 percent. It was determined that for submergence less than 90 percent, flows can be corrected to within +/-3 percent of actual and submergence greater than 90 percent can be corrected to +/- 5 percent. A detailed process was given allowing standard Parshall flumes to be corrected when settlement and submergence are present.

As is evident from the paper of Abt and Staker (1992) and the field experience of the authors, many pre-manufactured flumes do not exhibit the extreme precision and tight tolerances that Parshall (1936) and others deemed necessary to ensure reliable and accurate Parshall flume flow measurements. For example, the location that upstream water depth or head (H_a) should be recorded for accurate measurement is at $2A/3$, where A is defined as the length of the approach wall measured from the start of the throat to the

wingwall as shown in Figure 5 (Parshall 1936; Bos 1978; USBR 2001). Unfortunately, field installations often incorrectly locate the H_a measurement. Abt et al. (1997) assessed 149 Parshall flumes in use and reported that 27.5 percent had no H_a staff gauge. In addition, the authors documented from an ongoing study that included 49 Parshall flumes, that 61 percent of the Parshall flumes inspected did not measure H_a in the correct location. In the same study it was also noted that 31 percent of flumes inspected in the field did not have approach wingwalls as suggested by Parshall (1936) and Blaisdell (1994).

Because of the disparity noted in field inspections and the lack of information in the literature, this study was commissioned to investigate differences associated with improperly installed and instrumented Parshall flumes. The objective of this study was to determine the flow rate sensitivity for Parshall flume staff gauge location and entrance wingwall configuration and present the findings such that users of Parshall flumes may more accurately measure flow when flume installation is not ideal.



LOCATION OF WATER SURFACE MEASUREMENTS UPSTREAM OF CREST		
	(in)	(cm)
	2.5	6.4
	5.0	12.7
	10.0	25.4
	15.0	38.1
	20.0	50.8
	25.0	63.5
	30.0	76.2
	32.5	82.6
	35.0	88.9
	37.5	95.3
2/3A	40.0	101.6
	42.5	108.0
	45.0	114.3
	47.5	120.7
	50.0	127.0
	52.5	133.4
	55.0	139.7
	57.5	146.1

Figure 5. Overview of test setup.

TEST FACILITY AND SETUP

A 2-ft (61-cm) Parshall flume was constructed to Parshall design specifications (Parshall 1936) at the Utah Water Research Laboratory using clear acrylic sheeting. The flume was installed level in an 8-ft (243.8-cm) wide, 5.25-ft (160.02-cm) deep and 555-ft (169.16-m) long constant head test flume at the laboratory. The Parshall flume was installed 16 inches off the floor of the test flume with an approach ramp of 1:4 vertical to horizontal as recommended by Parshall. The flume was located 134-ft (40.84-m) downstream of the water supply with a series of baffle walls and floating wave suppressors to provide 75feet (22.86-m) of wave free approach. The flume was supplied with water from a pipe containing both a 6-in and 24-in (15.24- or 60.96-cm) magnetic flow meter calibrated by the authors to +/- 0.5 percent accuracy.

Head measurements were taken within the flume's approach section at 55 locations, including the design location of 2*A*/3. Eighteen 5/16-in (0.79-cm) diameter stilling well ports located 1.25 inches (3.18-cm) above the floor at 2.5- and 5-in (6.35- and 12.7-cm) spacing upstream of the flume's crest were installed on the left approach wall (looking downstream) and connected to individual 3/4-in inside diameter acrylic graduated stilling wells that could be read to 0.05 inches (0.13 cm) and estimated to 0.025 inches (0.064 cm). An additional 1 5/16-in (3.33-cm) stilling well port was located 1.25 inches above the floor at the design 2*A*/3 location (40-in, 101.6-cm) on the right side of the flume for side-to-side comparison and to ensure that port diameter would not give different results. Figure 5 illustrates the measurement locations on the laboratory test flume as black dots for the 55 locations.

