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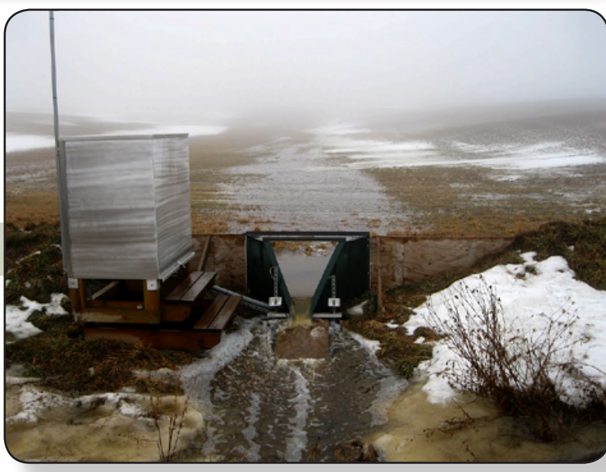
Implications of Flume Slope on Discharge Estimates from 0.762-meter H Flumes Used in Edge-of-Field Monitoring



Open-File Report 2013–1082

U.S. Department of the Interior
U.S. Geological Survey

Cover images:

Upper left: U.S. Geological Survey employee testing 0.762-meter H flume at the Colorado State University Hydraulics Laboratory, Fort Collins, Colorado.

Upper right: Edge-of-field monitoring station showing installed 0.762-meter H flume with wingwall and gaging station.

Lower left: Edge-of-field monitoring station showing use of 0.762-meter H flume to measure snowmelt runoff.

Lower right: Edge-of-field monitoring station showing use of 0.762-meter H flume to capture rainfall runoff.

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By Matthew J. Komiskey, Todd D. Stuntebeck, Amanda L. Cox, and
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U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2013

Suggested citation:
Komiskey, M.J., Stuntebeck, T.D., Cox, A.L., and Frame, D.R, 2013, Implications of flume slope on discharge estimates from 0.762-meter H flumes used in edge-of-field monitoring: U.S. Geological Survey Open-File Report 2013–1082, 11 p.

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Area	
acre	0.4047	hectare (ha)
acre	0.004047	square kilometer (km^2)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in)
millimeter (mm)	0.03937	inch (in)
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
	Volume	
cubic meter (m^3)	264.2	gallon (gal)
cubic meter (m^3)	0.0002642	million gallons (Mgal)
	Flow rate	
liter per second (L/s)	15.85	gallon per minute (gal/min)

Acknowledgments

The authors would like to thank Randy Mentz and Justin Daugherty of the University of Wisconsin–Platteville Pioneer Farm program and Eric Cooley, Aaron Wunderlin, Tim Radatz, and John Frame of the University of Wisconsin–Madison Discovery Farms program for field support in the edge-of-field studies and the staff at the Colorado State University Hydraulics Laboratory, Fort Collins, Colorado, for support during the flume-slope tests. Thanks also are extended to David Owens and Frank Younger of the U.S. Geological Survey for their technical assistance.

Implications of Flume Slope on Discharge Estimates from 0.762-meter H Flumes Used in Edge-of-Field Monitoring

By Matthew J. Komiskey,[1] Todd D. Stuntebeck,[1] Amanda L. Cox,[2] and Dennis R. Frame[3]

Abstract

The effects of longitudinal slope on the estimation of discharge in a 0.762-meter (m) (depth at flume entrance) H flume were tested under controlled conditions with slopes from −8 to +8 percent and discharges from 1.2 to 323 liters per second. Compared to the stage-discharge rating for a longitudinal flume slope of zero, computed discharges were negatively biased (maximum −31 percent) when the flume was sloped downward from the front (entrance) to the back (exit), and positively biased (maximum 44 percent) when the flume was sloped upward. Biases increased with greater flume slopes and with lower discharges. A linear empirical relation was developed to compute a corrected reference stage for a 0.762-m H flume using measured stage and flume slope. The reference stage was then used to determine a corrected discharge from the stage-discharge rating. A dimensionally homogeneous correction equation also was developed, which could theoretically be used for all standard H-flume sizes. Use of the corrected discharge computation method for a sloped H flume was determined to have errors ranging from −2.2 to 4.6 percent compared to the H-flume measured discharge at a level position. These results emphasize the importance of the measurement of and the correction for flume slope during an edge-of-field study if the most accurate discharge estimates are desired.

Introduction

Monitoring surface runoff from agricultural fields is a critical component to understanding the impacts of agriculture on the environment. Evaluating data from fields representing different on-farm practices and management styles can help to determine how each affects runoff-water quantity and quality. There is a need to document and quantify the environmental benefits realized by the various management efforts and to identify and promote the most successful, cost-effective techniques (Bishop and others, 2005).

In order to accurately quantify the impact of on-farm management strategies, a comprehensive method to measure runoff and to obtain representative water-quality samples must be established. Harmel and others (2006a) provided practical guidance for monitoring discharge and collecting water-quality data at the field and small-watershed scale and described the use of pre-calibrated control structures to estimate runoff volumes. Also noted was the inherent uncertainty introduced into measurement of water-quantity and -quality data that is often overlooked in many study designs (Harmel and others, 2006b). These uncertainties included laboratory analysis and data-collection techniques, which could potentially influence the interpretation of study results.

Use of pre-calibrated control structures to estimate runoff from fields or small watersheds has been well documented (Kilpatrick and Schneider, 1983; Thornton and others, 1998; McDowell and others, 2001; Udawatta and others, 2002). When used properly, these control structures offer advantages over open-channel (stream) methods. Unlike streams, development of a stage-discharge relation is typically not necessary. This is especially helpful at locations where manual measurement of discharge during flashy runoff events is problematic. Since the stage-discharge relation is known from the beginning of a study, discharge-based sampling methods can be employed. In a stream, channel features that control the stage-discharge relation can often change over time; this is not the case for a pre-calibrated control structure.

