A Comparative Study of Stream-Gaging Methods Employed in Nonpoint Source Pollution Studies in Small Streams

Charles E. Mitchem, Jr.

Thesis submitted to the Faculty of the

Virginia Polytechnic Institute and State University

In partial fulfillment of the requirements for the degree of

Master of Science

in

Biological Systems Engineering

Saied Mostaghimi, Chair

David Kibler

Mary Leigh Wolfe

December 10, 1999

Blacksburg, Virginia

Keywords: Stream, Gaging, Flow, Measurement

Copyright 1999, Charles E. Mitchem, Jr.

A Comparative Study of Stream-Gaging Methods Employed in Nonpoint Source Pollution Studies in Small Streams

By

Charles E. Mitchem, Jr.

Dr. Saied Mostaghimi, Chair

Biological Systems Engineering

(ABSTRACT)

The U.S. Geological Survey started measuring stream flow in 1888 as part of a public land irrigation study. The demand for accurate stream flow measurement has increased with the rising concern about nonpoint source (NPS) pollution. NPS pollution studies, such as TMDL development, often involve quantification of flow in small first and second order streams. This application of technology intended for use in larger streams presents special problems that must be addressed by the user.

The goal of this study was to conduct a comparative analysis of the current technologies used to measure flow in small streams with respect to accuracy and cost. The analyses involved field investigations, laboratory experiments, and a cost analysis. The specific study objectives were: 1) Compare the accuracy of various methods for estimating stream discharge in small first and second order streams, 2) Compare the accuracy of various methods for estimating stream discharge in a controlled laboratory environment, and 3) Evaluate the costs associated with installation, operation, and maintenance of each of the systems investigated.

Ten stream-gaging methods were evaluated for their field performance, laboratory performance, and costs. Analysis of the field investigation data indicated that Marsh McBirney current meter

and the One-orange method were the most accurate among the methods studied. The results of the laboratory experiments imply that the Starflow acoustic Doppler and Valeport BFM001 current meter performed best among the ten methods. The Starflow acoustic Doppler device also proved to be the most cost-effective method. Overall, the Marsh McBirney and Valeport BFM001 current meters exhibited the best performance for both field and laboratory situations among the methods evaluated.

Acknowledgments

I would like to thank my advisor, Dr. Saied Mostaghimi, for his guidance, wisdom, and patience. I would also like to thank my other committee members, Dr. David Kibler and Dr. Mary Leigh Wolfe. I would like to express my appreciation to the Virginia Department of Conservation and Recreation, Division of Soil and Water Conservation for partial funding of this research. I would like to thank Eugene Powell and his staff at the Virginia Department of Environmental Quality and Harold Henderlite of the United States Geological Survey for their contributions and assistance in this study. Thanks to Jan Carr, Julie Jordan, and Philip McClellan from the Biological Systems Engineering Department for their contributions to this study. I would also like to thank Julie Petruska from Civil Engineering for contributing the glassware and fluorometer. Thanks to my fellow graduate students in the department for their help with the field study, especially Byron Petrauskas. Of course I would mostly like to thank my wife, Kim Mitchem, for her inexhaustible support and patience throughout this experience.

Table of Contents

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1
INTRODUCTION

The U.S. Geological Survey started stream flow measurement in 1888 as part of a public land irrigation study. By 1967 the stream-gaging network included about 9,000 continuous-record stations and about 7,200 partial-record stations (Carter and Davidian, 1968). Today, there are 161 gaging stations and 219 measuring sites in operation in Virginia alone (White et al., 1997). Gaging stations are installations that facilitate systematic collection of discharge data, whereas measuring sites are used to collect flow data as required outside the systematic data-collection system.

Flow in streams is of special interest because it is the only hydrologic cycle component that can be measured with any significant degree of accuracy (Carter and Davidian, 1968). With rising concern about nonpoint source (NPS) pollution, there is an increasing demand for accurate measurement of water quality (Yoder et al., 1998). In any study involving estimates of sediment, nutrient, or bacteria loadings in surface water, accurate measurement of flow in the stream of interest is critical. Flow rates, along with concentrations of various pollutants in water samples are used to determine the pollutant loadings in streams.

An example of a study where flow measurement directly impacts the estimation of pollutant load is the development of total maximum daily loads (TMDLs). In the development of TMDLs, accurate stream flow measurement is critical to estimating the contaminant loads in the impaired stream reaches. Often, these stream reaches are low-order streams with low discharges and flow velocities. These conditions present a challenge to traditional methods of stream-gaging, which are typically applied to larger streams with higher discharge rates. The flow velocities encountered in smaller streams are often below the recommended minimum velocities for most methods. Choosing a method to measure discharge in such conditions is at the discretion of the hydrologist.

In the past, artificial control structures, such as flumes and weirs, have provided researchers and hydrologists with an accurate means of measuring stream flow. However, current environmental regulations discourage the use of such structures in most streams in the interest of habitat protection for plants and animals. These regulations force the researcher to rely on natural control structure and other means of measuring stream flow velocity and depth to estimate flow.

Some degree of error is added to the estimation of actual pollutant loadings to the stream during each step of the loading estimation process. Some of the error can be attributed to other sources such as sample analysis, but stream flow measurement error must also be considered. Herschy (1985) lists the most important sources of error associated with measurement of open channel flow as:

- hydraulic conditions of flow,
- measurement of head or stage,
- number of verticals taken in a current meter measurement,
- coefficient of discharge in the weirs and flumes methods,
- stage-discharge relation in the velocity-area method, and
- operation and maintenance of the station.

Some researchers have questioned whether certain current technologies, such as ultrasonic Doppler systems, are reliably applicable to stream-gaging applications. Ackers and others (1978) noted that even though electromagnetic and ultrasonic techniques had been developed for use in small rivers and tributaries, these applications less suited to the technology than when the section is fixed and constant. Similar questions have been raised concerning other methods of stream-gaging (Kulin and Compton, 1975).

The sophistication and costs of the technologies used in gaging stations and discharge measurements have increased throughout the years. Open channel flow measurement techniques employed today range from using the simple "floating orange" to the complex ultrasonic method. While it is easy to predict which of these two methods would be more expensive, it is not always that easy to accurately determine the total cost of a monitoring system. The initial cost of equipment and installation is easily determined. However, operation cost, maintenance cost, and the cost of extracting the monitoring station is not always so evident. Quite often, there exist hidden costs that are not included in the price tag of an instrument. For example, a field evaluation of an acoustic velocity meter (AVM) system, used on penstocks in several dams on the lower Colorado river, was performed by Vermeyen in 1993. The author concluded that an experienced electronics technician was needed to properly operate and maintain the AVM system (Vermeyen, 1994). While this example involved pipe flow, it demonstrates the potential for unanticipated costs associated with flow monitoring systems.

References such as Geological Survey Water-Supply Papers 888 and 2175 (Rantz et al., 1982) could be used as a guide in choosing a specific method of stream flow measurement from a limited number of available options. These sources address the inaccuracies inherent in these methods and ways to account for them, but do not always address the overall uncertainty associated with these methods (Rantz et al, 1982). Other resources have looked rather extensively at uncertainty analysis, but have limited their analyses to the more established methods of flow measurement such as the use of control structures. In the NBS Special Publication 421, Kulin and Compton (1975) explain that “the traditional instruments and methods have been emphasized rather than newer, more sophisticated devices, because the majority of users will have only the traditional means available to work with, at least in the near future.”

To supplement these documents, some comparisons of specific methods have been performed by various researchers to evaluate current technologies and guide others regarding their potential applications. Probably the most comprehensive study is a comparison of current meters conducted by the U.S. Geological Survey in 1994 (Fulford et al, 1994). In this study, researchers conducted field and laboratory tests of various current meters including horizontal-axis meters, vertical-axis meters, and an electromagnetic meter. However, this study does not cover the broad range of technologies currently used in NPS pollution studies, including most of the mechanical current meters (horzontal and vertical axis), electromagnetic current meters, the float method, and acoustic Doppler devices. Therefore, there is a need for a current assessment of the accuracy and costs associated with stream-gaging technologies predominantly used in NPS studies.

Goal and Objectives:

The goal of this study was to conduct a comparative analysis of the current technologies used in NPS pollution stream-gaging applications with respect to their accuracy and total costs. These methods were evaluated for their applicability in low-flow conditions.

The specific study objectives were to:

1. Compare the accuracy of various methods for estimating stream discharge in small first and second order streams.
.
2. Compare the accuracy of various methods for estimating stream discharge in a controlled laboratory environment.

3. Evaluate the costs associated with installation, operation, and maintenance of each of the systems investigated.

CHAPTER 2
LITERATURE REVIEW

Introduction:

In this chapter, the methods and results of related studies are examined. The related studies evaluated current meter performance under a variety of adverse operating conditions, as well as comparisons of meters and meter components. The theory of selected methods investigated in this study is also discussed. Since this study assumes that weirs are accurate enough to be used as a reference in the analyses, the use of weirs as a statistical control is also discussed in this chapter.

Based on the literature reviewed in this study, there has not been a comparative study regarding accuracy and cost of stream-gaging methods used in nonpoint source (NPS) pollution studies. In chapter four of the United States Bureau of Reclamation Water Measurement Manual (1997), the authors list eighteen criteria one should consider when selecting a stream flow measuring method. The first two criteria listed are accuracy requirements and costs (USBR, 1997). The accuracy of most flow measurement devices is quite good in both laboratory (as good as ±1%) and field (as good as ±5%) settings when applied and maintained properly. Otherwise, they can result in a substantial reduction in measurement accuracy (±10%) (USBR, 1997). In a study of the effect of longitudinal settlement on the performance of Parshall flumes, it was noted that flume accuracy is highly dependent on its slope and that a change of ±10% in the slope of the flume resulted in a flume rating error of 32% (Abt et al., 1989).

Many attempts have been made to compare the performance of various current meters, but the newer technologies currently used in NPS pollution studies have not been included in these studies. Most of these studies were performed prior to 1960, and thus did not include the technology more recently developed for stream flow measurement (Fulford et al., 1994). As Kulin and Compton (1975) noted, the traditional, rather than newer methods and instruments for stream flow measurement, are emphasized because the majority of users only have access to the traditional means.

Thibodeaux (1992) reviewed the research that has been performed concerning accuracy of stream-gaging methods. By examining the pertinent literature, one can gain a sense of the history of stream-gaging technological development. While no formal time line could be found, some significant dates were found in the literature reviewed for this study. Table 2.1 contains a list of significant innovations in technology used for stream-gaging, along with the year or period they happened. The exact year some devices were developed is not well-defined in the literature, in which case the year the earliest known publication investigating a method is listed in Table 2.1.

Table 2.1 – Chronology of developments in stream-gaging technology.

Development	Year(s)*
Stream-gaging began	1888[3]
Vertical axis current meters	1880s[3]
Price AA current meter	1896[3]
Parshall flume first used	1920s[2]
Horizontal axis current meters developed	1931[1]
Pygmy current meter	1936[3]
Tracers used to measure stream flow	1967[2]
Electromagnetic current meter	1976[1]
Acoustic Doppler current meter	1978[1]
One-orange method	1994[4]

*Year or period each development happened.
[1]Thibodeaux, 1992 [2]Kulin and Compton, 1975 [3]Smoot and Novak, 1977
[4]Christensen, 1994

Related Studies:

As mentioned previously, no studies were found during the course of the literature review that included a comprehensive analysis of the various flow measuring techniques. In 1994, Fulford et al. performed a comparative study of fourteen current meters for the United States Geological Survey (USGS), including five mechanical vertical-axis current meters, eight mechanical horizontal-axis meters, and one electromagnetic current meter. The five vertical-axis meters studied were the Price type-AA, optic Price type-AA, Price pygmy, winter Price type-AA and winter Price-AA with polymer rotor. The eight horizontal-axis meters studied included the Ott C31 with metal, plastic, A, and R impellers, Valeport BFM001 and BFM002, and People's Republic of China LS25-3a with metal and plastic impellers. A change of impeller or cups on a given model of current meter constitutes a different current meter. The electromagnetic meter included in the study was the Marsh McBirney 2000 (Fulford et al., 1994). The current meters were tested in both the laboratory and in the field.

The laboratory testing was performed in the jet tank at the USGS Hydraulic Laboratory Facility in Mississippi and included repeatability testing and oblique flow response testing (Fulford et al., 1994). The latter provides a measure of the effect on the accuracy of the velocity measurements due to the instrument not being correctly oriented with the flow. For oblique angles of ±10°, the absolute errors of the current meters were less than 6%, except for the pygmy meter, which resulted in absolute errors of up to 8.9%. The repeatability test was performed to measure the consistency of the velocity measurements obtained by each current meter (Fulford et al., 1994). In this experiment, ten velocity measurements were made at each of five reference velocities ranging from 7.62 to 243.84 cm/s. The reference velocities were controlled using the pull-cart at the test facility. Ten data points for each velocity were used to compute the percent standard errors for each current meter. For all the meters tested, the standard error were at or below 2.0%, with the majority of the standard errors below 0.8% (Fulford et al., 1994). The highest standard errors resulted from the metal Ott, Ott A, Ott R and Valeport BFM001 used at the lowest velocity. In addition to the calculation of the percent standard error, the measured velocities (50 data points) were regressed against the five reference velocities. The RMS errors were tabulated with the slopes and intercepts of the regression, and ranged from 0.524 to 1.999 cm/s.

Fulford et al. (1994) justified the need for field testing of the current meters by stating:

> "Laboratory testing approximates and does not duplicate the field conditions in which current meters are used. In the field, meters are subjected to changing velocities and to an unknown range of flow angles. Meters in the laboratory may not be subjected to the entire range of flow angles tested in the field. Field testing is necessary to help interpret the importance of the laboratory findings."

Field testing was conducted at four sections in Mississippi (one rip-rap lined floodplain trapezoidal channel and three grass-lined floodplain sections) and five mountain stream locations in Colorado and Wyoming with sand and cobble bottoms. Not every current meter was used at each location and the combination of user and current meter varied widely (Fulford et al., 1994). Each of the three authors made discharge measurements at each site. Various other gagers used different current meters at some sites, but not at all of the sites. There was no formal rotation of current meters among the gagers involved, and some current meters were used exclusively by particular users throughout the field tests. All of the current meters were used in conjunction with the USGS top-setting rod while wading in the stream (Fulford et al., 1994).