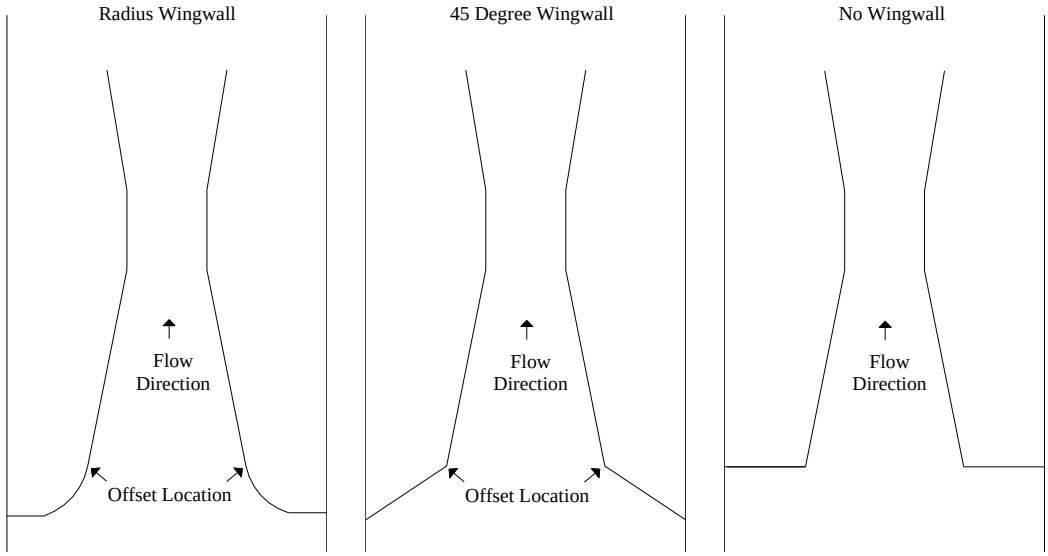


Figure 6. Wingwall configurations.

As seen in Figure 5, two point gauges, accurate to 0.001-ft (0.035-cm), were used to measure 36 water surface measurements. Each point gauge was attached to a sliding bar which allowed head measurements to be made at the left side wall and flume centerline adjacent to the stilling well locations. The water surface measurement along the side wall was made to simulate a staff gauge attached to the wall of the flume and the centerline water surface measurement was made to simulate a suspended ultrasonic depth gauge.

The recommended radius wingwall, a 45-degree wingwall and no wingwall were installed on the laboratory flume and individually tested. Each wingwall was tested at seven different flow rates from 0.42 to 33.1 cfs (0.012 to 0.94 m^3/sec) representing the full range of flows recommended by Parshall (1936), Bos (1978), and USBR (2001). During field construction it is often difficult to exactly align wingwalls with the approach to a Parshall flume, especially when steel or fiberglass flumes need to be fit into pre-

poured concrete wingwalls. As a result, the radius and 45 degree wingwalls were each installed with and without a 0.5 in (1.27 cm) offset at the start of the approach section. The 0.5 in (1.27 cm) offset is representative of typical offsets seen in field installations. Figure 6 illustrates the different wingwall configurations that were tested. Additionally, the wingwall configurations that were tested are summarized in Table 4.

RESULTS AND ANALYSIS

Baseline Tests. The acrylic flume was first calibrated using the recommended radius wingwall design as a comparison to the rating provided by Parshall for a 2-ft (61-cm) flume (baseline tests). When the indicated Parshall flume discharge was compared to actual flows at the design location, the discharge was overestimated by 6 percent at 0.42 cfs (0.012 m^3/sec), which corresponds to the minimum recommended flow rate for the flume (Parshall 1936; Bos 1978). This result was consistent with the results of Wright and Taheri (1991) and Wright et al. (1994). All other deviations during these baseline tests were within Parshall's recommended accuracy of +/- 3 percent. It is interesting to note that all of the data points determined from the baseline tests (except the minimum flow) underestimated the flow when compared with actual.

Table 4. Summary of Tests

Size of Throat (ft)	Wingwall Type	Number of Tests	Flow Range (cfs)
2	Radius	10	0.42 to 33.33
2	Radius with Offset	7	0.42 to 32.86
2	45 Degree	7	0.42 to 32.85
2	45 Degree with Offset	7	0.42 to 32.66
2	None	7	0.42 to 32.76

Upon further investigation, this is not surprising given the construction notes provided by Parshall (1936) on the construction of his initially calibrated flumes (*emphasis added)*:

> The sills and posts were 2- by 4-inch pieces, while the floor and walls were made of 1-inch boards surfaced on both sides. In the building of these structures particular care was taken to have *all dimensions exact*. When the side walls and floor became wet they swelled, and due allowance was made in having the throat width or size of flume *slightly greater* than the nominal length in order that, when the structure was completely soaked, the *swelling would bring the dimension close to the true value.* Dimensions of the structure were checked occasionally to see whether or not they remained within practical limits (p. 11).