Pre-calibrated structures do have limitations, particularly owing to constraints in discharge ranges for which they are calibrated with respect to their physical size, drainage area, and topography of the watershed in which they are utilized. To accurately estimate discharge, these structures typically require open-flow conditions (no interference of flow within the structure) and stability with respect to the flow (the structure is level and in line with the flow) (Brakensiek and others, 1979). Each of these conditions can be compromised by environmental conditions (freeze/thaw processes, saturated soils, etc.) and by measurement errors that can introduce error into the estimation of discharge.

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H flumes offer advantages over other pre-calibrated control structures in that their design allows for relatively accurate estimation of both low and high flow. In addition, they are capable of passing runoff that contains a heavy sediment load and are capable of shedding floating debris (Hudson, 1993). The stage-discharge relation developed for H flumes assumes that they are installed level, both side to side and front to back, that water entering the flume is at subcritical velocity and nonturbulent, and that water exiting the flume is unimpeded (not operating in a submerged condition) (Grant and Dawson, 2001).

At the edge-of-field setting, the standardized stage-discharge relationship for the H flumes is used as the discharge rating, assuming the flume is level. An H flume should be level from side to side and from front to back, with the bottom of the flume at the same elevation as the inlet. Compromises to this ideal configuration owing to installation characteristics or support and substrate instability from episodic environmental conditions such as frost heave or soil saturation can compromise the standardized stage-discharge relation. In addition, due to the infrequency in the timing of flow and short duration of runoff events, check measurements of discharge to confirm or develop a new rating is difficult and calibrating each H flume is cost prohibitive.

While several tests have been done on a variety of flume types and sizes regarding the effect of slope and submergence on discharge determination, the majority of work seems to have been conducted on Parshall flumes. Abt and others (1995) reviewed literature results evaluating the effects of settlement and submergence on Parshall flumes and developed a comprehensive method to correct the discharge. Limited published work is available on correcting for submergence of an H flume (Brakensiek and others, 1979; Gwinn, 1984; Bos, 1989), and no studies were found that evaluate the effect of flume slope (*FS*) on discharge estimates.

Purpose and Scope

This report summarizes the corrections used to compute discharge from the standard stage-discharge relationship for an H flume in situations where calibration or verification of the H flume rating is not possible and the H flume level may vary.

The primary objectives of this study were to determine how the standard stage-discharge relation for a 0.762-m (depth at flume entrance) H flume is affected by longitudinal slope and to develop a simplified correction method. A secondary objective was to determine the implications of using post-corrected discharge data on annual discharge estimates using real datasets.

Methods

Many of the techniques described in this report were developed by the U.S. Geological Survey (USGS) for use in cooperative projects with the Discovery Farms and Pioneer Farm programs (*http://www.uwdiscoveryfarms.org/, http://www.uwplatt.edu/pioneerfarm/*, accessed April 9, 2012). These programs are tasked with monitoring agricultural runoff from a variety of geographic locations and farm-management styles. This report highlights specific data and situations that occurred at Pioneer Farm, but is representative of typical conditions that were encountered for both programs.

Pioneer Farm is a mixed-livestock farm owned by the University of Wisconsin–Platteville, located in northwest Lafayette County, Wisconsin. The 30-year annual average precipitation for Pioneer Farm is 916.9 millimeters (mm), and the farm receives 1,041.4 mm of snow/sleet/ice per year, on average (Midwestern Regional Climate Center, 2011). Soils on the farm are classified as Tama silt loam (U.S. Department of Agriculture, 2009), a fine, silty-clay loam with moderately high permeability. Soil- and water-conservation practices on the monitored fields include conservation tillage, grassed waterways, conservation-crop rotation, strip-cropping, and terraces. Twelve edge-of-field monitoring stations were installed at Pioneer Farm at various times, beginning in March 2002, to measure surface-runoff volumes and to collect samples of runoff from grassed waterways that drain small agricultural basins ranging in size from 2.6 to 74.7 acres, with slopes ranging from 2 to 7 percent. H flumes were used to monitor flow from these edge-of-field locations. Surface runoff is monitored year-round in all weather conditions. Station locations were chosen to be representative of typical runoff amounts and quality of sediment and nutrients from a farm in a corn-alfalfa rotation with conservation tillage in southwest Wisconsin. The measured discharges from six of the sites are used as examples in this report.

The procedure for the installation and maintenance of H flumes on the Pioneer Farm is described by Stuntebeck and others (2008). The installation was designed to have low impact on agricultural activities by minimizing soil disturbance and limiting the equipment needed for construction. In any of the installation techniques described, there have been situations where the H flume level was compromised from environmental conditions, primarily frost heave and ice formations under the flume supports. Currently, level bubbles have been installed on the H flumes to track flume levels during site visits and flume level is measured when changes in the bubble level are recorded.

Factors Influencing the Discharge Accuracy of H Flumes

The accuracy of discharge estimated from H flumes is dependent upon a number of factors, not the least of which is proper construction. The dimensions of the flume must adhere to standardized dimensions, and the construction material must be strong and rigid enough to prevent deformation during periods of high flow.

Proper installation of the H flume also is crucial for accurate discharge estimation. Care must be taken to ensure that the flume is level from front to back and from side to side. In the edge-of-field setting, however, this requirement can be challenging to maintain. Changing environmental conditions and site characteristics can affect the level of the flume; thus, affecting the accuracy of discharge estimates. *FS* can be compromised for a variety of reasons including frost heave during frozen-ground periods, sinking or failure of the flume supports, and flexing of the wing wall.

Proper entrance and exit conditions are another important aspect of accurate discharge estimation. Water should enter the flume at subcritical velocity and under nonturbulent flow conditions, while water exiting the flume should be unimpeded (unsubmerged) (Grant and Dawson, 2001). Submergence issues can be especially problematic in landscapes with low slope, as vegetation or ice downstream from the flume can impede flow and cause backwater.