The flows in the streams were not measured by any other means in the field tests, thus the results of the current meter discharge measurements were compared against each other (Fulford et al., 1994). The discharge mean residual ratios, area mean residual ratios, and the number of measurements associated with each current meter and stream gager were graphed. The mean residual ratios are a measure of the performance of the current meters, while the mean residual ratios of the gagers account for uncertainty introduced by human error (user bias). The authors reported that all of the current meters operated satisfactorily, even in the 110° F water of the Hot River in Wyoming. The mean discharge residual ratios for the current meters ranged from -0.008 to 0.025. The same ratios for the gagers ranged from –0.015 to 0.019.

The first phase of the study conducted by Fulford et al. (1994) was a comprehensive literature review. The purpose of the literature review was to determine the extent and types of testing that have been performed through the years by various researchers to evaluate performance characteristics of different types of current meters. The current meter types considered in the literature review included mechanical vertical-axis and horizontal-axis type, the electromagnetic, and point-type acoustic current meters. The authors reported that the performance of mechanical current meters has been studied since the 1890’s. Thibodeaux (1992) noted that the earlier studies cannot be applied directly to the current meters in use today, since the methods and procedures used to test the methods have changed. More than 100 articles and reports were reviewed in this study, but only the more noteworthy ones are included in the literature review (Thibodeaux, 1992). Thibodeaux (1992) found that the majority of the research on current meters has been performed on mechanical current meters since they have been around the longest. Vertical-axis current meters have been tested with regard to pulsation of flow; vertical oblique flow; horizontal oblique flow; proximity to boundaries; turbulence; and temperature. Many of these adverse conditions are encountered in NPS pollution studies. Horizontal-axis current meters have been tested for the same parameters as the vertical-axis type, except for vertical oblique flows. Very little work has been reported on the flow measuring characteristics of electromagnetic current meters (EMCMs) (Thibodeaux, 1992). There has been some work on the response of the EMCM to pulsation of flow, vertical oblique flow, proximity to boundaries, and turbulence. Similarly, there has been little work performed on the performance characteristics of acoustic point velocity meters. Thibodeaux (1992) lists one study that investigated the current meter response to oblique flows of various types.

Fulford (1990) investigated the effects of turbulence on the rotors of Price AA current meters in both the field and the laboratory. The field study consisted of paired measurements using both the original cups on a Price AA type current meter and a new solid polymer cup design, following the procedures outlined by Rantz et al. (1982). The water depth was measured using the wading rods the current meters were mounted on. Fulford (1990) acknowledges that the stage and area pairs were not the same for most of the paired measurements. However, the difference in the stage and area pairs was less than 4%.

The laboratory experiments were performed in a stationary flume with a tow cart. The purpose of the laboratory trials was to investigate the effects of oblique flow on current meter performance through simulation of oblique flow (Fulford, 1990). The study concluded that there was a marked difference in the performance of the two rotor cup types. Also noted was a negative influence on velocity measurements with the Price AA type current meter caused by poor current meter alignment. The poor alignment was thought to create friction within the current meter, thus causing the meter to underestimate the velocity.

Kallio (1966) investigated the effect of vertical motion on current meter performance. The purpose of the study was to evaluate the impact of the adverse conditions encountered while using current meters in a boat to perform a discharge measurement. While these conditions are not encountered when wading in a stream measuring discharge, the procedures and equipment used in the study are relevant to this research. The current meters used in the study included the Ott, Price, and vane types (Kallio, 1966). The study consisted of laboratory and field tests. The laboratory tests were performed in the rating flume, with the current meters suspended from the tow cart. While measuring velocity in a stream, the current meters were manually raised and lowered using a sounding cable or a section of pipe placed in guides. The cycle periods and amplitudes were varied and carefully controlled. The cycle periods ranged from 1 to 30 seconds (Kallio, 1966). The field tests were conducted from bridges, using a control meter for comparison of velocity measurements. The control meter was a meter of the same type as the one being tested, suspended at the same depth as the test depth but in a stationary fashion. Prior to each test from the bridge, the test meter and control meter were suspended at the same depth and the readings were compared. If there was a difference in these two measurements, the subsequent readings were adjusted by the amount of the difference (Kallio, 1966).

The author concluded that the velocity measurements using each of the meter types tested were significantly affected by vertical motion when used in streams with low flow velocities (Kallio, 1966). Low velocities in this study were defined as 0.5 to 2.4 fps. The vertical motion in the range used in this study did not have a significant effect in velocities of 2.5 fps and above.

Pierce (1941) studied the effects of shallow stream depths on current meter performance. The results are relevant to this study as the depth range in the study by Pierce (1941) was limited to 0.2 and 1.5 feet range. The primary purpose of the study was to develop correction factors to be applied to velocity measurements under such conditions. All other phases of the study, including the effects on current meter performance of flow pulsation, close proximity to side walls, and close proximity of the water surface were considered incidental to the primary purpose (Pierce, 1941). All the experiments in this study were conducted in a 12-foot flume using a sharp-crested weir as the standard for comparison. The sharp-crested weir was placed at the end of the flume during the experiments, and the current measurements were taken at the opposite end. The distance between the measurement section in the flume and the weir was about 99 feet (Pierce, 1941). Current meters studied in this investigation included the Price AA type and the then-experimental pygmy current meters.

Velocities measured in the flume ranged from 0.1 to 15 fps. Use of Price type current meters to measure velocities below 0.2 fps violates standards that have been established since that study (Rantz et al., 1982). Pierce (1941) noted the low velocity limitations of current meters:

> "Velocities as low as 0.1 foot per second can be measured with the current meter, but the precision of the measurements is generally better for velocities of 0.5 foot per second and higher than it is for extremely low velocities."

However, Pierce (1941) pointed out that such ranges of velocity are often encountered when measuring discharge in streams, particularly in low water conditions. The water depths used to define the cross section in the flume were obtained by soundings as well as with an engineer's level.

Another objective of the study was to investigate the effects of the proximity of the current meters to the flume sidewalls on current meter performance. The comparisons showed that the effects of the flume walls were equal on opposite sides of the current meter, and therefore offset each other (Pierce, 1941). No appreciable effect of overestimation or underestimation could be detected.

The study resulted in a series of coefficients to be applied to field current meter measurements under water depth and velocity conditions in the range of those in the laboratory measurements (Pierce, 1941). In addition to velocity and depth, the coefficients were based on velocity measurement method and current meter type.

Flow Measuring Techniques in Open Channels:

There are four basic techniques used to measure flow in open channels (Ackers et al., 1978):

1. Hydraulic structures,
2. Velocity-area methods,
3. Dilution techniques, and
4. Slope-hydraulic radius-area method.

Hydraulic structures is a broad classification of devices constructed to control flow to allow for a highly accurate measurement of discharge. Flumes, weirs, dam outlets, and other structures are included in this category. Weirs are of particular interest in this study as they were used as statistical control in both the field and laboratory components. Discussion of weirs and justification of the use of weirs as statistical controls are presented in the next section.

Velocity-area methods include most of the stream-gaging methods employed in stream-gaging (Kulin and Compton, 1975). Current meters, acoustic Doppler devices, floats, and other methods fall under this classification. All of these methods involve the measurement of flow velocity and area components of a measurement section in a stream. Current meters are the best example of this category, where mean velocity and depth are measured for a set of subsections that constitute a measurement section. The product of the individual subsection areas and subsection velocities constitute an incremental discharge, and the sum of the incremental discharge values is a total stream discharge. The velocity-area methods investigated in this study are further discussed in subsequent sections of this chapter. These methods include the Price AA current meter; pygmy current meter; Valeport BFM001 current meter; Marsh McBirney Flo-mate model 2000 current meter; Isco acoustic Doppler device; Starflow acoustic Doppler device; One-orange method; and the Global flow probe.

Dilution techniques, commonly referred to as dye-tracing methods, determine the discharge in a stream by measuring the dilution and dispersion of a suitable dye tracer. Dilution techniques can be based on color, conductivity, fluorescence, or radioactivity of the tracer injected into the waterway (Kulin and Compton, 1975). Implementation of such methods is rare relative to other stream-gaging methods, mainly due to the time and cost requirements associated with these methods. However, dilution techniques have their own merits and represent a potentially accurate means of discharge measurement. Rhodamine WT dye was used in this study to measure discharge in the field component of the study. Details of the theory and implementation of such a technique are included in later sections of this chapter.

Slope-hydraulic radius-area method is the most commonly employed indirect discharge estimation technique (Rantz et al., 1982). This technique involves the measurement of parameters for use with the Manning's equation:

$$Q = \frac{1.486}{n} AR^{2/3} \sqrt{S} \qquad (2.1)$$

Where:

Q = discharge, cfs;

A = cross-sectional area, $ft^{2;}$

R = hydraulic radius, ft;

S = friction slope, ft/ft; and

n = roughness coefficient.

This method was not used in this study, and no further discussion of this method is contained in this document.

Weirs as Statistical Controls:

In the field component of this study, flow measurements by various methods were statistically compared to those obtained through the use of weirs already existing in the stream. A weir is a hydraulic structure used to measure flow in open channels by supressing the flow into a nappe. The weir is one of the oldest structures used to measure discharge in open channels and has long been a standard measuring device for such applications (USBR, 1997). Discharge over a weir is determined by the relationship of the height of the water surface upstream of the weir to that of the crest of the weir. The water surface elevation should be measured upstream of the weir at a distance of at least four times the maximum head to be encountered at the gage site (Ackers et al., 1978). The main reason these control structures have been used so much in the past is that the unique relationship between stage and discharge can be predefined. In a natural stream, however, a lot of variability exists in the stage-discharge relationship. The variability is dependent on (Ackers et al., 1978):

1. Channel roughness, which may change with flow conditions and is subject to seasonal and temporal changes in the composition and shape of the stream bed;
2. Stream bed level, which can be changed by the removal and deposition of sediment;
3. Temporal change of flow, which results in a hysteresis effect depending on the rate of rise or fall of the discharge; and
4. Influence of downstream conditions, both natural and those resulting from other control structures.

The four basic categories of stream flow measurement listed at the beginning of this section involve the development of the relationship between stage and discharge in the stream. Weirs fall under the first category of hydraulic structures. The methods to be evaluated in this study fall under the second and third categories. These methods are best suited for occasionally measuring open channel flow at a particular time and place, but are not necessarily appropriate for long term monitoring of stream discharge (Ackers et al., 1978). This is primarily due to the fact that the measurements have to be repeated many times to cover the entire range of anticipated discharge rates and to calibrate the curve relating stage and discharge. Conversely, if a standard type of control structure (e.g. weir) is used and constructed according to established guidelines, no field calibration or measurements other than a continuous recording of stage are required to create a continuous discharge measurement (Ackers et al., 1978). It is because of this established standard of accuracy and the control of flow variation that weirs are commonly used as the statistical control for field investigations.

Current Meters:

Current meters are still the most widely used method of measuring velocity in a stream (Powell, 1999). The majority of current meters are of a mechanical design, where stream velocity is related to the angular velocity of the rotor (Herschy, 1985). This relationship is determined by counting the number of revolutions of the rotor (counted by the user as clicks) over a designated period of time. Mechanical current meters can be divided into two groups based on the orientation of the axis of the rotor: vertical-axis rotor meters also known as cup-type meters, and horizontal-axis rotor meters referred to as propeller-type current meters (Herschy, 1985). The cup-type current meters require little maintenance and the rotor can be changed without changing the rating of the meter. Advantages of horizontal-axis current meters include the fact that the propeller is less likely to become tangled in grass and debris. The Price-AA and pygmy current meters, both included in this study, are vertical-axis, cup-type current meters. The pygmy meter appears to be a smaller version of the Price AA meter, but the internal working mechanisms differ slightly (Smoot and Novak, 1977). Figure 2.1 (Smoot and Novak, 1977) shows a Price AA (top), pygmy (bottom, left), and vane ice current meter.

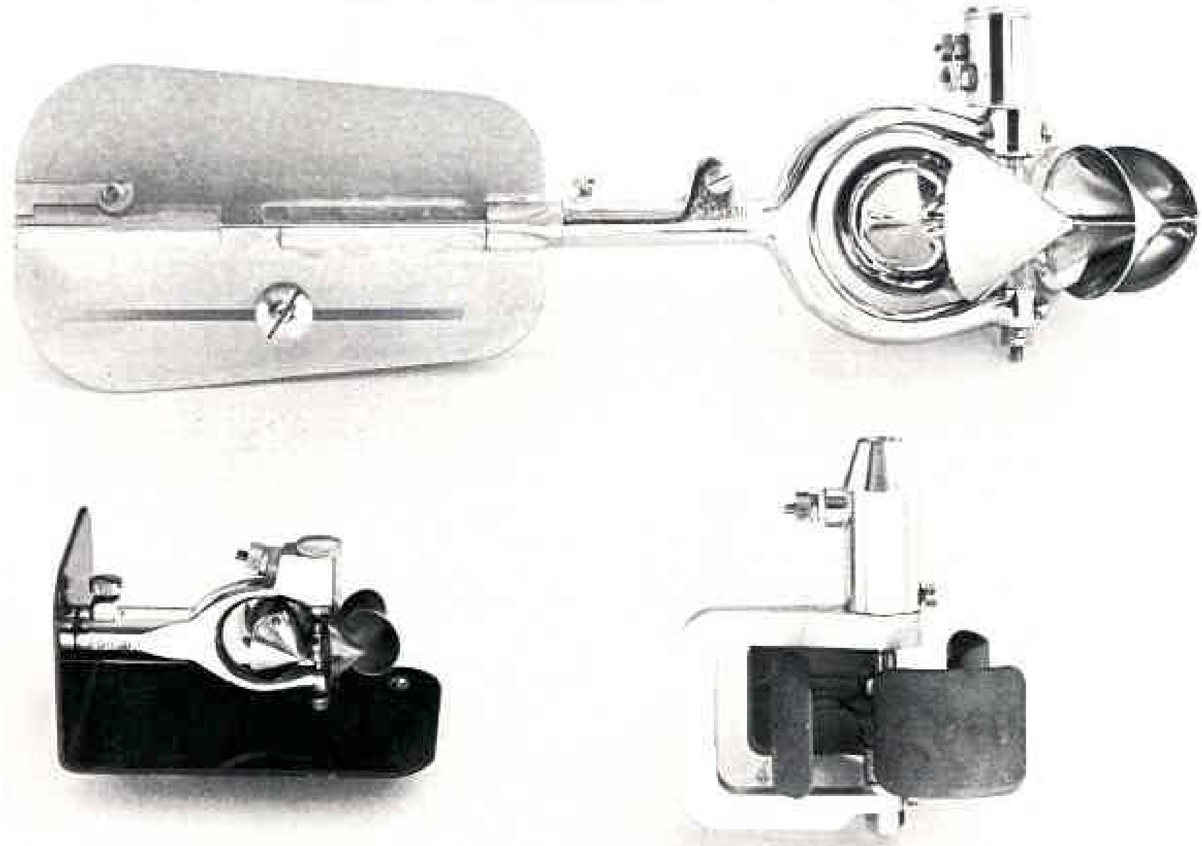


Figure 2.1 - Price AA (top), pygmy (bottom, left), and vane ice (bottom, right) current meters (Smoot and Novak, 1977).