> In the building of the framed structures it is suggested that the pieces which compose the floor and walls be laid with *sufficient space* between them to allow for swelling when wet, otherwise the swelling may be sufficient to warp the surfaces seriously and interfere with the proper functioning of the device. Ordinarily, if the cracks between the planks or boards are *1/8 to 3/16 inch wide*, the swelling will not cause distortion and yet will make a tight joint (p. 36).

If the planks were unable to swell to tightly join the 3/16-in (0.48-cm) gap the rating created by Parshall would underestimate the flow rate due to water escaping or flowing through the gaps. The objective of the baseline tests was to validate the acrylic Parshall flume in the laboratory to Parshall's rating curve for the 2-ft (61cm) flume so that tests containing varying flume wingwall configurations and stilling well locations could be compared. After verifying that the laboratory baseline deviations were within an acceptable range and were consistent with the work of previous authors, it was determined that all subsequent data would be referenced and compared to the baseline rating for this study created from the stilling well located on the left side of the flume at the 2*A*/3 (40-in, 101.6-cm) location. Comparing different staff or stilling well locations

and different wingwall configurations to the baseline case allowed the effects of each to be determined.

Stilling Well Port Diameter. Comparison between the left side 5/16-in (0.79-cm) diameter stilling well ports located 1.25 inches (3.18-cm) above the floor at 2*A*/3 location (40-in, 101.6-cm) and the right side 1 5/16-in (3.33-cm) stilling well port located 1 1/4-in (3.18-cm) above the floor at the design 2*A*/3 location (40-in, 101.6-cm) showed no deviations from each other which indicated that stilling well port size does not adversely affect the standard Parshall ratings.

Stilling Well Port Location. For the data corresponding to the stilling well measurements, linear regressions were applied to the data at each stilling well location. The regressions were used to compare the actual flow with the indicated flow and were of the form:

$$Q_i = mQ_a + b \tag{1}$$

where Q_i is the indicated discharge from the theoretical Parshall rating in cfs, Q_a is the actual discharge in cfs, m is the slope of the regression line and b is the y-intercept and is equal to zero. Linear regression slopes ranged from 0.388 to 1.034 with coefficients of determination (r^2) from 0.991 to 1.000. Because the slope of the linear regression of a stilling well located at 2*A*/3 (40-in, 101.6-cm) is 1.0, the linear regression slopes of the other locations are used as the corrections factors.

Figure 7 shows a plot of 4th and 5th order polynomials that were curve fit to the location ratio (α) and the correction factors found from Equation (1). The location ratio (α) is defined as the actual head measurement location measured from the crest divided by the design location for the head measurement (2*A*/3) as shown in Figure 5. The

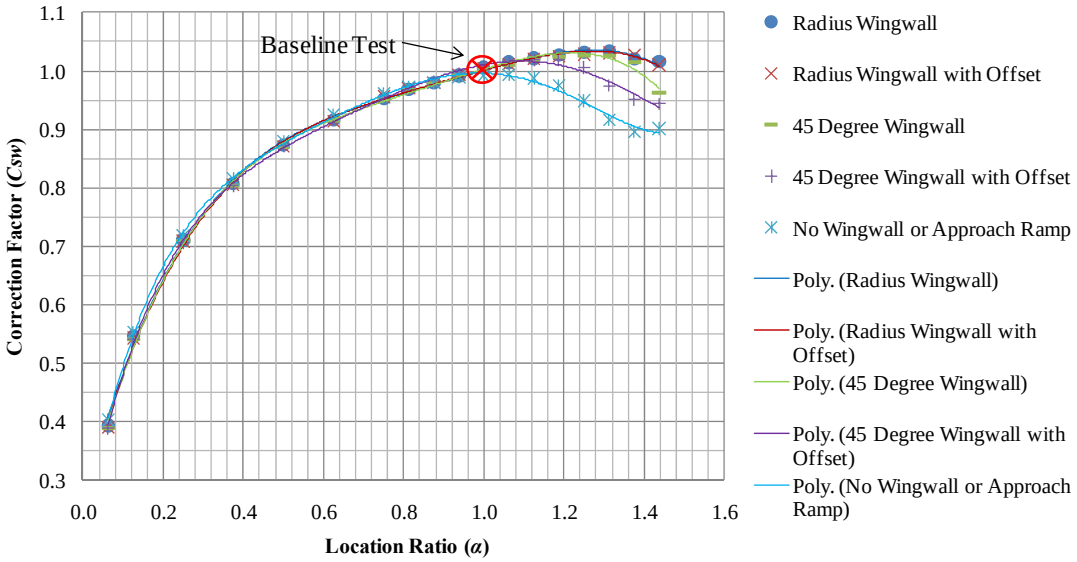


Figure 7. Correction factors for stilling well port locations.