Differences between the recorded stage and the actual stage also affect discharge accuracy. A continuous record of discharge often is desired, and various types of stage-measurement sensors are available; however, instrument error, calibration error, and ice or snow in the flume can cause the continuous stage readings to be inaccurate. If the stage readings are inaccurate, the resultant discharge will be inaccurate as well.

Finally, the location of stage measurement can affect discharge accuracy. There is a drawdown curve in flumes (a decrease in water-surface elevation as water accelerates toward the exit), which makes the stage measurement location important. For H flumes, the proper measurement location is at a distance of 1.05 times the flume depth, upstream from the tip of the flume exit (Grant and Dawson, 2001). In a 0.762-m H flume, this distance is 0.80 m.

Types of Corrections

There were two basic types of corrections applied to the stage and discharge data collected as part of the Pioneer Farm monitoring program. The first type was a datum correction applied to the stage record to compensate for measurement error. Frequent staff-gage readings were obtained during runoff events and compared to the concurrent stage reported by the continuous-measurement sensor. The staff gage readings were assumed to be the "true" depth of flow in the flume. Datum corrections were applied when the differences between the staff gage and the sensor reading exceeded 0.003 m. For example, if the stage output by the sensor was 0.031 m and the staff gage reading in the flume was 0.046 m, a datum correction of +0.015 m was applied to the sensor record. During water years[4] (WY) 2002–9, several datum corrections were applied among the sites at Pioneer Farm, ranging from −0.015 to 0.079 m. Corrections were the result of ice/sediment in the flume, sensor malfunction, and sensor drift.

The second type of correction was a rating shift, which was applied for periods when the flume rating was compromised or biased. This primarily occurred when the flume was not installed level or the slope of the flume changed during the monitoring period. Rating shifts were applied similarly to datum corrections and were either constant or variable depending upon site conditions. For example, if the flume was installed with a slight drop in elevation from the entrance to the exit, a rating shift was applied to increase the discharge per unit stage from the standard rating. Freeze/thaw processes had a tendency to change the *FS* at some sites. To track these changes, the flumes were surveyed several times a year to monitor the slope. Small bubble levels were attached to the outside of the flume to enable periodic visual checks during site visits. Rating shifts were applied when survey data indicated changes in the *FS* by more than 0.003 m. Shifts were sometimes related to high-flow periods when the weight of water pressed down the flume supports. In these cases, rating shifts were either prorated from the event start to the peak or were applied after a series of events. Freezing and thawing conditions were sometimes problematic. Flume supports occasionally sank after the ground thawed (causing the flume exit to tilt downward), while the flume sometimes was thrust upward because of ice formation beneath the flume or when frost heaved the flume supports. Measured *FS* at Pioneer Farm ranged from 7 to −5 percent (fig. 1) during WY 2002–9.

Hydraulic Setting for Initial Case Study

The USGS initially conducted an independent test on the effect of changes in longitudinal slope on discharge estimation for a 0.762-m H flume at a local lake. Portable pumps were used to supply water at rates ranging from 1.24 to 7.27 liters per second (L/s). Four different *FS*, ranging from 1.7 to −0.7 percent, were evaluated (table 1). Negative slopes indicated that the flume exit was below the entrance.

[4]Water year is the 12-month period October 1, for any given year through September 30, of the following year. The water year is designated by the calendar year in which it ends and which includes 9 of the 12 months. Thus, the year ending September 30, 2002 is called the "2002" water year.

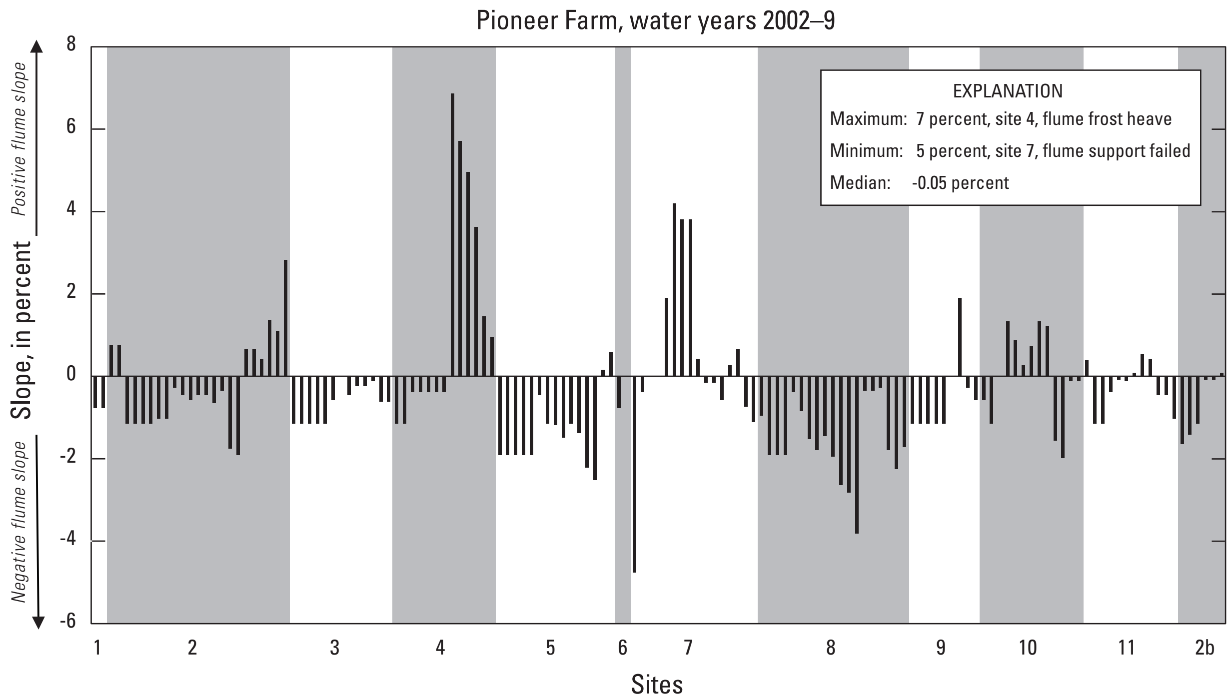

Figure 1. Measured flume slopes at University of Wisconsin–Platteville Pioneer Farm, Platteville, Wisconsin, water years 2002–9.