When measuring discharge, the logical choice of procedures to follow is those used by the USGS, since they have been measuring flow in streams longer than anybody else in America. These procedures are amply described in Geological Survey Water-Supply Paper 2175 (Rantz et al., 1982) and Book 3, Chapter A8 of the Techniques of Water-Resources Investigations of the United States Geological Survey (Buchanan and Somers, 1984). These two documents describe the theory, equipment, techniques, and procedures for measuring flow with current meters for various situations. In this study, the concern is the application of these techniques to smaller streams usually associated with NPS pollution studies, such as the development of total maximum daily loads (TMDLs). Therefore, information relevant to measuring flow in such streams is included in this section. The specific techniques used to measure flow by each method are described in the next chapter.

The total flow discharge measured by a current meter is the summation of partial areas contained in a stream cross section and the corresponding average velocities (Buchanan and Somers, 1984). This relationship is represented by:

$$Q = \sum_{i=1}^{n} (av)_{\mathrm{i}} \tag{2.2}$$

Where:

Q = discharge;

n = total number of partial sections;

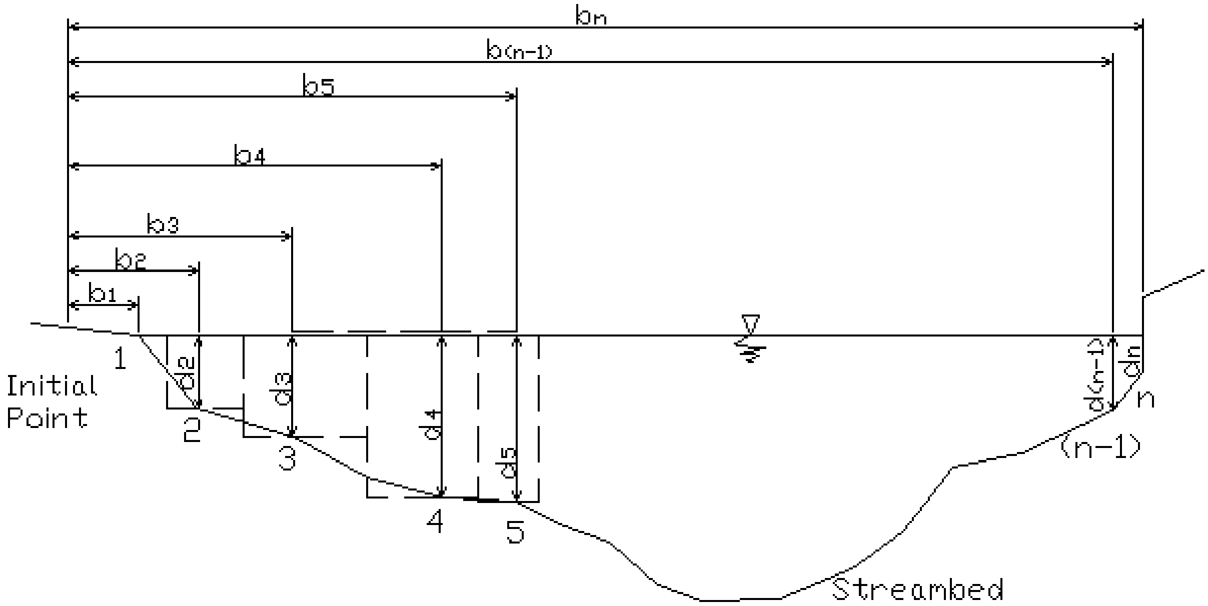
a = area in the partial section i; and

v = average velocity in the partial area i.

Two methods have been used to calculate discharge using data collected in a current meter discharge measurement. They include the mean-section method and the midpoint method

The mean-section method was used by the USGS prior to 1950 (Rantz et al., 1982). In this method of discharge computation, the verticals in the measurement section represent the two sides of a partial area. Depth and velocity are measured for a given vertical in the measurement section, then the average values corresponding to each of the verticals are used to calculate the discharge in the partial area.

In contrast, the midpoint method assumes the depth and velocity values measured at a given vertical are representative for the partial area centered on that vertical. The boundaries on either side of the partial section are defined as the midpoint between the vertical and adjacent verticals on each side. This procedure is much simpler to use when calculating discharge using the measured data, and has been concluded to be a slightly more accurate method than the mean-section method (Rantz et al., 1982). As depicted in Figure 2.2, this method defines the partial



LEGEND

1, 2, 3, …n	Observation verticals
b1, b2, b3, . . . bn	Distance from the initial point to the observation vertical, feet
d1, d2, d3, . . . dn	Depth of water at the observation vertical, feet
Dashed lines (---)	Partial section boundaries

Figure 2.2. – Midsection method definition sketch (Buchanan and Somers, 1984).

area as a rectangle, which is centered at the measurement vertical with depth equal to the measured depth at the section vertical. The width of the partial area extends to the halfway point between the section vertical and the adjacent vertical on either side.

The stream measurement section is defined by *n* observation verticals in each discharge measurement. The average flow velocity of an observation vertical is determined by measuring the velocity with a current meter. This velocity is assumed to represent the average velocity in the entire partial area (Rantz et al., 1982). The discharge in the partial area is then calculated using the equation (Buchanan and Somers, 1984):

$$q_i = v_i \left[\frac{b_{(i+1)} - b_{(i-1)}}{2} \right] d_i \tag{2.3}$$

Where:

q_i = discharge in the partial area i;

v_i = mean velocity vertical i;

b_i = distance from the initial point to the vertical i;

$b_{(i-1)}$ = distance from the initial point to vertical (i-1);

$b_{(i+1)}$ = distance from the initial point to vertical (i+1); and

d_i = depth of water at vertical i.

The procedure is similar when calculating the discharge in the partial areas at the ends of the stream section. The "preceding" or "next" vertical that does not exist is considered to be coincidental with vertical 1 or n, respectively. Equation 2.3 is then written:

$$q_1 = v_1 \left[\frac{b_2 - b_1}{2} \right] d_1 \tag{2.3a}$$

<or>

$$q_n = v_n \left[\frac{b_n - b_{(n-1)}}{2} \right] d_n \tag{2.3b}$$

From equations 2.3a and 2.3b, one can see that if the depth at the end of the section is zero, the discharge in that partial section is zero. This is not always the case. If the boundary at the edge of the stream is a vertical line, the depth at that edge is not zero and the velocity at that observation vertical may not be zero. Since the velocity at this sidewall can not be measured accurately with a current meter, it is necessary to estimate it as a percentage of the adjacent vertical. The velocity at a vertical located very near the sidewall can be related to the mean velocity in a vertical at a distance equal to the depth (Rantz et al., 1982). Table 2.2 defines the relation between the sidewall velocity and the velocity at the adjacent observation vertical.

Table 2.2. – Relation of sidewall velocity and adjacent vertical velocity (Rantz et al., 1982).

Distance from sidewall, as a ratio of depth at sidewall	Mean vertical velocity, as related to V_d*
0.00	$0.65V_d$
0.25	$0.90V_d$
0.50	$0.95V_d$
1.00	$1.00V_d$

* V_d is the mean velocity in a vertical located at a distance from the wall equal to the depth.

The performance of mechanical current meters under various adverse conditions has been investigated by various researchers (Thibodeaux, 1992). Studies that are more relevant to this research were reviewed in the first section of this chapter.

Electromagnetic Current Meter:

The electromagnetic current meter measures stream flow velocity using electromagnetic induction, as explained by the Faraday law (Marsh McBirney, 1994). This law states that when a magnetic flux passes through a multi-turn coil, a voltage is induced. This voltage is termed an electromotive force (emf). The relation between the emf, the flux, and the turns of the coil is described by (Bobrow, 1985):

$$e = N\frac{d\phi}{dt} \tag{2. 4}$$

Where:

N = number of turns in the coil

ϕ = flux

e = electromotive force induced

t = time

As Equation 2.4 demonstrates, the magnitude of the emf produced is directly proportional to the velocity at which the coil moves through the magnetic flux. This is the key to the operation of the electromagnetic current meter. The flow sensor includes an electromagnetic coil that produces the magnetic field, and a pair of carbon electrodes to measure the voltage induced by the moving conductor. The moving conductor in this case is the flowing water surrounding the sensor (Marsh McBirney, 1994). The voltage across the carbon electrodes produced by the flowing water is measured by the electronics in the control case and displayed as a velocity measurement.

The only field calibration required by the Marsh McBirney Flo-Mate Model 2000 is a zero check (Marsh McBirney, 1994). This procedure calibrates the linear velocity relation to the induced velocity at the zero velocity position. The process is described in the user's manual of the device and involves placing the sensor in a bucket of water and allowing it to settle. The velocity registered on the control front panel in this instance should be zero (Marsh McBirney, 1994). If the velocity registered by the current meter does not equal zero, an adjustment is made using the front panel. The procedure to calibrate the current meter to zero under these conditions is described in the User’s Manual (Marsh McBirney, 1994).

The maintenance requirement for an electromagnetic current meter is minimal. The batteries must be changed as required for proper operation. When a low battery condition exists, a warning is displayed on the front panel to alert the user. The sensor must be cleaned with soap and water only as required. Nonconductive coatings such as grease and oil can interfere with the operation of the probe. A very fine sand paper can be used to clean persistent coatings from the sensor, but solvents are not to be used for cleaning the sensor (Marsh McBirney, 1994).

The operating range of the Marsh McBirney Flo-mate model 2000 current meter is –0.5 fps to 19.99 fps, with a specified accuracy of ± 2% of the measured velocity + zero stability (Marsh McBirney, 1994). The zero stability is the variability of the velocity reading in still water, and is estimated at ± 0.05 fps. The operating temperature range is from 32 °F to 160 °F. No data were found indicating any effect temperature has on the accuracy of an electromagnetic current meter, but Derecki and Quinn (1987) found that suspended ice and weeds can have a significant impact on the performance of such devices. While using a Marsh McBirney model 585 to measure flow in the St. Clair and Detroit Rivers, they encountered frazil (jellylike) ice formation. The presence of the ice reduced the velocity readings of the current meter by up to 50 %. The accumulation of weeds on the sensor had a similar effect on the velocity readings of the Marsh McBirney model 585 current meter (Derecki and Quinn, 1987).

One-orange Method:

The float method is the simplest method used to measure flow velocity in a stream. While this technique is not typically employed in NPS pollution studies, it represents a lower level of technological sophistication in estimating stream discharge. In its simplest form, a floating object is dropped into the stream, then the time the object takes to travel a specified distance is recorded, and the maximum velocity is calculated as the ratio of the distance to the travel time. The cross-sectional area of the flow is measured and the discharge is estimated as the product of the velocity and area. Obviously, this method is very rough and inaccurate (Kulin and Compton, 1975).

An improved version of the float technique was reported in the National Handbook of Recommended Methods for Water-Data Acquisition (USGS, 1980). The authors mention that the method should only be used as an approximation of the discharge and is not very accurate. In this approach, the stream is divided into sections and the depth on either side of each section is used to determine the area of the section. The same approach is used to determine the maximum velocity of each section, but a coefficient is used to convert the maximum velocity to the mean velocity. This coefficient is typically about 0.85, but may be as low as 0.80 or as high as 0.95 (USGS, 1980). Discharge for each partial section is calculated and the discharge values for individual sections are summed to determine the total stream discharge.

An updated version of the float technique of discharge measurement was presented by Christensen (1994), which uses a buoyant object and the stream section geometry to estimate maximum velocity, mean velocity, and discharge, among other parameters. Deemed the “One-orange method”, this approach is considerably more calculation-intensive than previous versions of the “float” technique. At a reference point near the middle of the stream ($L = 0$) and at time $t = 0$, a slightly buoyant orange is released from the bottom of the stream (Christensen, 1994). The time at which the orange surfaces is recorded as $t = T_1$, and the distance from the vertical reference point at the end of the ascent is $L = L_1$. The orange is then allowed to float a designated distance downstream from the point of emergence. When the orange has traveled the predetermined interval, the distance from the vertical reference point and time, $L = L_2$ and $t = T_2$, are recorded. These data can then be used to determine many properties associated with the flow or stream, as described by Christensen (1994). In this study, only the procedures outlined for determination of discharge were used. Thus, only these procedures are described here. The maximum flow velocity, V_{max}, is estimated from the relationship:

$$V_{max} = \frac{L_2 - L_1}{T_2 - T_1} \tag{2.5}$$

As defined in Equation 2.5, the maximum velocity is equal to the distance traveled by the orange after it surfaces divided by the corresponding elapsed time. This relationship assumes that the flow, and thus the orange, exhibit a constant velocity. Flow velocity in natural streams is not constant, but rather is continuously pulsating. Much like measuring velocity for at least 40 seconds with a current meter is intended to average out the variations in flow velocity, making the distance L_2-L_1 sufficiently large will minimize errors associated with pulsating flow velocity.

Assuming the orange rises at a constant velocity, the mean flow velocity is expressed as:

$$V_{mean} = \frac{1}{d}\int_0^d v\,dy = \int_0^{T1} v v_r\,dt \tag{2.6}$$

Where:

d = depth;

v = local time-mean velocity at distance y from the bed; and

v_r = constant rising velocity of the orange.

Equation 2.6 can then be expressed as:

$$V_{mean} = \frac{1}{d}\int_0^{T1} \frac{dl}{dt} \cdot \frac{d}{T_1}\,dt = \frac{1}{T1}\int_0^{L1} dl = \frac{L_1}{T_1} \tag{2.7}$$

With the mean and maximum velocities determined, the next step is to find the equivalent sand roughness of streambed. Christensen (1994) assumed a logarithmic velocity profile, and used the following formula to describe the relationship between the velocity profile and the roughness of the streambed:

$$\frac{v}{v_f} = 2.5 \ln \frac{29.7y}{k} \qquad (2.8)$$

Where: v = velocity at a distance from the streambed, y;
v_f = friction velocity; and
k = equivalent sand roughness.