following relationships can be used to estimate the correction factors for locations of the stilling well that deviate from that defined by Parshall. Unfortunately, significant differences in ratings were found for each wingwall configurations. Consequently, equations (2)-(6) were developed to determine the correction factor C_{sw} (different stilling well locations) in terms of α for each case.

Radius Wingwall:

$$C_{sw} = -0.841\alpha^4 + 3.000\alpha^3 - 4.027\alpha^2 + 2.609\alpha + 0.259 \quad (2)$$

Radius Wingwall with Offset:

$$C_{sw} = -0.805\alpha^4 + 2.889\alpha^3 - 3.921\alpha^2 + 2.580\alpha + 0.258 \quad (3)$$

45 Degree Wingwall:

$$C_{sw} = -1.038\alpha^4 + 3.509\alpha^3 - 4.457\alpha^2 + 2.745\alpha + 0.244 \quad (4)$$

45 Degree Wingwall with Offset:

$$C_{sw} = 1.135\alpha^5 - 5.223\alpha^4 + 8.947\alpha^3 - 7.443\alpha^2 + 3.385\alpha + 0.208 \quad (5)$$

No Wingwalls or Approach Ramp:

$$C_{sw} = 1.691\alpha^5 - 7.052\alpha^4 + 11.01\alpha^3 - 8.444\alpha^2 + 3.571\alpha + 0.212 \quad (6)$$

where C_{sw} is the correction factor for incorrect stilling well location and α is the location ratio. Equations (2) through (6) all have coefficients of determination (r^2) of 0.998.

Staff Gauge and Centerline Measurement Locations. Figure 8 and Figure 9 contain plots of the correction factors for wall staff gauge location (C_{wall}) and center line head measurement location (C_{center}) versus the location ratio for the wall staff gauge and centerline head measurements. Irregularities in the water surface profile caused by not having the proper wingwall configurations prevent realistic equations from being fit to the data as a result only plots and tables to determine correction factors are available. Thus, linear regressions are still used but only provide corrections to +/- 5 percent for location ratios of 0.5 and above.

Wingwall Configurations. As noted by Parshall (1936) and Blaisdell (1994) a standing wave followed by a trough is present at all flows, but only affects the head readings located at 2*A*/3 during larger flows. Similar standing waves and troughs were observed during testing and are shown in the actual water surface profile plots in Figure 10 and Figure 11, for two different flow rates.

General Observations. It is apparent that the flow rate through Parshall flumes is highly sensitive to the location at which the upstream head (H_a) is measured. If a stilling well is located 2.5 inches (6.35- cm) upstream of the flume's crest, the measured flow rate from the flume can be as much as 60 percent lower than the actual flow. This is caused by the water surface elevation in the stilling well being reduced due to higher local velocities as the water approaches critical depth near the crest of the flume.