Table 1. Case study test results for initial flume-slope correction.

Measured discharge (Q_m), in liters per second	Flume stage (H_a), in meters	Apparent discharge (Q_a), in liters per second	Flume slope (*FS*), in percent	Corrected reference stage (H_r), in meters	Final discharge (Q_f), in liters per second
1.97	0.043	1.50	0.7	0.048	1.87
1.97	.059	2.68	1.7	.047	1.75
1.97	.035	1.07	−1.5	.047	1.79
3.90	.065	3.11	−.6	.069	3.55
7.27	.093	6.10	−.6	.098	6.72
1.24	.030	.80	−.6	.034	1.04

The flume and an approach area were installed on an elevated dock. *FS* was adjustable and runoff water was captured from the flume exit in a calibrated container. Free-flow conditions prevailed for all test measurements. *FS* was calculated using survey data of multiple fixed points within the flume. Once the desired *FS* was determined, the portable pumps were activated to achieve a constant discharge. The factory installed staff gage was used to determine stage (read to the nearest 0.3 mm), and discharge was evaluated by determining the time it took to fill the calibrated container as water exited the flume. Several evaluations of stage and discharge were done at each of the four slopes, with one value reported for each of the six trials.

Hydraulic Setting for Refined Correction Case Study

A more robust evaluation of the impacts of *FS* on the standardized H-flume stage-discharge rating was conducted at the Colorado State University (CSU) Hydraulics Laboratory. In this setting, a larger range of discharges could be tested. A 0.762-m H flume was installed in a 2.44 m wide, 60.96 m long, and 1.22 m deep recirculating flume. Water was supplied by a 125-horsepower pump, and discharge was measured in the supply line using an orifice plate accurate to ±2.5 percent. The maximum discharge capacity of the recirculating flume was 1,557.4 L/s, and the bed slope could be adjusted from horizontal to approximately 2 percent. For this study, the slope of the recirculating flume was positioned at 0.53 percent.

The flume was installed level in the lateral direction within the recirculating flume using transition wing walls that were fit and sealed to the flume entrance. An adjustable bracket was placed at the exit section of the flume to allow adjustment of the longitudinal slope (fig. 2). Seven discrete *FS*, ranging from −8 to +8 percent, were tested at four discharges corresponding to approximately 20, 40, 60, and 80 percent of the maximum flume depth (at 23, 68, 166, and 323 L/s, respectively) using the standard rating. Free-flow conditions prevailed for all test measurements. Seven evaluations of stage and slope were done at each of 4 discharges, for a total 28 trials.

Discharges measured by the orifice plate in the recirculating flume (Q_m) were adjusted to reach each target discharge. Staff-gage readings (H_a) recorded to the nearest 0.3 mm were used to determine the apparent discharge (Q_a), based on the standard 0.762-m H-flume rating equation. *FS* was calculated using survey data of multiple fixed points within the flume and on the exterior flume structure. Survey data were recorded to the nearest 0.3 mm using an auto level. Fixed locations on the H-flume exterior framework were used as survey reference points to compute *FS* during higher discharges when water velocity in the flume made it difficult to accurately position the survey rod. *FS* was negative when the flume exit was lower than the flume entrance.

The test procedures were consistent for each set of discharge/slope evaluations. Flow in the recirculating flume was increased until the target discharge was reached and the flume was then surveyed and adjusted to the desired slope (table 2). The stage was allowed to stabilize (verified with continuous readings from a non-submersible pressure transducer) prior to recording H_a. Once all slopes were evaluated for a given discharge, the flow was increased to the next desired discharge and the process was repeated.