Equation 2.8 is then applied at the depths corresponding to the maximum and mean velocities, yielding:

$$\frac{V_{max}}{v_f} = 2.5 \ln \frac{29.7y}{k} \qquad (2.9)$$

and

$$\frac{V_{mean}}{v_f} = 2.5 \ln \frac{29.7y}{ek} \qquad (2.10)$$

Where:

v_f = friction velocity;
k = equivalent sand roughness; and
e = base of natural logarithms.

Solving equations 2.9 and 2.10 for k yields:

$$k = \frac{29.7d}{e^{\frac{V_{max}}{V_{ma} - V_{mean}}}} \tag{2.11}$$

The next step is to estimate the wetted perimeter of the section of interest. This is done using the power expression:

$$z_b = Cx^n \tag{2.12}$$

Where:

z_b = the vertical distance from the deepest point in a section to a point on the wetted perimeter located a distance *x* from the centerline of the section;

C = a power expression constant; and

n = a power expression exponent, related to the areal aspect ratio.

The areal aspect ratio is defined by:

$$\omega = \frac{A}{Bd_{max}} \tag{2.13}$$

Where:

ω = areal aspect ratio;

B = width of the water surface;

d_{max} = maximum depth in the section; and

A = cross sectional area of the section.

Christensen (1994) then derived the following equation to define total discharge in the section as a function of the stream properties:

$$Q = V_{max,0} A \bullet \eta \left\{ \omega, \frac{d_{max}}{k} \right\} \tag{2.14}$$

Where:

$V_{max,0}$ = maximum velocity at the middle of the stream section;

k = equivalent sand roughness; and

η = dummy variable.

The η-function is a dummy variable, which is mathematically defined by Christensen, then evaluated by numerical integration and plotted to allow the user to solve for the total discharge. The axes of this plot are ω and $(Q/(AV_{max,0}))$. Christensen (1994) did not perform any experiments to test the One-orange method, and no studies could be found that evaluated it in either the field or the laboratory.

Ultrasonic (Acoustic) Doppler Flow Measurement:

Ultrasonic (acoustic) Doppler flow measurement devices represent a convenient means of measuring stream flow discharge. Development of a stream depth-discharge relationship is not required when using this method, as is normally the case in stream-gaging. This method consists of a velocity sensor, depth sensor, a data logger, and requires knowledge of the stream cross-section. The result of this method is an estimated discharge value based on the velocity-area method of flow measurement. Two such devices were employed in this study; the Isco 4150 Flow Logger with the standard velocity-area sensor, and the Starflow model 6526B Ultrasonic Doppler Instrument with Micrologger.

The velocity sensor uses the Doppler shift principal to measure the average flow velocity in the cross section. The Doppler effect is experienced when there is a relative motion between the source of energy waves and the observer of those same energy waves. While this effect is normally associated with sound waves, it is common to all harmonic waves including light. In this case, the flow velocity sensor acts as both the initial source and observer of the ultrasonic waves. As shown in Figure 2.3, the instrument is placed at a position in the streambed during operation. Ultrasonic sound waves are emitted from the sensor, and small suspended particles and bubbles entrained in the water act as acoustic targets. The acoustic targets reflect the ultrasonic sound waves back at the sensor, but at a slightly different frequency.

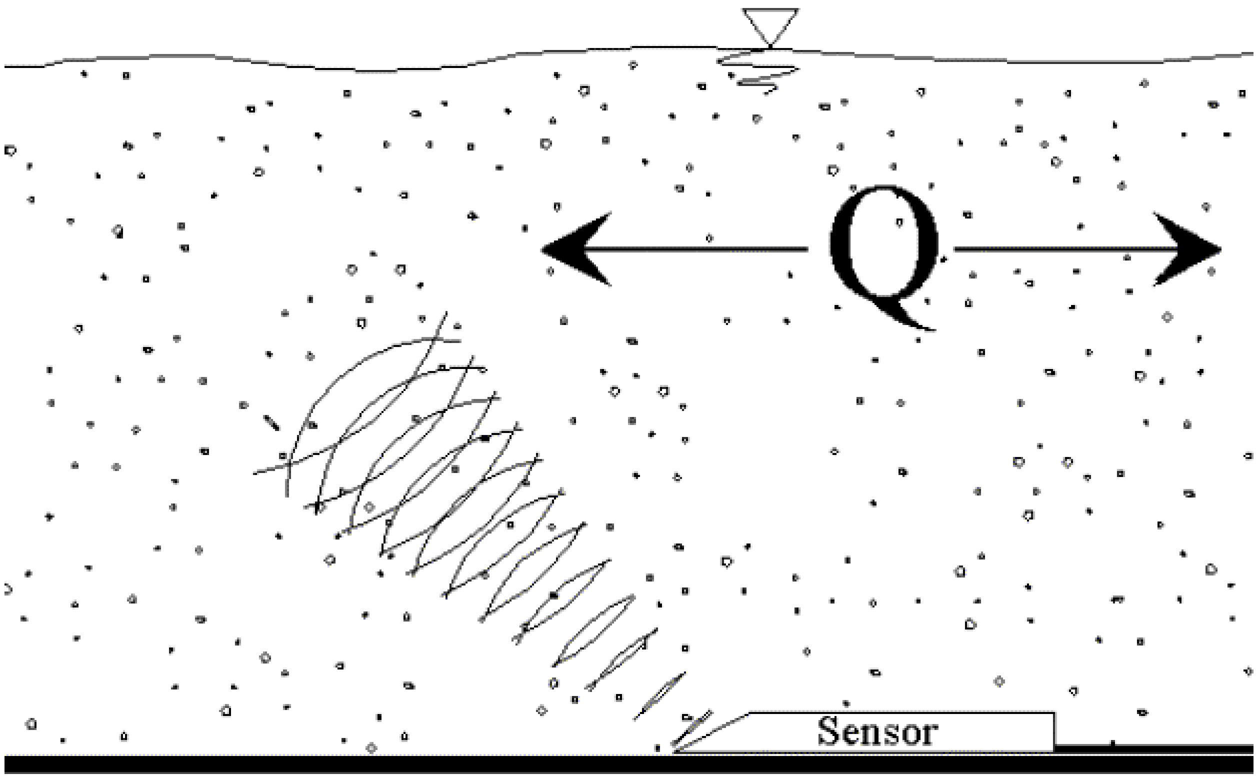


Figure 2.3 – Acoustic Doppler sensor in stream.

The sensor then measures the shift in the frequency of the ultrasonic waves to determine the average velocity in the stream section. The general equation used to describe this shift when the observer is at rest and the source is in motion is as follows (Serway, 1990):

$$f' = f\left(\frac{1}{1 \pm \frac{v_s}{v}}\right) \qquad (2.15)$$

Where:

f' = observed frequency;

f = source frequency;

v_s = velocity of source; and

v = velocity of the sound.

The signs ($\pm$) in Equation 2.15 refer to the direction of the motion of the source being toward or away from the observer. Generally, the term “toward” is associated with an increase in the observed frequency and the term “away from” indicates a decrease in the observed frequency relative to the source frequency (Serway, 1990). Since the devices can detect increases or decreases in ultrasonic wave frequency, it is appropriate to mount the device facing either upstream or downstream. If accumulation of sediment is a concern, facing the device downstream can minimize the amount of operational interference caused by such accumulation.

The Starflow device is an incoherent (continuous) Doppler, where a continuous signal is emitted at a fixed frequency. The device then measures the reflected signals from acoustic targets anywhere along the beam. The measuring circuit in the device detects frequency changes and the processing system collects the changes and determines the representative Doppler shift (Unidata, 1995). The processing system relates the Doppler shift to a water velocity component along the ultrasonic beam. The resolved velocity component is oriented with the beam, which is at an angle to the device. Therefore, the velocity is adjusted by the cosine of the angle of the beam to a horizontal line (Unidata, 1995).

The transformation of Doppler shift to water velocity is based on the speed of sound through fresh water at 20° C. The speed of sound in water varies with water temperature due to the change in water density. Such a difference is also present when using the device in salt water due to density differences. Water at 30° C will yield a measurement error of 1.8% (Massey, 1996). Similarly, water at 10° C will result in an error of 2.4%. It is possible to correct this situation with the Starflow device if it is believed that the water being monitored is significantly different from 20° C. The calibration factor can be changed to reflect this new water temperature.

There are other factors that affect the device's accuracy. The Starflow device is reported to measure velocity to an accuracy of ± 2% of the measured velocity and depth to within ± 0.25% of the calibrated range. The resolution of the measurements is 1mm/s for the velocity, and 1mm for the depth (Unidata, 1995). Resolution and accuracy data were not provided for the Isco model 4150 Flow Logger with standard velocity-area sensor.   Problems that could adversely affect device performance include improper installation, damage, blockage, and burial by sediment and other debris. Ultrasonic Doppler devices are often installed in pipes and artificial channels, but installation in natural streams is acceptable and guidelines for such installation are provided by Unidata (1995):

- Flows are laminar and the velocity measured can be related to the mean channel velocity;
- Channel cross section is stable so the level-area relationship is reliable;
- Velocity is greater than 20 mm/s;
- Sufficient particles and bubbles are present to reflect the ultrasonic signal for velocity measurement;
- Aeration is not excessive so as to affect the velocity of sound through the water; and
- Stream bed is stable enough to prevent burial of the sensor by deposits.

Other factors to be considered when installing such a device include the accessibility, safety, and security of the site. However, these criteria do not necessarily affect the performance of the device.

Discharge in a natural stream exhibits "surges" in velocity. These surges can be damped by the inertia of a mechanical current meter to some degree. This is the reason for averaging the velocity over a period of 40-70 seconds when measuring discharge in a stream using a current meter. Averaging the velocity readings over the log interval (time interval over which data is collected prior to storage in a data file) when recording data can smooth out the fluctuations in velocity. If velocity readings are to be compared to those obtained using a mechanical current meter, the display should be observed for a period of time sufficient to obtain a representative mean velocity (Unidata, 1995).

The ultrasonic Doppler devices also measure water depth to calculate the discharge in a section. The depth measurements are performed by a differential pressure transducer mounted beneath the device. The pressure transducer consists of a small stainless steel diaphragm transferring the hydrostatic pressure to a piezo-resistive element. The outer face of the diaphragm is exposed to both the atmospheric and hydrostatic pressure, while the inner face is exposed (referenced) only to the atmosphere by way of the vent tube (Isco, 1993). The difference between the measured and reference pressures is the hydrostatic pressure, which is directly proportional to the level of the water above the sensor. The pressure transducer is vented to the atmosphere by a vent tube in the signal cable. A desiccant canister is located at the end of the vent tube to prevent moisture from entering the tube.

As Thibodeaux (1992) indicated, there has been very little research performed on ultrasonic acoustic Doppler flow measurement devices. Appell (1978) performed the only study of acoustic point velocity meters noted by Thibodeaux (1992). This study was a limited performance evaluation of a new acoustic current meter (Appell, 1978). In that study, Appell (1978) investigated the effects of vertical and oblique flows on the performance of an NBIS ACM-1 acoustic current meter. The investigation consisted of laboratory experiments performed in an indoor basin with a tow carriage as the standard of velocity. The results of the various tests were documented in graphical form only. Appell (1978) concluded that the device excelled in its quick response to velocity fluctuations and low noise levels experienced with the devices. No conclusions were drawn concerning the accuracy of the device, but the author recommended further testing prior to implementation of the device.

Dilution Technique:

The stream flow discharge can also be determined by examining the dilution of a tracer that has been injected into the stream. A tracer is defined as any dissolved, suspended or floating material used to determine hydrologic characteristics of a stream (Wilson et al., 1986). This concept has been employed since 1863, and until recently has been performed primarily with chemical salts (Kilpatrick and Cobb, 1985). Use of fluorescent dyes as tracers in water began in the early to mid-1900's (Wilson et al., 1986). Discharge measurement using dilution techniques is not commonly performed for several reasons including the high sampling requirements, expense, uniform channel requirement, and difficulties in achieving complete mixing of the tracer (Kilpatrick and Cobb, 1985). Dilution is typically limited to small streams, although discharges of up to 2000 m^3/s have been measured accurately (Herschy, 1985). Kilpatrick and Cobb (1985) list the conditions under which dilution methods are useful:

- it is difficult or impossible to use a current meter due to high velocities, turbulence, or debris.
- due to physical reasons, the flow rate is inaccessible to a current meter or other measuring device.
- the rate of change of flow is such that the time to make a current meter measurement is excessive.
- the cross-sectional area cannot be accurately measured as part of the discharge measurement or is changing during the measurement.

Pipes, sewers, and ice-covered streams are just a few examples of such conditions for which dilution method is used (Kilpatrick and Cobb, 1985).

The skills of those carrying out the discharge measurement using the dilution technique is also of concern. This method is normally performed by specially trained personnel (Herschy, 1985). Kilpartick and Cobb (1985) urge the user to perform a dye-dilution measurement on a small ordinary stream prior to attempting such a discharge measurement on a larger, more complicated system.

Procedures used to perform the dilution method in the field are described in Chapter 3. The dilution method is based on measuring the degree of dilution of the known quantity of tracer in a stream, assuming that the tracer is completely mixed (Kilpatrick and Cobb, 1985). By assuming that the background concentration of the tracer used in the measurement is constant, there are two methods that allow the user to calculate the stream discharge while ignoring the background concentration (Herschy, 1985). These methods are the constant rate injection and slug injection techniques. The method of interest in this study is the slug injection technique due to the relatively small quantity of specialized equipment required to perform the measurement.

In addition to the relative simplicity and reasonable equipment requirements, another advantage of the slug injection method of dilution discharge measurement is the small reach lengths typically required. Long reach lengths, such as those used in tracer time-of-travel studies likely result in a significant loss of tracer and thus inaccurate discharge measurements (Kilpatrick and Cobb, 1985).

In the slug injection method, a known volume of fluid containing a known concentration, C_1, of a suitable tracer is poured into the beginning of the measurement reach, also know as the mixing reach (Herschy, 1985). As discussed earlier, the mixing reach should have a fairly uniform cross section and a constant discharge throughout its length. At the second cross section defining the reach, the water is sampled over a time sufficient to allow the entire cloud of tracer to pass the section. Thus, the second section in the reach is called the sampling section. By analyzing these samples, the concentration of the tracer as the cloud passes the sampling section can be determined. By assuming that all the tracer that was injected into the stream passes through the sampling section, the discharge in the stream can be calculated from the following equation (Herschy, 1985).

$$M = VC_1 = Q\int_{t_0}^{\infty} C_2(t)dt \tag{2.16}$$

Where:

M = mass of tracer injected at the first section of the reach,
V = volume of solution injected at the first section,
C_1 = tracer concentration of the injected solution,
Q = stream discharge,
$C_2(t)$ = tracer concentration at the sampling section over time,
t = elapsed time; t=0 at the instant the tracer solution is injected, and
t_0 = time at which the first molecule of tracer passes the sampling section.