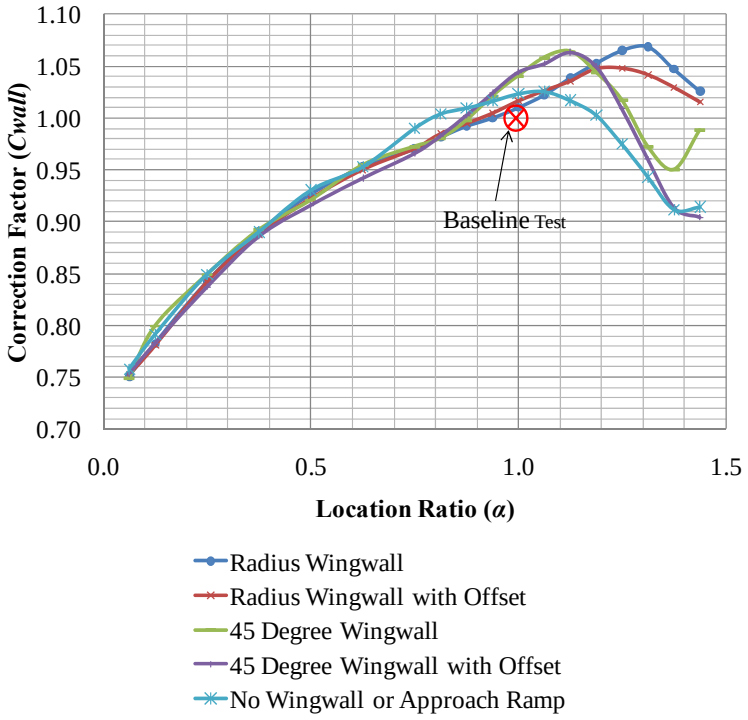


Figure 8. Correction factors for wall staff gauge locations.

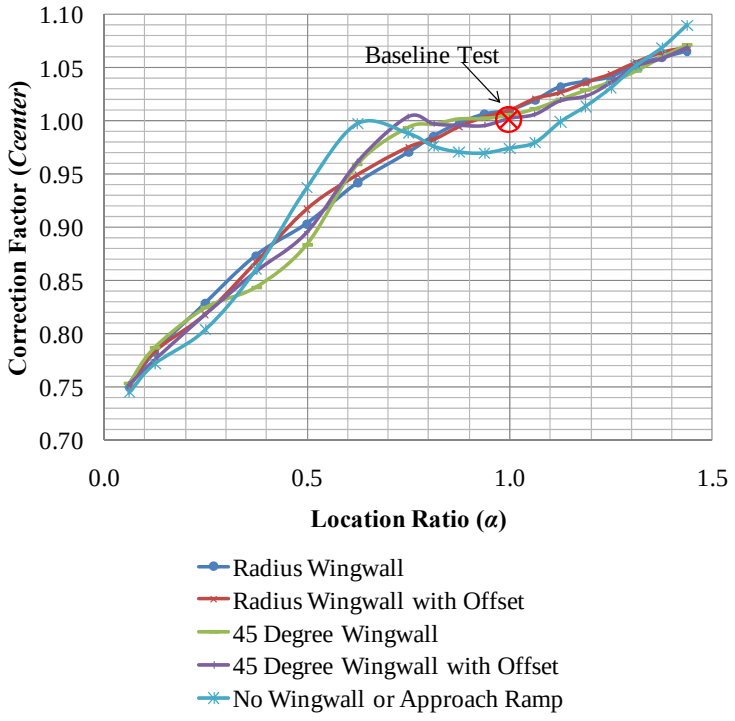


Figure 9. Correction factors for centerline head measurements.

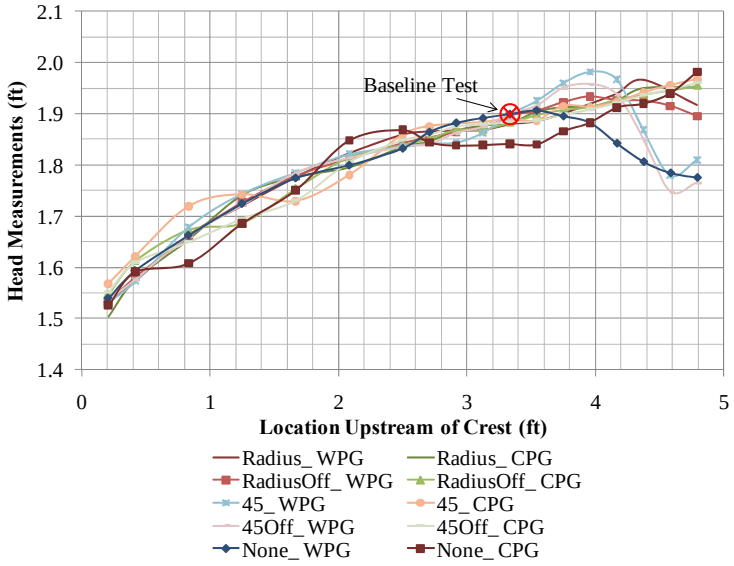


Figure 10. Water surface profiles at 22.21 cfs (0.63 m^3/sec).