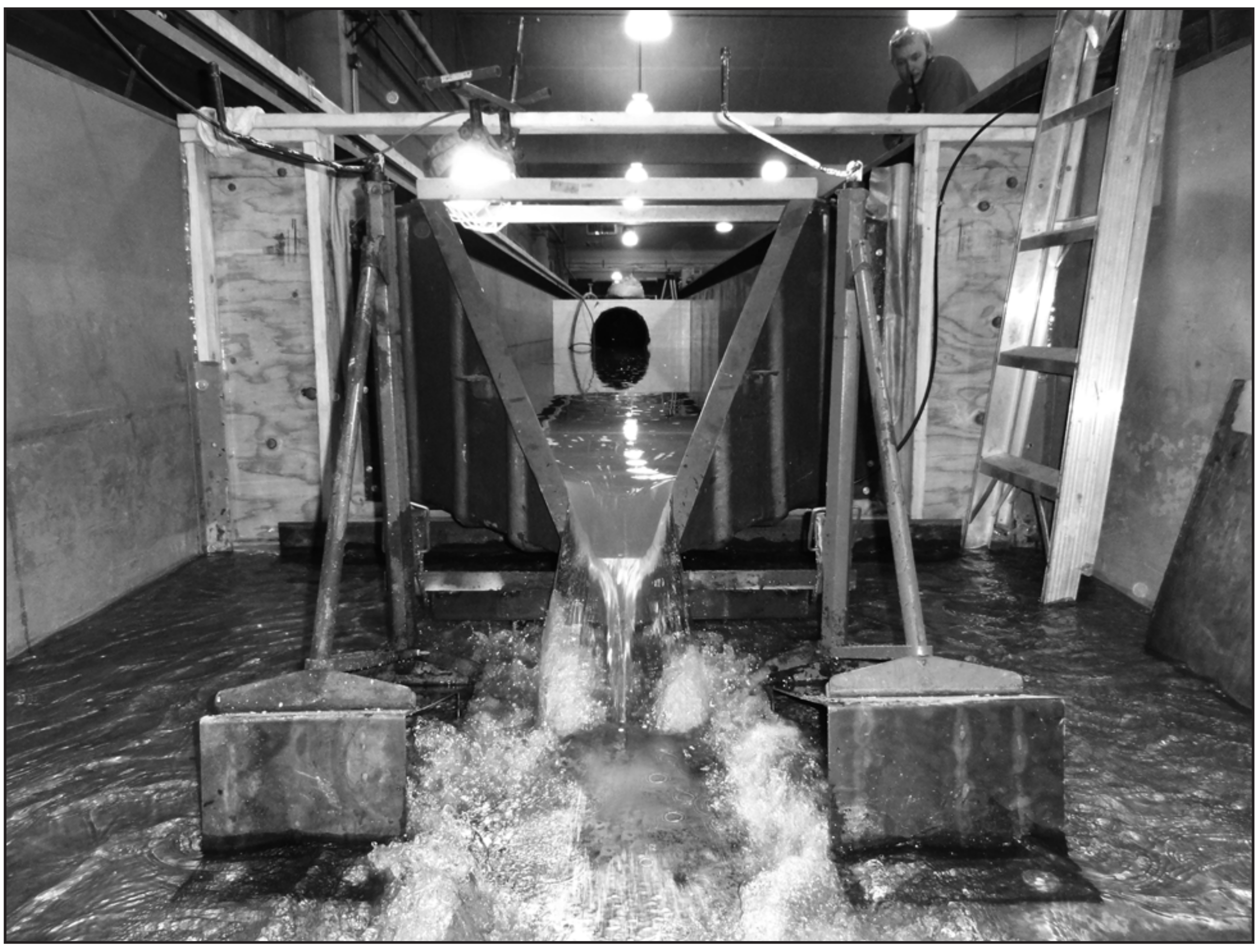

Figure 2. H-flume test installation at Colorado State University Hydraulics Laboratory, Fort Collins, Colorado.

Table 2. Case study test results for refined flume-slope correction.

[Unknown accuracy of measured discharges at 20 percent of flume depth not reported]

Flume slope (*FS*), in percent	Flume stage (H_a), in meters	Measured discharge (Q_m), in liters per second	Apparent discharge (Q_a), in liters per second	Difference between Q_a and Q_a at 0 percent flume slope position at each trial, in percent	Corrected reference stage (H_r), in meters	Final discharge (Q_f), in liters per second	Difference between Q_f and Q_f at 0 percent flume slope position at each trial, in percent
40 percent flume depth							
0	**0.313**	**68.0**	[1]**72.3 (6.4 percent)**	0.0	**0.313**	**72.3**	**0.0**
−1	.310	68.0	70.5	−2.5	.316	73.9	2.3
−2	.304	68.0	67.8	−6.2	.317	74.4	2.9
−3	.293	68.0	63.0	−12.9	.314	72.6	.5
−8	.264	68.0	49.8	−31.1	.317	74.4	2.9
4	.345	68.0	89.5	23.8	.318	74.9	3.6
8	.370	68.0	104.2	44.2	.316	73.6	1.9
60 percent flume depth							
0	**0.470**	**165.9**	[1]**178.1 (7.3 percent)**	0.0	**0.470**	**178.1**	**0.0**
−1	.461	165.9	170.2	−4.5	.467	175.8	−1.3
−2	.454	165.9	165.1	−7.3	.468	176.3	−1.0
−3	.445	165.9	157.7	−11.5	.465	174.2	−2.2
−8	.416	165.9	135.5	−23.9	.470	177.8	−.2
4	.495	165.9	200.2	12.4	.468	176.3	−1.0
7	.518	165.9	222.9	25.1	.471	179.5	.8
80 percent flume depth							
0	**0.625**	**322.8**	[1]**345.5 (7.5 percent)**	0.0	**0.625**	**345.5**	**0.0**
−1	.619	322.8	337.3	−2.4	.626	346.3	.2
−2	.613	322.8	329.6	−4.6	.627	347.2	.5
−3	.608	322.8	301.0	−12.9	.628	348.3	.8
−8	.584	322.8	293.6	−15.0	.638	361.3	4.6
4	.647	322.8	374.6	8.4	.620	338.4	−2.0
7	.667	322.8	401.8	16.3	.620	338.4	−2.0

[1]Percent difference between flume discharge (Q_m) and standard rating (apparent) discharge (Q_a).

Results and Discussion

Initial Case Study

The range in discharges tested was relatively small for a 0.762-m H flume (approximately 0.22 to 1.3 percent of maximum capacity), owing to the capacity limitations of the portable pumps. Nonetheless, a linear relation was observed between *FS* and the change in observed stage from the stage observed at a level position.

Data from this evaluation show that the differences between the apparent and actual discharge are a function of *FS* (table 1). Apparent discharges (Q_a) were negatively biased (underestimating measured discharge) when the flume was sloped downward from entrance to exit, and positively biased (overestimating measured discharge) when the flume was sloped upward.

The case study indicated that a direct rating shift applied to the measured stage, as a function of the *FS*, provided accurate discharges. *FS* was determined by

$$FS = 100\left(\frac{EP - MP_1 - \left(\frac{MP_2 - MP_1}{2}\right)}{0.80}\right) \qquad (1)$$

where

FS = the flume slope, in percent;
MP_1 = elevation of interior survey point next to the staff gage in the flume, in meters;
MP_2 = elevation of interior survey point opposite the staff gage or stage-measurement location, in meters;
EP = elevation of interior survey point at the exit of the H flume, in meters (fig. 3); and
0.80 = distance from exit of the 0.762-meter H flume to the head measurement section, in meters; use 2.625 if using a 2.5-foot H flume and measurements are in feet.