The integral in this equation is equal to the area under the response curve measured at the sampling section, thus the relationship could be expressed (Kilpatrick and Cobb, 1985) as:

$$Q = \frac{M}{A_C} \tag{2.17}$$

Where:

A_C = area under the response curve obtained from analysis of samples collected at the sampling section.

Because it is a general formula, units were ignored in equation 2.17. A constant is required to yield a dimensionally correct equation (Kilpatrick and Cobb, 1985). To be used with units, Equation 2.17 could be written:

$$Q = 5.89x10^{-7} \frac{S_G V_I C}{A_C} \tag{2.18}$$

Where:

Q = discharge in the stream, in cfs,

S_G = specific gravity of the injected solution,

V_I = volume of concentrated dye solution in the injection solution, in ml,

C = concentration of injection solution, in μg/l., and

A_C = area under response curve, in min. μg/l.

When using equation 2.18, one assumes that the response curve is identical at every point in the sampling section, reflecting complete mixing. This condition is neither practical, nor is it necessary for an accurate discharge measurement using the dilution technique (Kilpatrick and Cobb, 1985). A quality measurement can be achieved in what is termed the optimum reach length, where the mixing of the tracer is about 95% complete.

A minimum of three points must be sampled across the sampling section in this method as shown in Figure 2.4. Use of the optimum reach length facilitates the measurement of the response curves at multiple points across the sampling section within a reasonable amount of time. With an excessively long measurement reach, the travel of the tracer will be hindered at the banks, which will tend to lengthen the response curves at these points. This concept is illustrated in Figure 2.4. The optimum reach length also reduces the chance of significant tracer loss in the reach and allows the tracer to be fully recovered.

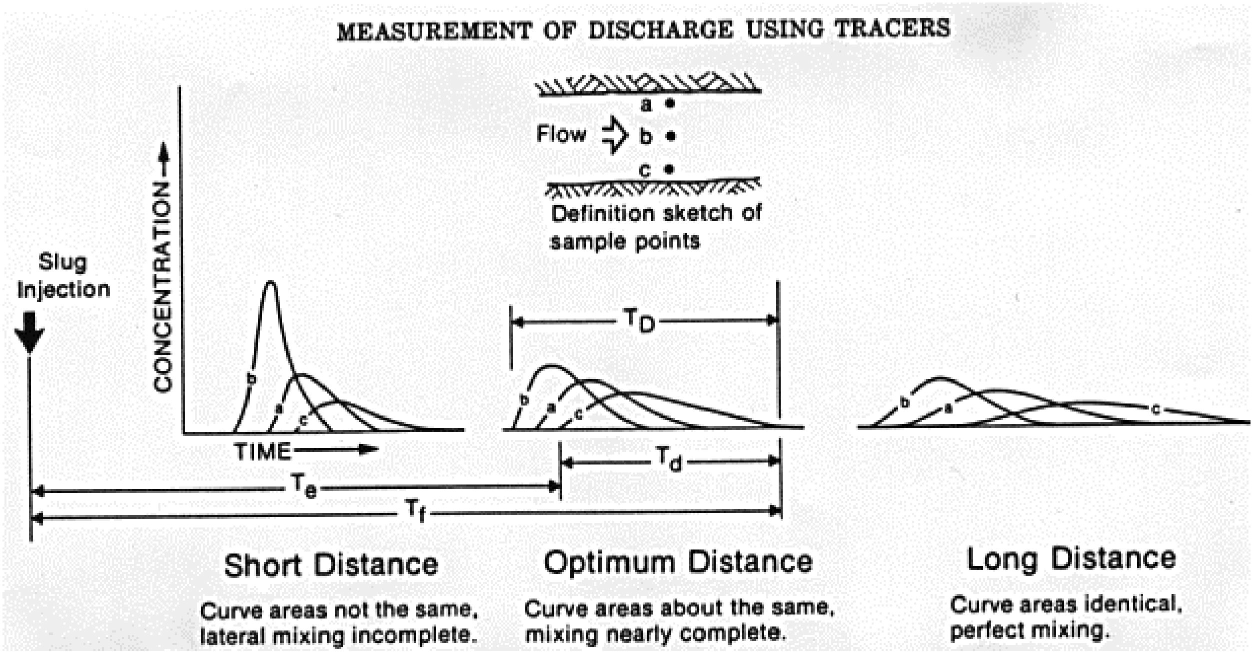


Figure 2.4 – Characteristic response curves for points in a measurement section various distances downstream from the point of tracer solution injection.

Limited experiments have been performed to evaluate the accuracy of the dilution method, thus it is difficult to determine the total accuracy of such discharge measurements. Kulin and Compton (1975) reported that Kilpatrick achieved an accuracy of $\pm$ 2% for a limited number of laboratory trials using the constant rate injection method. They also indicated that the results achieved in natural streams must be assumed to be less accurate, since no such research had been performed (Kulin and Compton, 1975). One would have to further assume that the results obtained using the slug injection method would be even less accurate than those resulting from the constant rate injection method. Furthermore, the USGS publications on the subject do not assess the accuracy of this method.

Pressure Transducers:

Pressure transducers represent a fairly inexpensive and very reliable means of measuring water level at a stream-gaging station. A pressure transducer uses a four-element piezo-resistor bridge to sense changes in pressure. The sensor measures differential pressure and is vented to the atmosphere to account for changes in barometric pressure. The purpose of using the sensor is to relate hydrostatic pressure caused by the water column over the sensor to a change in resistance caused by that pressure. The change in resistance can then be related to stage. This relationship is linear, with correlation coefficients of near 1 when a proper calibration of the sensor is conducted (Keeland et al., 1997).

One advantage of the pressure transducer when measuring water stage is the ease of data collection and reduced maintenance requirements, compared to a chart recorder. Once calibrated, the transducer can be connected to a datalogger for collection of stage data. The data collection requirements depend on the memory capacity of the datalogger and storage schedule of the datalogger program used. To ensure proper operation of the transducer, the device should be kept uncovered by sediment and other debris. This can be achieved using a stilling well as is utilized with a chart stage recorder. However, if conditions permit, mounting the sensor directly in the stream would allow the user to avoid the costs associated with installation and maintenance of a stilling well. An instrument shelter would still be required to keep the datalogger and other associated equipment dry and secure.

The sensor exhibits a linear response within the pressure range of the device; however, pressures above this range can result in a non-linear response and possibly damage to the sensor. This condition can be avoided by installing the transducer in such a location that the maximum anticipated stage would not produce extremely high pressures.

Another potential source of error associated with water stage measurement using pressure transducers is the effect of temperature variation during measurement. These errors can reach $\pm$ 4 cm in a 35 °C temperature variation (Keeland et al., 1997).

Each transducer must be calibrated individually as each sensor will exhibit slightly different response characteristics. Calibration should be performed in a laboratory to provide controlled conditions. Calibration can be performed by any means that allows the user to relate the change in resistance that occurs in the piezo-electric bridge within the sensor to the depth of the water above the transducer. The calibration should cover the anticipated range of depths in the field setting. Once installed in the field, the transducer should be field calibrated to minimize possible measurement errors caused by differences in dataloggers, power sources, etc.

CHAPTER 3
METHODS

Introduction:

The goal of this study was to compare the accuracy of each stream gaging method's performance in both field and laboratory environments. To ensure that a legitimate comparison of accuracy can be performed among the various methods included in this study, established procedures must be used with each device. The methods used with each stream-gaging device are discussed in this chapter.

Field Methods:

Field Study Sites:

Field investigations were performed at the outlets of two small agricultural watersheds. Neither of the stream sections used in this study fit the criteria outlined by Rantz et al. (1982), as listed in Chapter 2. The measurement sections used in this study were not always in a straight stretch of stream. Velocities encountered were usually below 0.5 ft/s, and the stream bottom was not uniform. However, these are the type of adverse flow measuring conditions frequently encountered by researchers performing NPS pollution studies. The presence of functioning control structures was the primary reason these sites were used in this study. A total of five sites were considered, but these two were considered the most suitable based on the condition of the weirs and the relative adequacy of flow measurement sections.

Prior to collection of stream flow discharge data at each site, an FW-1 float and weight stage recorder was installed in the instrument shelter of the stilling well. These recorders were equipped with potentiometers to electronically record the stream level for comparison with the data collected by the pressure transducers. The potentiometer and pressure transducers were connected to a Campbell 21X datalogger (Campbell Scientific, 1996). The datalogger was programmed to receive and transform signals from all the devices, and then record the pertinent data. The software program used with the datalogger is included in Appendix A. Surveys of the measurement sections used for the acoustic Doppler measurement devices were used to develop stage-area tables as discussed later in this chapter.

One of the gaging sites used in this study is located at the outlet of the Crab Creek watershed (Figure 3.1). A map of the watershed is shown in Figure 3.1. This watershed is located in Montgomery County on Route 11 between Christiansburg and Radford, Virginia. The drainage area of the watershed is 786 acres. The average slope of the watershed is 12.14% (Carr and Burford, 1967). The land use for the Crab Creek watershed is listed below (Carr and Burford, 1967). These land use data are from 1967, but this area has not changed significantly since that time.

- Cultivated 40%
- Pasture 42%
- Wooded 13%
- Idle 4%
- Roads 1%

The soil types present in the watershed are listed below as a percentage of the total area (Carr and Burford, 1967).

- Lodi loam 34.8%
- Frederick silt loam 26.6%
- Greendale silt loam 15.6%
- Litz silt loam 8.6%
- Melvin silt loam 5.0%
- other silt loams 9.4%

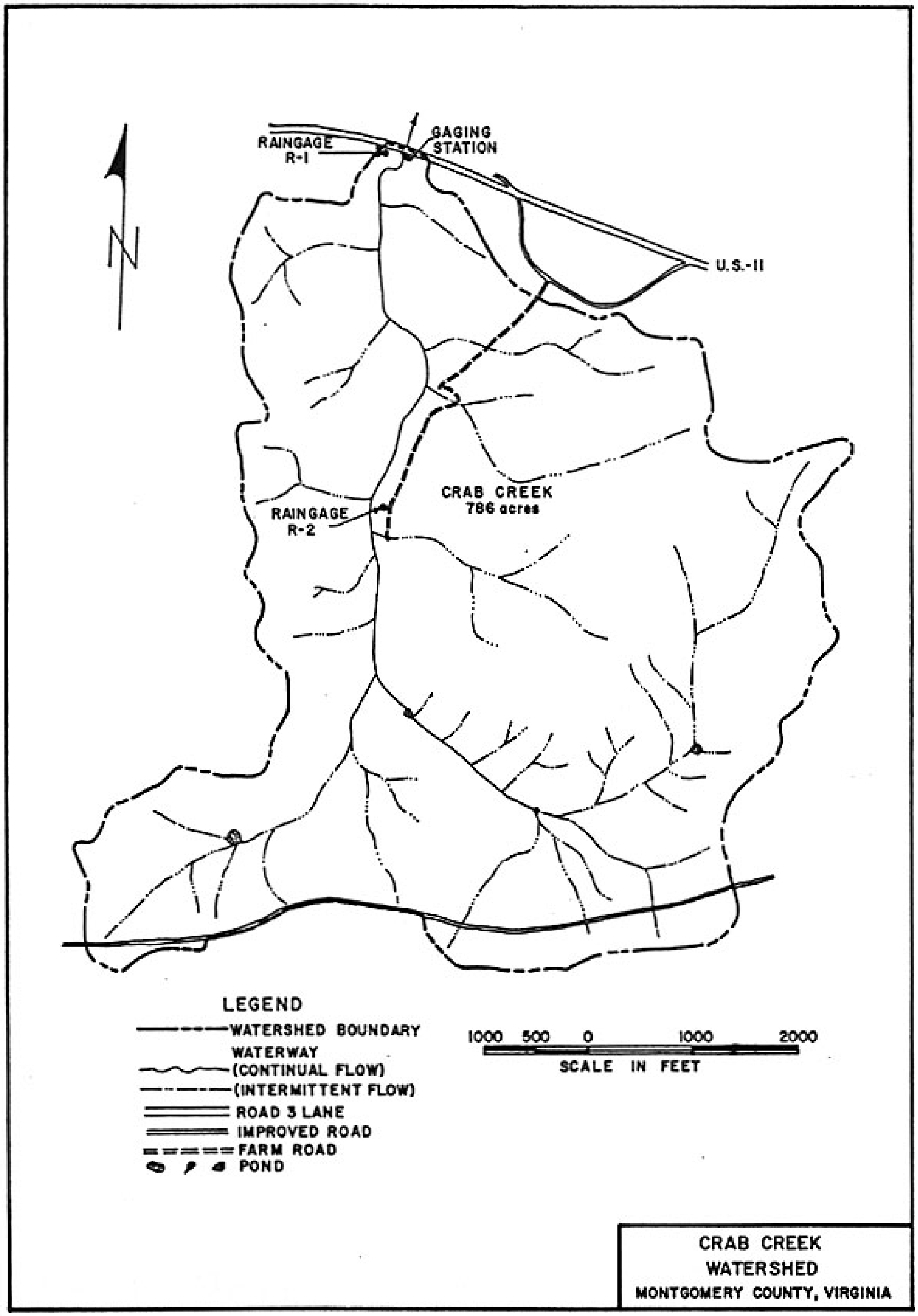


Figure 3.1 – Map of the Crab Creek watershed.

The United States Department of Agriculture (USDA) monitored this watershed from August of 1957 through 1979. The flow control structure at the Crab Creek gaging station is a double 6' x 6' rectangular culvert modified with a twin Virginia V-notch weir. A stilling well with a small instrument shelter and a staff gage were still present at the gaging station.

To prepare the site for operation in this study, the gaging station had to be refurbished. The access catwalk to the instrument shelter was rebuilt, and the shelter itself was repaired. The stilling well was stabilized using additional guy wires and anchors. The stilling well intake pipe, which was covered with sediment, was flushed out by pumping water into the stilling well. This allowed the intake and stilling well to operate properly. As can be seen in Figure 3.2, the original streambed has been partially filled by sediment deposition near the control structure. It was decided that removing the sediment from this part of the stream would be costly, time consuming, and would disturb the surrounding area. An area around the staff gage and in front of the control structure was manually excavated and cleared. This area was sufficient to allow the water to pond prior to flowing over the weirs and to approximate conditions present when the rating curve for the site was originally developed.