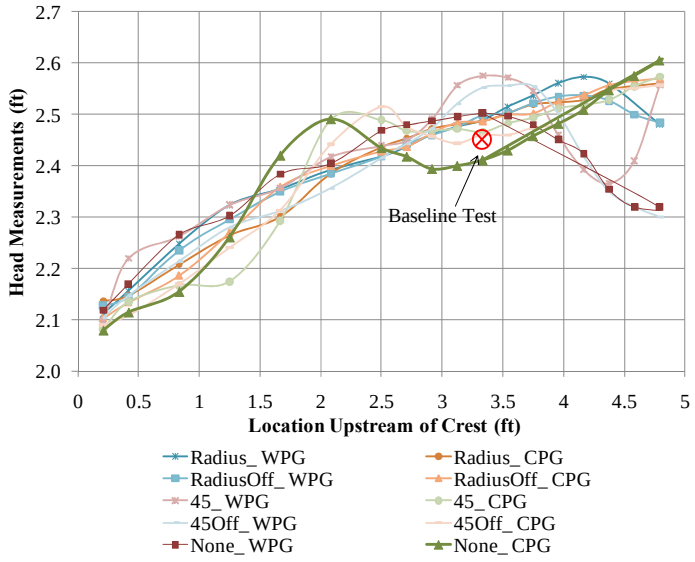


Figure 11. Water surface profiles at 33.10 cfs (0.94 m^3/sec).

As the stilling well ports approach the 2*A*/3 location, the stilling well depth more accurately depicts the water surface elevation and errors are minimal unless no wingwalls are present.

Similar results were found with the wall and center point gauges. As head measurements were taken closer to the flumes crest, larger errors occurred, with the maximum deviation being 40 percent low at the same location 2.5 inches (6.35-cm) upstream of the crest. Unfortunately another hydraulic component is added for applications where a staff gauge is attached to the sidewall of the flume, or head measurements are taken down the centerline of the flume. Even with the most favorable design (radius wingwalls), standing waves and water surface depressions commonly form along the centerline and wall of the approach section of the flume making accurate water surface elevations difficult to obtain. Standing waves and depressions that form throughout the flume's approach depend largely upon the type of wingwall that is attached and what flow rate is being measured. The recommended radius wingwall reduces the effects of the standing waves and depressions, but did not eliminate the issue at the maximum flow rate recommended by Parshall (1936). When 45-degree wingwalls or no wingwalls were present, the waves and depressions became unstable and hard to predict resulting in reduced flow measurement. As the flow rate was increased, the waves and troughs travel downstream and adversely affect the head measurement at the 2*A*/3 location for measurements taken from staff gauge or ultrasonic methods.

RECOMMENDATIONS

As the head measurements in Parshall flumes get further away from the desired design 2*A*/3 location, flow measurement errors increased. Having no wingwall or a 45 degree wingwall can increase the errors even more. Because of these potential errors, it is recommended that the standard rating equation for a 2-ft Parshall flume include a correction factor and be modified to the form

$$Q_{cor} = \frac{Q_{ind}}{C_{SW}} \tag{7}$$

where Q_{cor} is the corrected flow rate, C_{SW} is the correction factor determined by Equations (2)-(6), Figure 7, or Table 5, depending on the wingwall configuration and Q_{ind} is expressed as

$$Q_{ind} = aH_a{}^b \tag{8}$$

where Q_{ind} is the flow from the standard Parshall rating in cfs, a and b are size specific coefficients determined through Parshalls experiments (1926, 1936) and H_a is the upstream head measurement in ft. When correcting for misplaced staff gauge or ultrasonic depth meters, replace C_{sw} in (7) with C_{wall} or C_{center} respectively, where C_{wall} and C_{center} are the correction factors for different wall and center point gauge corrections and can be determined graphically from Figure 8 and Figure 9, or by interpolation from Table 5. The results of this research are valid for 2-ft Parshall flumes, and extending the data to other sizes of flumes is at the operators own risk.

APPLICATION

Consider the following example for the practical application of this paper. A 2-ft Parshall flume has no wingwalls or approach ramp and a stilling well with the port located 2 ft (76.2 cm) upstream from the crest. The flume operator records H_a = 1.5 ft (45.72 cm) and uses a standard Parshall rating table to determine a flow of 15 cfs (0.425 m^3/sec). Considering that the design port location (2A/3) for a 2-ft Parshall flume is 3.33 ft (101.5 cm) as given by Parshall, the current flume improperly measures H_a. In addition the flume does not have the specified wingwall design. In order to correct the flumes discharge several simple steps must be taken. First the location ratio (α) must be determined by dividing the port location of 2 ft (76.2 cm) by the design location of 3.33 ft (101.5 cm) resulting in an α = 0.60. Next, the correction factor C_{sw} can be determined by inserting α = 0.60 into Equation (6) resulting in C_{sw} = 0.91. Third, the correction factor can be applied as given in Equation (7) where Q_{ind} is the flow determined by the water operator of 15 cfs (0.425 m^3/sec) and the correction factor C_{sw} = 0.91, dividing Q_{ind} by C_{sw} give the corrected flow rate Q_{cor} = 16.48 cfs (0.467 m^3/sec) a difference of 9 percent.