For example, if the elevation of MP_1 was 0.3050 m; the elevation of MP_2 was 0.3110 m (indicating that MP_2 is higher in elevation than MP_1); and the *EP* was 0.2990 m, the resulting *FS* would be −1.13 percent slope. Typically, the stage in the flume is referenced to a staff gage on one side of the flume wall. This equation accounts for *FS* in both the lateral and longitudinal direction if the stage-measurement sensor is adjusted to match the staff gage.

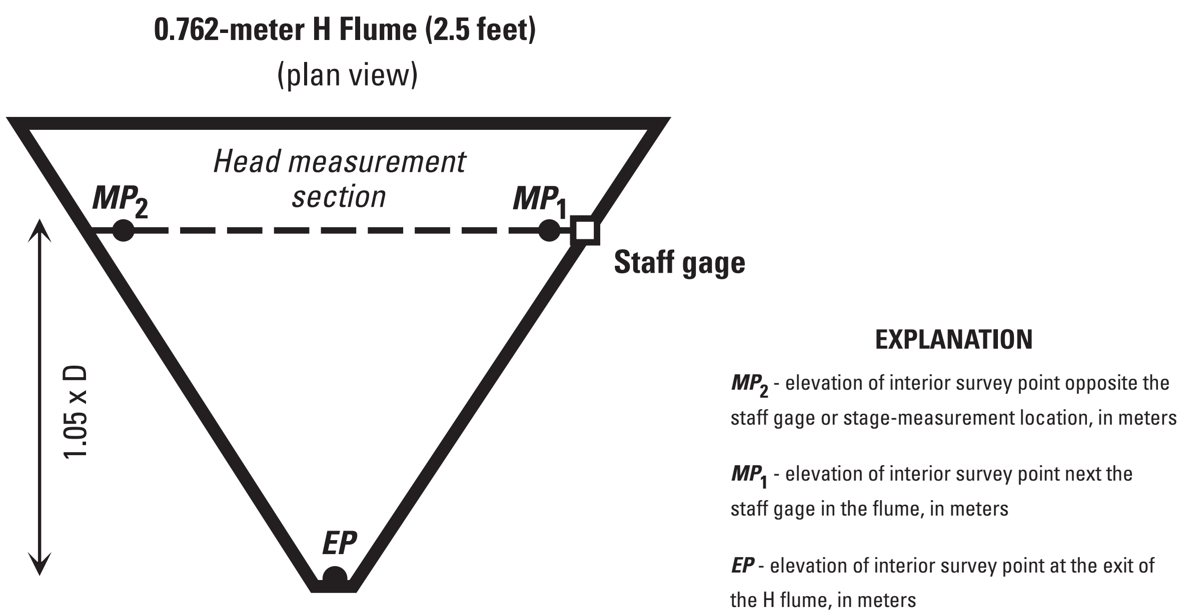

Figure 3. Plan view of 0.762-meter H flume showing measurement points for slope computation and proper head measurement location.

This observed relation between *FS* and the rating shift yielded the following initial equation:

$$H_r = H_a - 0.008\,FS \qquad (2)$$

where

H_r = corrected reference stage, in meters, the stage at which discharge is computed using the standard rating table for a 0.762-meter H flume;

H_a = measured flume stage, in meters;

FS = flume slope, in percent; and

0.008 = constant to convert flume slope to a decimal, in meters; use 0.02625 if using a 2.5-foot H flume, where H_r and H_a measurements are in feet.

Flumes with negative slopes ($MP_1 > EP$) necessitate a positive correction to the H_a measurement. For example, the corrected reference stage (H_r) for a flume with −0.009 m drop in elevation (−1.13 percent slope in a 0.762-m H flume) at a stage (H_a) of 0.0610 m would be 0.0700 m.

Use of equation 2 yielded discharge errors from 5 to 16 percent, with larger errors computed at the lower discharges. The discharge error was up to 46 percent with no correction. Computed discharge errors from small changes in discharge at the low flow can yield large percentage differences.

Refined Correction Case Study

The capacity of the CSU flume allowed for a more thorough comparison of the accuracy of the tested 0.762-m H flume to the standard rating for a range of discharges. The equivalent discharge at 20 percent depth was not used for any analyses because accuracy of the measured discharge through the CSU recirculating flume was unknown and variable at such a low rate. Differences between measured discharge (Q_m) and apparent discharge (Q_a) for a level flume (0.0 percent longitudinal slope) revealed that the flume overestimated discharge by approximately 7 percent at discharges equivalent to 40, 60, and 80 percent of flume capacity (table 2).

This finding stresses the importance of calibrating flumes prior to use if highly accurate discharge data are desired. However, limited availability of testing facilities and the costs to perform these calibrations typically result in use of the standard stage-discharge rating. Development of a new stage-discharge rating using manual discharge measurements can be difficult because runoff from fields can be short-lived and runoff rates can change rapidly. At the least, verification of the flume dimensions seems prudent.

Because the flume did not match the standard rating, *FS* test data were evaluated using the apparent discharge (Q_a) from the level flume position as the actual discharge. Results are therefore independent of the measured discharge.

Similar to the initial test, biases between the apparent and actual discharge were a function of the *FS*. In addition, these biases increased with increasing slope and with lower depth of flow in the flume (fig. 4).

Several approaches were evaluated using the stage, discharge, and slope data to determine a correction method or equation. By applying a best-fit linear regression through the data, a new equation—referred to as a refined correction—was defined as

$$H_r = H_a - 0.006716\,FS \qquad (3)$$

where

0.006716 = multiplier, in meters; use 0.022034 if using a 2.5-foot H flume, where H_r and H_a measurements are in feet.