Stream measurement sections were located as shown in Figure 3.2. Multiple sections were used to facilitate simultaneous use of multiple measurement techniques. Two measurement sections were designated for use with current meters to expedite the current meter data collection at this site. Current meter data were collected simultaneously at both of the measurement sections. The distance and riffle between measurement sections prevented one stream gager from interfering with another. The first current meter measurement section was located below the riffle, upstream from the stilling well. This section was desirable due to the close proximity to the control structure and had a fairly uniform streambed. However, there was a portion of the section at the left edge of water (LEW) that had small flow velocities. This condition further limited the number of measurement verticals available to make a current meter measurement. The second current meter measurement section was located upstream of the first measurement section and the riffle.

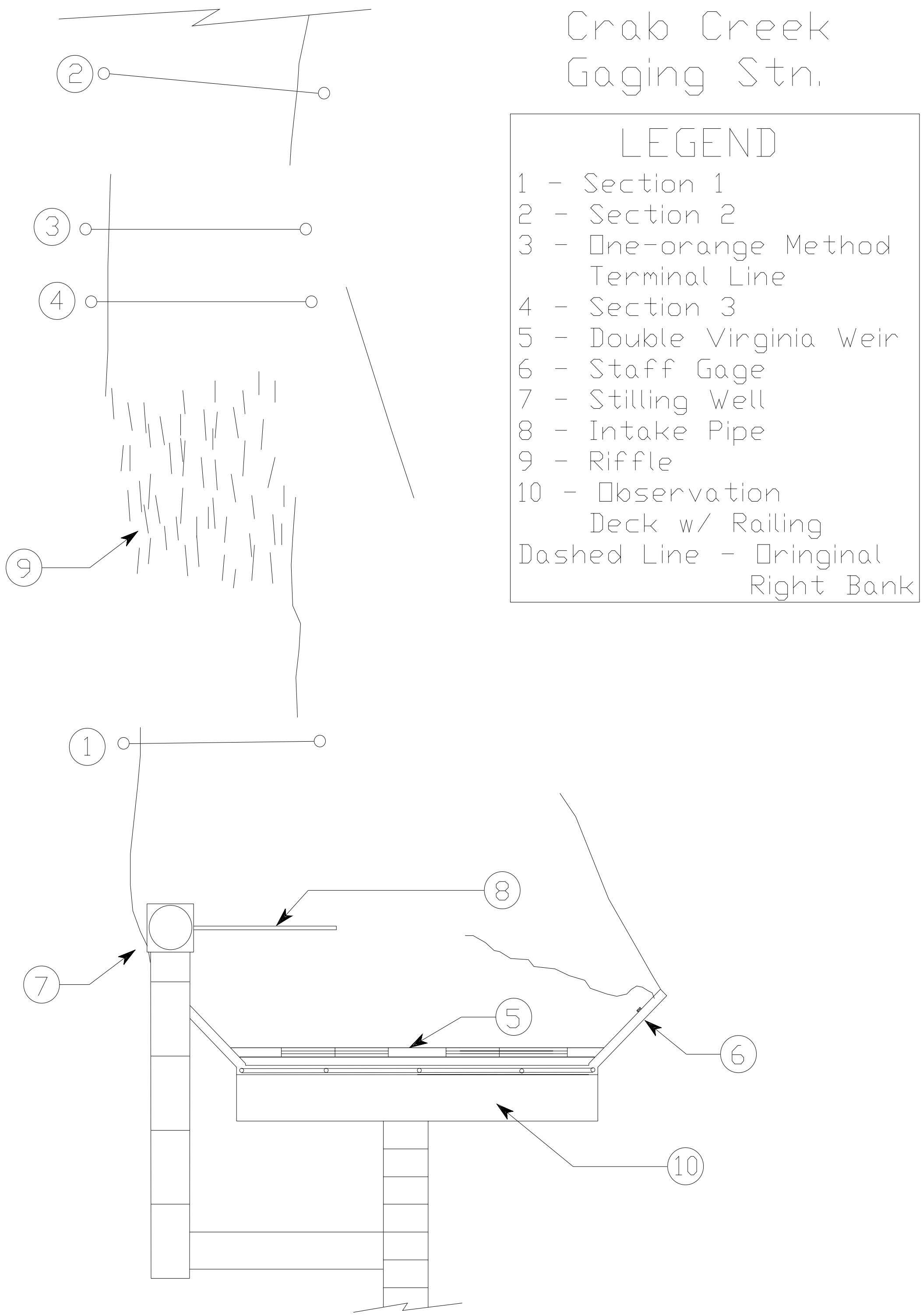


Figure 3.2 – Plan view of the Crab Creek gaging station (not to scale).

The stream bottom in this section was somewhat parabolic in shape, and the flow velocity was concentrated in the middle of the section.

The second watershed used in the field study was the Thorne Springs Branch watershed Figure 3.3). The gaging station is located on Route 11 in Pulaski county between Dublin and Pulaski, Virginia. The drainage area of this watershed is 3054 acres. Monitoring of this watershed began in June of 1957 with construction of the control structure and stilling well by the United States Department of Agriculture. Monitoring continued until 1969, when the station was given to the USGS, who now operates the station to record maximum/minimum flow rates. The hydraulic control at this watershed is a large concrete dam with a broad-crested v-notch weir in the dam. There is also a larger rectangular weir in the dam extending beyond either side of the v-notch weir, but this control was not used in this study. Like the Crab Creek watershed, this watershed is agricultural. Land use data from 1967 are still representative of the watershed and are:

- Cultivated 34%
- Pasture 59%
- Wooded 4%
- Idle 2%
- Roads 1%

The average slope in the watershed is 10.26%. Soils present in the watershed listed as a percentage of the total watershed area include (Carr and Burford, 1967):

- Groseclose silt loam 30.4%
- Frederick silt loam 14.1%
- Lodi loam 17.4%
- Litz loam 11.5%
- Greendale silt loam 8.2%
- Carbo rock silty clay loam 4.0%
- 12 other loams 14.4%

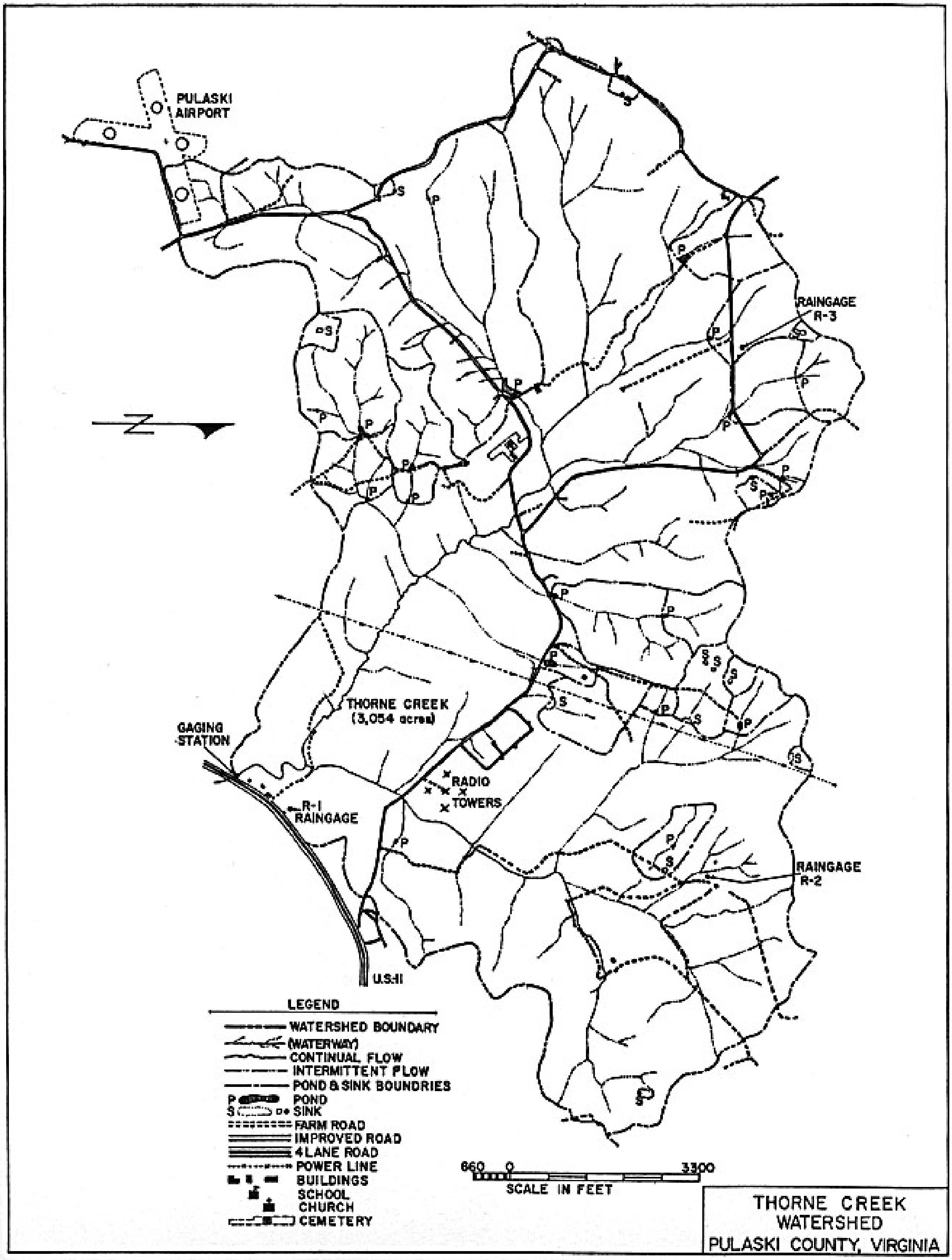


Figure 3.3 - Map of the Thorne Springs Branch watershed.

A sketch of the Thorne Springs gaging station site can be seen in Figure 3.4. In addition to the control structure, the site is equipped with a stilling well with a staff gage located inside the stilling well. Since the gaging station is in operation, relatively little work was required prior to collecting data at this site.

One problem encountered at this site was the accumulation of silt behind the dam. Sediment had completely covered the intake pipe to the stilling well, but the representative from the USGS assured me that this did not significantly affect the operation of the stilling well (Henderlite, 1999). This sediment deposition was very deep and prevented the measurement of stream discharge at a location above the dam, which was the more desirable location. The stream above the dam had more straight sections, higher velocity, and a more uniform streambed. However, the deep sediment accumulation prevented wading of the stream. No other suitable site was available further upstream of the dam. Thus, the stream measurement sections were located about 70 feet downstream of the dam.

The stream flows over the weir and drops about 5 feet into a large pool, before flowing into the culvert (Figure 3.4). The transition from the pool to the culvert was not smooth and produced a lot of eddy currents. To correct this situation, a curved transition region was constructed from rocks in and around the stream. This transition straightened out the flow lines in the measurement section, and flow was allowed to stabilize for 2 days prior to measuring discharge at the site. The measurement sections are shown in Figure 3.4. The site was inspected for additional flow into or out of the stream between the control structure and the measurement sections, and none was found. The first current meter measurement section was located at the mouth of the culvert, as this site possessed the most uniform stream bed and had the best distribution of discharge across the section at the site. A second current meter measurement section was designated downstream from section 1, but this section was not used for current meter measurements due to excessive sediment accumulation in the section. Instead, this section was used exclusively for the One-orange method. A third measurement section, the alternate section, was created near the downstream end of the transition structure. This measurement section was used only for acoustic Doppler flow measurement devices.

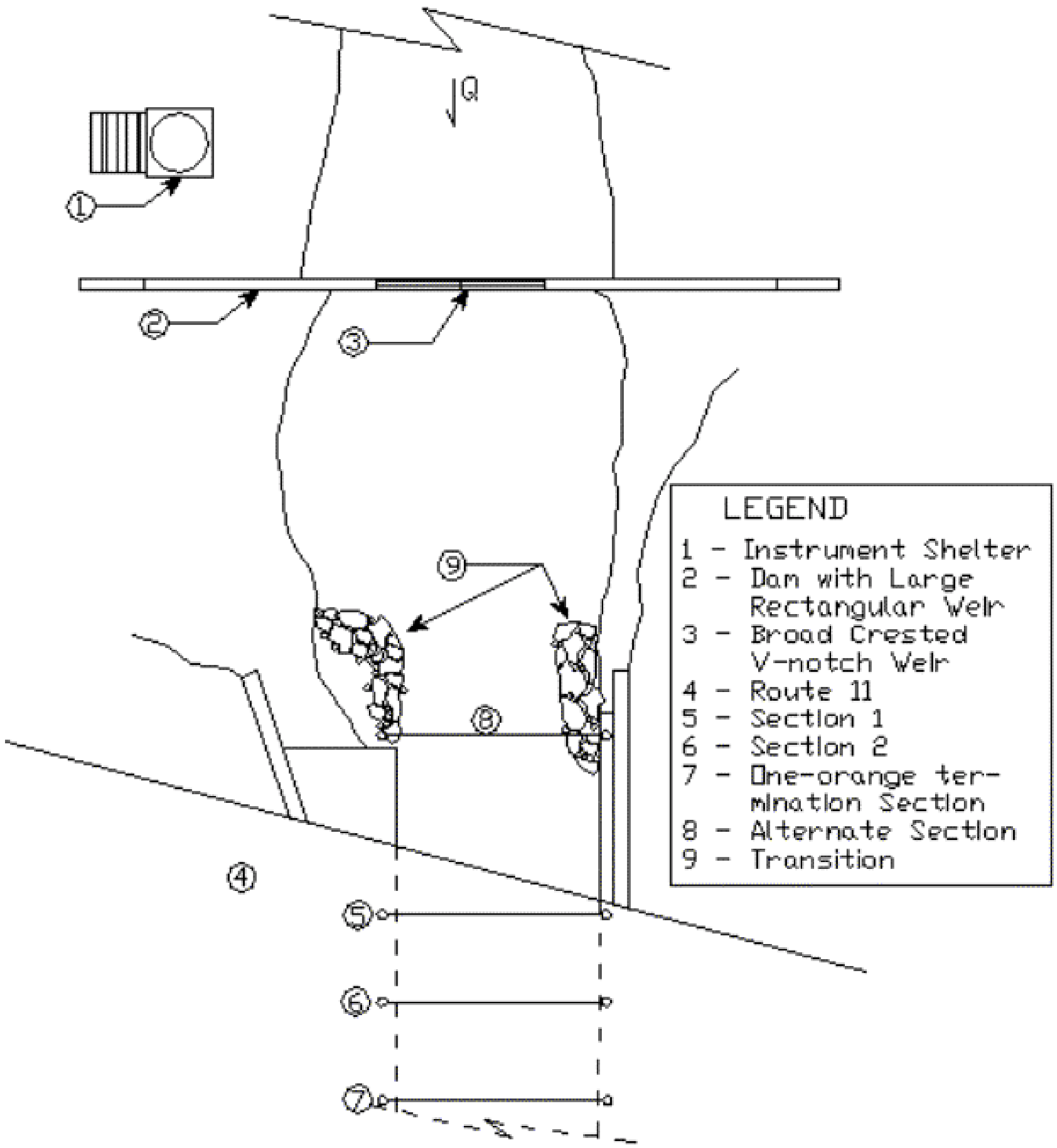


Figure 3.4 - Plan View of the Thorne Springs Branch gaging station (not to scale).