CONCLUSIONS

The results of the research presented in this paper show that the accuracy of Parshall flumes is sensitive to the location of upstream head readings (H_a) and the configuration of entrance wingwalls. This research defined appropriate corrections so that the discharge measured with a 2-ft Parshall flume can be corrected for misplacement of staff gauge and different entrance wingwall configurations. Errors of up to 60 percent can occur if a stilling well is located just upstream of the crest. Similarly, up to 40

Table 5. Summary of Correction Factors

	Location Ratio (α)	0.063	0.125	0.250	0.375	0.500	0.625	0.750	0.813	0.875
Centerline Head Corrections	Radius Wingwall	0.750	0.782	0.829	0.873	0.903	0.942	0.970	0.986	0.997
	Radius Wingwall Offset	0.751	0.783	0.818	0.867	0.917	0.949	0.975	0.982	0.994
	45 Degree Wingwall	0.753	0.787	0.824	0.844	0.884	0.959	0.994	0.997	1.002
	45 Degree Wingwall Offset	0.753	0.776	0.819	0.859	0.896	0.962	1.004	0.998	0.996
	No Wingwall or Approach Ramp	0.745	0.772	0.804	0.861	0.937	0.997	0.988	0.976	0.971
Wall Staff Gauge Corrections	Radius Wingwall	0.751	0.783	0.842	0.890	0.927	0.953	0.970	0.982	0.992
	Radius Wingwall with Offset	0.753	0.781	0.842	0.888	0.922	0.950	0.970	0.985	0.995
	45 Degree Wingwall	0.749	0.799	0.849	0.892	0.921	0.954	0.972	0.980	0.998
	45 Degree Wingwall with Offset	0.754	0.783	0.837	0.886	0.916	0.942	0.966	0.983	1.002
	No Wingwall or Approach Ramp	0.758	0.791	0.849	0.890	0.930	0.953	0.990	1.004	1.010
Stilling Well Corrections	Radius Wingwall	0.393	0.546	0.711	0.807	0.873	0.916	0.952	0.968	0.979
	Radius Wingwall with Offset	0.390	0.543	0.708	0.805	0.870	0.913	0.956	0.971	0.980
	45 Degree Wingwall	0.388	0.540	0.709	0.804	0.869	0.914	0.952	0.969	0.980
	45 Degree Wingwall with Offset	0.389	0.541	0.706	0.804	0.871	0.917	0.956	0.971	0.983
	No Wingwall or Approach Ramp	0.402	0.553	0.718	0.815	0.880	0.926	0.960	0.972	0.980

	Location Ratio (α)	0.938	1.000	1.063	1.125	1.188	1.250	1.313	1.375	1.438
Centerline Head Corrections	Radius Wingwall	1.006	1.010	1.019	1.032	1.037	1.041	1.053	1.059	1.065
	Radius Wingwall Offset	1.003	1.010	1.021	1.026	1.036	1.044	1.055	1.064	1.069
	45 Degree Wingwall	1.002	1.006	1.011	1.020	1.029	1.037	1.047	1.060	1.072
	45 Degree Wingwall Offset	0.996	1.003	1.007	1.019	1.024	1.036	1.052	1.059	1.070
	No Wingwall or Approach Ramp	0.970	0.974	0.980	0.999	1.014	1.031	1.052	1.068	1.090
Wall Staff Gauge Corrections	Radius Wingwall	1.000	1.010	1.022	1.039	1.053	1.065	1.069	1.047	1.026
	Radius Wingwall with Offset	1.004	1.016	1.026	1.035	1.047	1.048	1.042	1.029	1.015
	45 Degree Wingwall	1.021	1.041	1.058	1.064	1.044	1.017	0.972	0.950	0.988
	45 Degree Wingwall with Offset	1.024	1.044	1.052	1.063	1.050	1.009	0.960	0.914	0.904
	No Wingwall or Approach Ramp	1.016	1.024	1.026	1.017	1.003	0.975	0.943	0.912	0.914
Stilling Well Corrections	Radius Wingwall	0.992	1.005	1.015	1.021	1.027	1.032	1.034	1.020	1.016
	Radius Wingwall with Offset	0.994	1.005	1.012	1.020	1.025	1.029	1.031	1.027	1.010
	45 Degree Wingwall	0.994	1.003	1.010	1.019	1.023	1.027	1.026	1.015	0.962
	45 Degree Wingwall with Offset	0.996	1.006	1.014	1.019	1.019	1.006	0.975	0.951	0.944
	No Wingwall or Approach Ramp	0.990	0.992	0.994	0.988	0.975	0.949	0.916	0.895	0.901