Discharges computed using equation 3 had biases ranging from 0.2 to 4.6 percent compared to the errors up to 44.2 percent with no stage correction. Effectively, the corrected stage (H_r) corresponds to the theoretical stage value, in meters, for a given discharge and rating equation for a horizontal *FS*. For flumes that have negative slopes ($EP < MP_1$), a positive correction would be applied, which would result in a corrected stage value greater than the measured stage within the flume. Using equation 3, a flume with a slope of −1.13 percent and a measured stage of 0.0610 m, would have a corrected stage (H_r) of 0.0686 m. A discharge value of 3.47 L/s would be computed using this corrected reference stage value.

More rigorous evaluations of the data were reviewed to determine if a multi-linear regression could be used to improve upon the refined linear correction. Regression equations for stage correction (H_r) that were a function of both *FS* and measured H_a were evaluated. Including the measured H_a as a predictor for the stage correction did not produce lower average percent errors than equation 3, which uses only *FS*.

When evaluating the new slope correcting method to compensate for change in *FS* and flow depth, it was apparent that despite some variability in the measurements, the computed Q_a values were less than 4.6 percent of the horizontal H-flume measured discharges. Reported accuracies of pre-calibrated flow-control structures such as H flumes are approximately ±5–8 percent (Harmel, 2006b). Therefore, it was determined that the stage-correction method was a reasonable predictor for discharge correction and could be easily measured and applied.

When developing runoff-monitoring designs with the use of H flumes, the size of the flume in relation to the depth of water anticipated should be considered. As depicted in figure 4, it is apparent that the effect of *FS* is greater at lower depths of flow and subsequent discharge. Though not evaluated in this report, it is suspected that H flumes with larger exit openings (HL flumes, for example) would be more sensitive to discharge bias owing to *FS* and depth of flow.

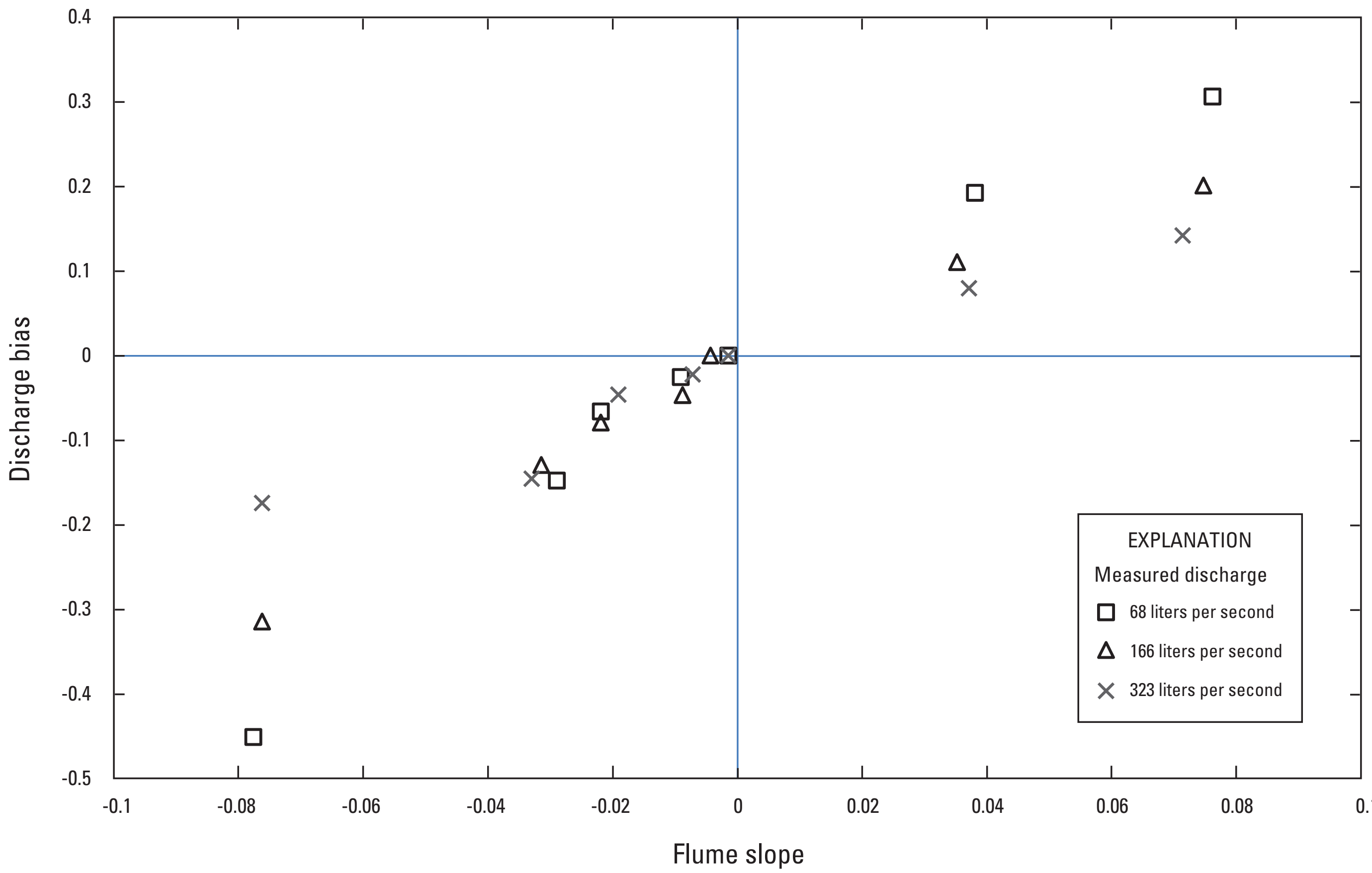

Figure 4. The relation between flume slope and the discharge bias for each tested flow and slope condition. Discharge bias is the percentage error between the apparent discharge (Q_a) and the Q_a at 0 percent flume slope.