Use of Current Meters in the Field Investigations:

The procedures described by the USGS (Rantz et al., 1982) were followed in collecting data by all current meters used in this study. Due to the small size of the streams used in the field investigations of this study, some deviation from the USGS procedures was necessary. The most notable modification was a reduction in the number of measurement verticals used in the discharge measurements by current meter. This section explains the methods used in this study.

Since the purpose of the field study was to compare the discharge rates obtained by various methods, with those obtained using the artificial control structure as the standard method, the choice of sites for the field study were primarily dependent on the presence of the artificial control structure. This condition necessitated the use of field investigation sites that were not quite as desirable for testing current meters as other sites that were available in the region. The criteria for a suitable section for discharge measurement by current meter, as described by Rantz et al. (1982), include:

1. Cross section lies within a straight reach, and streamlines are parallel to each other.
2. Velocities are greater than 0.5 ft/s (0.15 m/s) and depths are greater than 0.5 ft (0.15 m).
3. Streambed is relatively uniform and free of numerous boulders and heavy aquatic growth.
4. Flow is relatively uniform and free of eddies, slack water, and excessive turbulence.
5. Measurement section is relatively close to the gaging-station control to avoid the effect of tributary inflow between the measurement section and control and to avoid the effect of storage between the measurement section and control during periods of rapidly changing stage.

It should be noted that not all of the criteria can be met at every site, so one must use judgement to select the best site available for the discharge measurement.

The two sites used in this study had limited straight sections suitable for the current meter measurements. Two sections were chosen for current meter measurements at the Crab Creek gaging station to expedite the data collection process. Each of these sections was located in a straight section of the stream that was close to the gaging station. At the Thorne Springs gaging station, one suitable section was identified for current meter measurements. Other sections farther downstream in the culvert were not used due to a large accumulation of sediment. The first criterion used by the USGS to describe a suitable measurement section is to select a straight section of the stream with streamlines parallel to one another. To meet this condition at Thorne Springs Branch, a transition was constructed from the pool the water flowed into from the weir to the culvert.

The second criterion listed by the USGS to define a suitable measurement involves selection of a section that includes velocities that are generally greater than 0.5 ft/s. The velocities measured by current meters at the two sites ranged from 0.01 - 0.394 ft/s, which are considerably smaller than that called for in the second criterion. This created some problems, particularly with the mechanical current meters at the Thorne Springs Branch gaging station.

The third criterion describing a desirable measurement section suggests the streambed be relatively uniform and free of numerous boulders and heavy aquatic growth. The measurement section at the Thorne Springs Branch gaging station was not very uniform. There were rather large rocks in and around the section. The sections at Crab Creek were fairly uniform, with a few large stones but the stream bottom consisted mostly of smaller cobbles with some sediment in the streambed. Significant accumulation of sediment was present at both sites.

The measurement sections at both sites contained flow that was fairly uniform and free of eddies, slack water, and excessive turbulence. Section 1 at Crab Creek had some dead area (area with no flow of water) toward the REW (right edge of water), and a concentration of flow on the other side. Section 2 at Crab Creek was more uniform across the middle of the section, but with no flow on the edges. The measurement section at Thorne Springs Branch had a fairly uniform section with regard to velocity distribution; although there was a shallow dead area at the LEW (left edge of water). This was corrected by the presence of the transition structure upstream of the measurement section.

At both sites, the measurement sections were close enough to the gaging station to avoid tributary inflow and the effect of storage between the measurement sections and the control. Both measurement sections at Crab Creek were located at less than 125 ft upstream of the control structure, with no inflow or outflow between the sections and the structure. At Thorne Springs Branch, the measurement section was located downstream of the control structure. The water ran over the weir, into a pool, then through the transition and into the culvert which included the measurement section. If precipitation fell during the measurement process, measurement was stopped at the first sign of runoff entering the stream.

After selection of the measurement section, the next step in the process is to pull a tag line or measuring tape across the stream to designate the section and facilitate determination of the station and stream width. The tag line must be placed across the stream perpendicular to the direction of flow to avoid horizontal angles in the cross section (Rantz et al., 1982).

Since several measurements were to be taken at each site using current meters, semi-permanent tag lines were placed at the sections. They were constructed of nylon string and steel stakes driven into the ground on each bank of the stream, and formed a line perpendicular to the stream flow in order to minimize errors in flow measurements. Each line was marked with a permanent marker at increments of 0.25 feet with a triple mark at every foot. The length increments were transposed from a surveying rod, which was also used to support the chord to prevent it from stretching while marking it. These markings were used to measure the location of the observation verticals during the discharge measurement. An “observation vertical” is an imaginary line representing the point in the measurement section where the water depth and mean velocity are measured, and represents the defining line of a measurement partial area. The observation vertical is designated by its station, or horizontal distance from the initial point, as shown in Figure 2.1.

The observation verticals to be used for discharge measurement were determined as the next step. Each stream gager was instructed that upwards of 25 verticals were desirable for a discharge measurement, and that each vertical should represent no more that 10% of the total flow (Rantz et al., 1982). Therefore, the spacing should be closer where velocity and depth is greater in the stream. This goal was not always achieved at the sites used in this study, given the small stream width and even smaller width contributing to the flow. If the cross section is smooth with a fairly even distribution of velocity, fewer verticals are permissible. Equal widths of partial sections are not recommended unless the discharge is well distributed across the stream section (Buchanan and Somers, 1984). Ideally, each partial area in the section should contain no more than 5% of the total discharge, though this is seldom achieved (Rantz et al., 1982).

The width of the current meter being used was often the limiting factor when determining the spacing between measurement verticals in the small streams. If a stream gager encountered flow velocity were they did not anticipate it and had used a wide spacing between measurement verticals, they would back up and insert a measurement vertical to decrease the spacing between measurement verticals. It is doubtful this would occur when measuring the discharge in larger streams with higher velocities and a more uniform streambed. The location of verticals sometimes shifted, particularly at the Thorne Springs measurement section. This often resulted in two successive discharge measurements with different sets of measurement verticals, defined by the stream gager at the time of the discharge measurement. The effective area, which is the area in the measurement section resulting in velocity measurement, was fairly consistent between stream gagers. Table 3.1 presents the number of verticals used for each current meter at each site.

The proper current meter should be chosen for the given section to be measured. When wading a section, the Price-AA or pygmy meter is used for measuring the velocity in the verticals (Rantz et al., 1982). The pygmy meter is suitable for depths up to 2.5 feet, and the type AA meter can be used in water depths of 1.5 feet and deeper. These Price-type meters are the only current meters mentioned in this section of the procedures, neglecting all other types of current meters. Rantz and others (1982) do not include other current meters in their tables intended to aid the user in

Table 3.1 – Number of verticals and velocity measurements by various current meters at the Crab Creek and Thorne Springs Branch watersheds.

	MEASUREMENT METHOD			
Watershed	Price-AA	Pygmy	Valeport	Marsh McBirney
Crab Creek	5-26, 8-4* (30)**	5-20, 6-1, 7-2, 8-3, 9-4 (30)	5-6, 6-18, 7-6, (30)	8-11, 9-9, 10-8, 11-2, 12-1, 13-3, 14-1, (35)
Thorne Springs Branch	0-1, 1-2, 2-3, 3-5, 4-1, 6-11, 7-1, 8-2, 9-3, 10-1, (30)	0-1, 1-1, 2-2, 3-5, 4-8, 5-1, 6-2, 8-3, 9-1, 10-4, 11-2, (30)	4-1, 5-3, 6-7, 7-5, 8-6, 9-6, 10-2, (30)	9-2, 11-2, 12-1, 13-2, 14-1, 16-1, 17-2, 18-2, 19-5, 20-3, 21-3, 22-1, 23-2, 24-4, 26-2, (33)

* The numbers indicate the number of measurement verticals where flow velocity was detected and the number of discharge measurements that resulted in that number of verticals (e.g. 8-4 indicates there were 8 verticals used in 4 discharge measurements for this meter).
** The total number of discharge measurements for a given method in parentheses.

choosing a current meter for a given flow depth and velocity condition. Neither of these current meters should be used to measure velocities slower than 0.2 ft/s, unless the measurement is unavoidable (Rantz et al., 1982).

Prior to beginning the discharge measurement at each station, the equipment was tested to ensure proper operation and adjustments were made as necessary. Testing and normal adjustments included:

- Mechanical current meters were field spin tested;
- Meter type and measurement time were adjusted on Aquacount device;
- Aquacount/current meter circuit was tested;
- Flow probe was set for average velocity; and
- Batteries were checked in Marsh McBirney current meter.

When field spin testing the pygmy current meter, the cup assembly was spun and protected from the wind. The cups were required to spin for at least 40 seconds to indicate proper meter performance. An Aquacount device was used with the Price-type current meters for counting revolutions (Price-AA) and calculating velocity (pygmy only). The circuit connecting the Price type current meter and the Aquacount device was checked and Aquacount device settings were adjusted as required. Settings adjusted included meter type and measurement time. The Marsh McBirney current meter used four sets of batteries during the field study, so the batteries were checked prior to each use by simply turning the device on and observing the "low battery" indicator.

A standard form for collection of current meter discharge measurement data was created based on the data sheet used by the USGS. The list of data included in the data sheet was modified to meet the needs of this study. A sample data sheet is included in Appendix A. The stream gager had to fill out the data sheet top sections prior to wading into the stream and beginning the measurement. The top portion of the sheet includes:

- site name,
- date,
- operator,
- current meter,
- stream condition – refers to the stream bed condition,
- serial number of the current meter,
- water and air temperatures – measured with a temperature probe,
- flow condition – refers to the state of the flow at the time of the discharge measurement,
- weather conditions,
- gage heights with corresponding times – recorded before and after each discharge measurement, and
- other relevant notes and remarks.

The stream gager was then ready to measure area and velocity. An appropriate method of estimating the average velocity in the vertical must be determined. The 0.6-depth method is recommended for depths up to 2.5 feet. The two-point method is recommended for depths greater than 2.5 feet.

The 0.6-depth method uses the velocity measured at 60% of the total depth from the water surface to estimate the average velocity in the observation vertical. Rantz et al. (1982) state that the pygmy meter should not be used with the 0.6-depth method to measure velocity in depths less than 0.75 feet. They also recognize the practical necessity to measure such flows.

The two-point method requires the measurement of velocity at 20% and 80% of the total depth from the water surface. The average of these two represents the mean velocity in the vertical. This method should not be used with price type meters when the depth is less than 2.5 feet since the meter would then be too close to the streambed (Rantz et al., 1982).

Another method that was used in the field component of this study was the 0.2-depth method. In this method, the velocity is measured at 20% of the depth from the surface only. The relation between the mean velocity and velocity at 0.2-depth can vary with depth and discharge. If sufficient historical data using the two-point method are available, this relation can be defined. However, without the historical data, a standard velocity profile must be assumed and a coefficient of 0.871 applied to the 0.2-depth velocity (Rantz et al., 1982). This method is not as reliable as either the 0.6-depth or two-point methods if flow conditions (velocity, depth, etc.) are equally favorable for all the methods (Rantz et al., 1982).

For each measurement vertical, the stream gager recorded the following:

- distance from the zero (stream bank),
- the measured depth, and
- observation depth.

The zero, which refers to the stream bank the stream gager began the discharge measurement with, was also recorded on the data sheet. The stream bank is designated as either LEW or REW, which indicates the left edge of water or right edge of water when facing downstream. The time is to be recorded in the notes while taking the measurement periodically. At the end of the measurement, the time and the stream bank the measurement is finished are recorded as well. The measured depth was the actual water depth measured at the given vertical.

The observation depth refers to the method of velocity measurement, whether it was 0.2-depth, 0.6-depth, or some other method. For each station, the method of velocity measurement was determined. The 0.6-depth method was used for the majority of the current meter measurements. The exception to this was the use of the pygmy current meter at Thorne Springs Branch gaging station. In this case, the flow velocities were very slow (.15 ft/s and less) at the 0.6-depth, thus the 0.2-depth method was employed.

For measuring velocity by the current meter at a given vertical, the device was given a minimum of three seconds to adjust to the water velocity present at the designated depth. The device was then operated for at least 40 seconds to obtain a velocity at the point of measurement and filter out potential surges in current velocity.

When measuring velocity in an observation vertical, the stream gager should stand in a position that minimizes the effect of their presence on the velocity of the water as it passes the current meter (Rantz et al., 1982). This can be achieved by standing facing the stream bank, about 3 inches from the tag line and 1.5 feet from the wading rod. The wading rod is held plumb against the tag line.

The pygmy meter, attached to the Aquacount device, automatically began counting time at the occurrence of a "click" (zero revolution) and finished counting time on a "click". The rating of the meter was already programmed into the Aquacount device, so the result was a velocity reading and not revolutions and time. The Price-AA current meter, also connected to the Aquacount device, was used in the same manner as the pygmy meter. However, since the rating of the meter was not programmed into the Aquacount, the number of revolutions and elapsed time were recorded, which had to be converted to velocity using the rating table that accompanied the current meter. The Marsh-McBirney Flo-Mate Model 2000 electromagnetic current meter sensor was mounted on the USGS top set rod and connected to the control unit. Upon operation of the current meter, the velocity for the point depth measurement was displayed by the control unit. The Valeport BFM001 current meter was used with the wading rod that accompanied it. The measurement depth had to be manually calculated when using this rod and the depth of the current meter had to be adjusted by hand. The current meter was connected to the unit's control unit. The controls were set to count revolutions for 50 seconds, though the elapsed time was required to stop on a "click". By stopping the elapsed time on a click, the time can be recorded that elapsed during a whole number of revolutions. The revolutions and elapsed time were recorded after each velocity measurement.