percent error can occur when a staff gauge or ultrasonic head measurement are taken at that same location. Additionally, when entrance wingwalls differ from the radius wingwall recommended by Blaisdell (1994) and the USBR (2001), standing waves followed by troughs occur throughout the converging approach section which adversely affects the standard ratings, especially at higher flow rates. A method correcting for out-of-place staff gauge location combined with different wingwall configurations is presented that applies to 2-ft Parshall flumes.

CHAPTER IV

SUMMARY AND CONCLUSIONS

In an attempt to help water users, managers and operators better understand the accuracies of different flow measurement devices at dams and other installations throughout Utah, the Utah Water Research Laboratory performed a study to assess the condition and accuracy of seventy flow measurement devices throughout the State of Utah. Each measurement device underwent a comprehensive visual inspection and had its standard calculated flow documented. The actual flow rate was determined by an appropriate method and compared to the standard measurement.

Two thirds of the tested flow measurement devices were unable to perform within their specified design accuracies. Thirty-seven percent of the incorrect measurements overestimated the flows, meaning that water users were not receiving their full appropriation of water.

Since over seventy percent of the tested flow measurement devices were Parshall flumes, a closer inspection of the major problems causing inaccuracies with these devices was investigated. Many possible causes for Parshall-flume flow measurement errors were documented, including: settlement, submergence, accumulation of debris and vegetation, and degraded physical integrity. Despite specific design requirements, many of the Parshall flumes were not measuring upstream head in the correct location, nor were they using Parshall's (1936) specified wingwall configurations. Not meeting these two design criteria renders standard Parshall flume rating equations and tables to provide erroneous flow measurements.

Nothing in the literature or published work was found which discussed corrections for either of these conditions. To provide further information on these subjects, a 2-ft Parshall flume was constructed at the Utah Water Research Laboratory. The flume underwent experiments that determined corrections for different entrance geometries and incorrect staff gauge locations. Errors of up to 60 percent can occur when head is measured incorrectly. Additionally, when entrance wingwalls differ from the recommended design, standing waves, followed by troughs, occur in the flume, reducing the accuracy of Parshall-flume flow measurements. A method to correct for out-of-place head measurement and different wingwall configurations was developed for 2-ft (throat width) Parshall flumes.

The information presented herein provides water users and operators with the knowledge enabling them to better understand what inaccuracies can occur with flow measurement devices. The correction procedure given herein allows Parshall flumes that do not met certain design criteria to provide accurate flow measurements. When water users and operators make a concentrated effort to increase the accuracies of flow measurement devices throughout the state, then accounting for the state's water will be performed more efficiently resulting in a more accurate and efficient distribution of this valuable resource.

CHAPTER V

FUTURE RESEARCH

The research presented herein provides readers a glimpse into the accuracies of flow measurement devices throughout the State of Utah. These findings can be applied to other infrastructures that use similar devices to measure flow. However, it is recommended that all water systems concerned with accurate flow measurements invest in the assessment of their own infrastructure. Doing so will allow owners of each system to identify the major causes of flow measurement errors in their systems and the most realistic method to improve their flow measurements.

It is also recommended that future research endeavors consider extending the correction factors to more Parshall flume sizes. Unfortunately, to build models for each flume size would involve extensive financial, space, and time investments, which make this endeavor difficult. As a result, preliminary data have been collected by the author, comparing physical model data with numerical model data acquired from the *Flow3D*™ software package. Data collected from both models are nearly identical when comparing centerline and staff gauge head measurements. Unfortunately *Flow3D*™ has been unable to match the head readings from different stilling well port or tap locations. If this problem can be overcome, future correction factors for other Parshall flume sizes can be created using *Flow3D* without having to purchase or construct the different sized flumes.

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