Scaling of Corrections to Other H-Flumes Sizes

The size of the H-flume flow-control opening is a function of the convergence angle and sidewall top slope (Grant and Dawson, 2001). H flumes of varying sizes maintain the same geometric scaling ratios in all directions; therefore, a new refined slope correction equation applicable to H flumes of varying sizes was produced and tested based on the principles of Froude scaling. A form of the correction equation that used dimensionless variable groupings was obtained by dividing both sides of equation 3 by the flume depth (*D*) of 0.762 m. Equation 4 provides a dimensionally homogeneous correction equation, which theoretically could be used for all standard H-flume sizes:

$$H_r = H_a + (-0.0088136\, FS * D) \quad (4)$$

where

D = flume depth, in meters.

This equation would not necessarily be valid for variants of the H flume (HS and HL) owing to differences in geometry.

Impacts on Estimated Annual Runoff Volume

The accuracy of discharge data among different sites could be highly variable because differences between the apparent and rated discharge in H flumes were determined to be a function of the direction of *FS* (positive or negative slopes), the degree of slope, and the depth of flow. Some sites may experience more problems (*FS* shifts or inaccurate stage measurements) than others. Diligence in frequently recording these changes and correctly applying shift corrections when necessary would be important as well. The range of discharges in proportion to the flume size also can affect accuracy (small biases for small discharges equal large percentage differences). For these reasons, discharge accuracy from project to project or from site to site should not be assumed for sites using H flumes.

To estimate the impact of correcting for *FS* among sites, a comparison was made between annual runoff volumes for sites at Pioneer Farm with and without rating corrections applied. The sites included those that had large slope changes owing to frost heave or flume-support failure (sites 1 and 2) and sites that maintained a relatively consistent *FS* (sites 3, 4, and 5).

Annual runoff volumes computed without corrections ranged from 29 percent lower than to 27 percent higher than the volumes computed with the refined equation (equation 3; table 3). Percentage differences were related not only to the magnitude of observed *FS*, but to the annual runoff volume as well (small differences for small volumes equaled large percentage differences).

Though these differences may not seem excessive, it is important to recognize that any discharge bias will carry through to the water-quality load computations and may cause problems with data interpretation for certain studies. This would be especially problematic if, for example, detected statistical trends were the result of changing discharges caused by uncorrected, changing *FS* instead of actual changes caused by management activities on the landscape.

Table 3 also shows differences between runoff volumes computed using the initial slope correction method (equation 2) and the refined slope correction method (equation 3). Annual runoff volumes computed using the initial equation ranged from 4 percent lower than to 6 percent higher than the volumes computed with the refined equation. These results indicate that, in general, the initial equation provided a relatively accurate method of correcting discharge for *FS*.

Table 3. Computed annual discharge comparison for different correction methods.

Water year	Annual discharge, in cubic meters			Observed flume slopes	
	No correction	Initial correction	Refined correction	Minimum, in percent	Maximum, in percent
Site 1					
2003	3,364	3,364	3,364	0.0	0.0
2004	7,676	8,919	8,688	0	4.8
2005	14,886	14,886	14,886	0	0
2006	5,927	5,933	5,933	0	0
2007	13,579	10,262	10,683	−4.2	.2
Site 2					
2004	4,132	4,740	4,578	1.0	1.0
2005	8,418	9,943	9,681	1.0	1.0
2006	1,510	1,824	1,748	1.0	1.0
2007	4,308	4,975	4,863	.8	1.9
2008	6,563	7,500	7,354	.3	3.8
Site 3					
2004	1,691	2,024	1,967	1.1	1.1
2005	2,105	2,550	2,472	1.1	1.1
2006	30	45	43	1.1	1.1
2007	2,858	2,987	2,967	.2	.5
2008	3,280	3,320	3,312	.1	.6
Site 4					
2007	2,034	1,843	1,872	−1.3	1.1
2008	2,430	2,391	2,392	−1.3	2.0
Site 5					
2007	1,027	1,045	1,038	0.1	1.1
2008	2,037	1,917	1,934	−.5	.5

Conclusion

This report describes the corrections used to compute discharge from the standard stage-discharge relationship for a 0.762-meter (depth at flume entrance) H flume, as well as highlights study results and determination of a simplified correction method for longitudinal flume slope changes. In addition to these discharge computation corrections, the implications of using the post-corrected discharge data on the annual discharge measurements were described.

Correcting for discharge biases introduced by flume slope can improve the accuracy of water datasets used by environmental managers, policymakers, and producers. The results from this study showed that the application of an empirical equation to correct for flume slope predicted discharge from −2.2 to 4.6 percent of the H-flume measured discharge at a horizontal position. Literature estimates for H-flume discharge error are reported to be ±5–8 percent for properly leveled flumes. In addition, annual runoff volumes computed without correction ranged from 29 percent lower to 27 percent higher than volumes when corrections were applied.

During the 10 years of edge-of-field monitoring and use of H flumes for the Pioneer Farm and Discovery Farms programs, the use and corrections relating to flume slope have improved overall accuracy of discharges from H flumes. Increases in accuracy from application of corrections not only improve the ability to properly evaluate the environmental benefits of a particular management practice, but also allow for cross-sharing of information from project to project, region to region, and State to State.

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Publishing support provided by the U.S. Geological Survey
Science Publishing Network,
Columbus Publishing Service Center

For more information concerning the research in this report, contact the

Director, Wisconsin Water Science Center
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Komiskey and others—**Implications of Flume Slope on Discharge Estimates from 0.762-meter H Flumes Used in Edge-of-Field Monitoring**—Open-File Report 2013–1082