These procedures produce data in the form of velocities or revolutions and elapsed times. For analysis and comparison, data were converted to discharge values. This was accomplished using the calculations described in Chapter 2. At least 30 discharge estimations were performed with each device at each of the two field investigation sites to provide an adequate sample of data for statistical analyses (Steeno, 1999).

In this study, the area represented was defined using the midpoint method, where the vertical is considered the center of a partial area of discharge. The average value of velocity in the vertical is adequately represented by the velocity at the 0.6 depth from the surface (Pierce, 1941). The same is true for the velocity measured at the alternate depths, such as the 0.2 depth, when multiplied by the correction factor which relates that velocity to the average velocity in the partial area (Rantz et al., 1982).

Operation of the Marsh McBirney current meter to make a stream flow discharge measurement is described in the User's Manual, and does not always agree with the procedures outlined by Rantz and others (1982). When Fulford and others (1994) used the electromagnetic current meter in their study, it was used just like any other current meter, which was the approach used in this study. The procedures recommended by the USGS, as outlined previously in this chapter, were followed. The sensor is easily mounted on a USGS top set rod. The 0.6-depth method was employed for water depths up to 2.5 feet as with the mechanical current meters, and the measurement period used was 40 seconds.

Use of the Global Flow Probe in the Field Investigations:

The Global Water flow probe FP101 was also used to estimate discharge at each of the sites in this study (Global Water, 1997). At Thorne Springs Branch, the flow probe was used to estimate discharge upstream of the dam, in a section of the stream with faster flow. This was necessary because the flow velocity in the current meter measurement section was too low to measure with the flow probe. The flow probe was operated in measurement section 1 at Crab Creek (Figure 3.2).

The manufacturer's guidelines for use of this device in small streams were followed to estimate discharge (Global Water, 1997). This involves measuring the area of the measurement section, then operating the flow probe throughout the section to obtain an average flow velocity for the section. The flow discharge is estimated as the product of the average velocity and cross-sectional area. The cross section of interest was measured using a USGS top set rod and tag line as describe for use with the current meters. Dead areas at the LEW and REW were omitted from the area calculation. After the area was estimated, the probe was placed in the stream and moved throughout the cross section back and forth and up and down. This process was continued for at least 40 seconds until a steady velocity was recorded. The resulting average velocity was recorded and multiplied by the section area to obtain a discharge estimate. The flow probe was used to estimate the discharge at least 30 times at each field investigation site.

The stated accuracy of the flow probe is $\pm$ 0.1 fps for an average velocity measurement, and 0.5 for an instantaneous velocity measurement (Global Water, 1997). It should be noted that some difficulty was encountered operating the flow probe. The device did not operate in relatively slow flow velocity, and appeared to only calculate an average velocity when the propeller was spinning. This results in an overestimation of the average flow velocity.

Implementing the One Orange Method in the Field Investigations:

The method described in Chapter 2 was followed for the One-Orange method. An orange was obtained from a local grocer for use in the study. The actual density and size of the orange was ignored since this point was not addressed in the method (Christensen, 1994). At Crab Creek, measurement section 2 was used as a starting point for the measurements and a second parallel line was established 16 ft downstream of section 2. One person was posted at the second line and one person performed the measurements while releasing the orange. The orange was held to the bottom of the stream at the deepest vertical in the section. The orange was released and the time and horizontal distance of travel were measured and recorded. The orange was then allowed to continue travelling downstream to reach the second line. The total elapsed time of travel to the downstream section was recorded. The method was performed 30 times to yield 30 discharge estimates for analysis.

Since the distance between the first and second lines was known, the second distance traveled was just the total distance between lines less the first distance recorded after emergence of the orange. The maximum velocity, mean velocity, and discharge were then derived as described in Chapter 2.

Use of Acoustic Doppler Devices in the Field Investigations:

The Isco standard range sensor and Starflow 6526B were the two types of acoustic Doppler ultrasonic flow measurement devices used in this study (Isco, 1993; Unidata, 1995). These devices require no calibration prior to installation such as that required for the pressure transducers. The only calibration required is the determination of the vertical offset during installation of the device. The offset is the vertical distance from a predetermined reference.

Prior to installation, the measurement section had to be selected just as with the current meters. The attributes of a suitable measurement site were discussed in Chapter 2. Section 4, as shown in Figure 3.2, was used as the ultrasonic Doppler device measurement section at the Crab Creek gaging station. Similarly, the alternate section, shown in Figure 3.4, was utilized for these devices. In each of these installations, the device was mounted in the stream facing upstream.

Special mounting plates were fabricated to facilitate the mounting of the Isco and Starflow acoustic Doppler devices. The mounting plates consisted of a 1/8" steel plate with a steel spike welded to the bottom. The steel spike was mounted perpendicular to the steel plate and was made of a sharpened section of 1/2" rebar. The hole pattern for the Starflow mounting plate was transferred to the new mounting plate and tapped for easy attachment of the Starflow device. No such hole pattern or factory mounting plate was provided with the Isco device, so other means were necessary to attach this sensor to the mounting plate. A piece of industrial Velcro was affixed to the Isco sensor and the mounting plate. To stabilize the device, a Velcro strap was stretched over the top of the sensor and attached to brackets on either side of the sensor. A hole was drilled in one corner of the steel plate to allow the insertion of a spike into the streambed after plate installation. The purpose of the spike was to prevent rotation of the plate after installation.

The mounting plate was installed in the stream prior to installation of the sensor. After the mounting plate was installed in the chosen measurement section, the section was surveyed in horizontal increments of 0.25' each. The data obtained in this survey were used to develop a relationship between stage and cross-sectional area, as required by each device.

The survey data were transformed to develop a table of distance/reduced level pairs file for use with the Starflow device. This file consists of pairs of coordinates describing the geometry of the cross section. Each pair of values represents a horizontal and vertical displacement from some arbitrary origin. The origin should be a point located above the highest anticipated water level at one bank of the stream.

The Isco device requires a file with pairs of elevations and corresponding cross-sectional areas. This file may contain up to 50 pairs of data. The file describing section 3 at Crab Creek contained 24 pairs of data with a vertical resolution of .025' (0.3"). For the alternate section of the Thorne Springs Branch gaging station, the file contained 32 pairs of data with the same resolution. These data were determined using the survey data in a computer-aided design (CAD) package. The measurement section was drawn, then trimmed to the horizontal line which represented a given elevation. An example of a cross section and the vertical trimming scale can be seen in Figure 3.5. The stream cross-section is trimmed on the right to provide detail of the vertical trimming scale. The bottom line of the scale represents the elevation of the mounting plate, and each line above that represents an incremental elevation.

Only one sensor at a time was used in the stream to prevent the possibility of interference between devices. The Isco device was attached to the mounting plate in the stream and connected to the model 4150 Flow Logger (Isco, 1995). The flow logger was then connected to a laptop computer. The Flowlink software was used to interface with the 4150 Flow Logger (Isco, 1995). The appropriate file was used to provide the stage/area information for the particular site. The field calibration that was previously discussed was performed using the following procedure. The water depth above the sensor was measured using a 1 mm resolution ruler. Then, the offset was adjusted to match the depth as measured manually. This iterative process was repeated until the depth displayed in the Flowlink software matched the measured depth.

Once calibrated, the acoustic Doppler device was allowed to operate and collect data for at least 1.5 hours. During this observation time, the device was monitored continuously and a sample of 30 random discharge readings was recorded on a data sheet. The data sheet used to collect current meter data was modified in the field for use with the acoustic Doppler devices. The only difference in the use of the data sheet was the discharge measurement data recorded. In this instance, only stage and discharge were noted for future analysis. The stream discharges corresponding to the recorded gage heights were paired with the measured discharges for analysis.

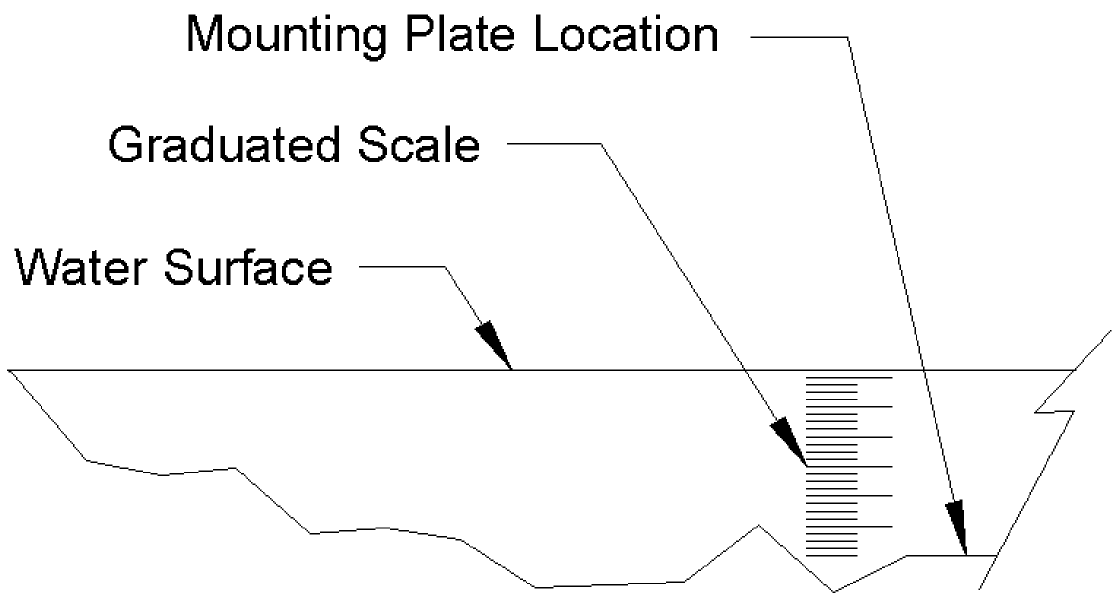


Figure 3.5 – Ultrasonic Doppler measurement section with vertical increments shown.

Performance of the Dilution Technique in the Field Investigations:

An overview of the recommended procedure for implementation of the dilution technique was provided in Chapter 2. This section will explain the detail of how this procedure was used in this study.

Prior to initiating the discharge measurements, the fluorometer had to be configured and calibrated. The Turner model 111 fluorometer was equipped with a U-type ultraviolet lamp, which is needed when using rhodamine WT. The excitation (primary) filter selected was a 546 nm filter. The emission (secondary) filter combination consisted of a 325-700 nm band pass filter in conjunction with a >570 nm sharp cut filter. This filter combination was chosen specifically for use with rhodamine WT, while the lamp is appropriate for a broad range of fluorometric analyses.

Kilpatrick and Cobb (1985) recommend the performance of a calibration for each lot of dye used in dilution experiments. This calibration does not have to be performed prior to analysis of the samples from the dilution experiment, but doing so gives the investigator some insight into which fluorometer scale to use when analyzing samples. Standards must be prepared for fluorometer calibration, and convenient tables are available for dilution of the tracer to standard concentrations. Standards are solutions containing known concentrations of the dye tracer used in the dilution study. These standards represent the full range of potential dye concentrations contained in samples collected in the study. With the standards prepared, Kilpatrick and Cobb (1985) provide the following guidelines when calibrating a fluorometer:

- Allow all samples to reach a common temperature to eliminate the necessity to measure sample temperature.
- Allow the fluorometer to sufficiently warm up, which can range from 10 minutes to 2 hours.
- Analyze all the standards in the fluorometer using the same cuvette and temperature.
- Plot the calibration results on rectilinear paper. After plotting, reconcile any data points that do not fit the curve by reanalyzing a fresh sample of the given standard or preparation and analysis of a fresh standard.

The first step in calibration of the fluorometer was to set the device to a zero reading. A cuvette of distilled water was used as a blank to set the zero, as it contains no compounds that would exhibit fluorescence. The cuvette of distilled water was placed in the sample holder and the door was shut. The zero adjust knob was turned until the dial read zero fluorescence, then secured in position with adhesive tape. To calibrate the fluorometer, standards had to be prepared by serial dilution as described in the USGS guidelines (Wilson et al., 1986). Starting with the rhodamine WT 20% solution, two dilutions were performed to yield a 100 μg/l concentration working solution. From this working solution, standards were prepared by dilution with concentrations of 1, 2, 4, 6, 10, 15, 20, 25, and 50 μg/l. The result was a set of standards ranging in dye concentration from 1 μg/l to 100μg/l, including the working solution. Cuvettes containing samples of each standard solution were placed in the fluorometer at each sensitivity setting as needed, and the fluorescence of the sample was read on the dial and recorded. Some concentrations were off scale for a given sensitivity and thus were not used for calibration at that sensitivity. The fluorescence and concentrations of the samples at the 1X, 3X, and 10X sensitivity settings were entered into a spreadsheet. A spreadsheet statistical package was used to perform a regression of fluorescence to dye concentration. The results of the regression were used to develop equations to define the calibration curve of each sensitivity setting for use in the analysis of samples. The results of the calibration are included in Appendix A.

The first step in the process of determining discharge using the dilution technique is to select the measurement reach. As with the measurement section selected for current meter discharge measurements, the reach should be close enough to the gaging station so that there is no inflow or outflow between the two (Kilpatrick and Cobb, 1985). Dead areas in the reach should be minimized to prevent elongation of the tracer cloud. The ideal mixing reaches have sections that are narrow and deep, not shallow fast-moving flow. At the Crab Creek gaging station, the area above the riffle was chosen. This section of the stream is close to the gaging station, and is relatively devoid of shallow fast-moving flow. At the Thorne Springs Branch gaging station, it was decided the section of stream above the dam would be used for the dilution technique. The relatively shallow and fast-moving water in this section was not ideal for application of this method and made it necessary to use a relatively long reach length. However, the stream section below the dam was even less suitable given the large pool and split flow past the first culvert. Though this section of Thorne Springs Branch was shallow and quick-flowing, it did contain some constrictions that aid the mixing of the dye. The selected reach is located in a pasture, which facilitates the long mixing reach length necessary for the section.

Kilpatrick and Cobb (1985) adapted the following relationship proposed by Yotsukura and Cobb (1972) to calculate the optimum reach length:

$$L_o = 0.088 \frac{vB^2}{d^{3/2} s^{1/2}} \quad (3.1)$$

Where:

L_o = optimum mixing length, in ft,

v = mean stream velocity, in fps,

B = average stream width, in ft,

d = average depth of stream, in ft, and

s = water surface slope, in ft/ft.

The mean stream velocity and average depth of the stream sections were determined using data from the current meter studies at the sites. The average stream width and water surface slope were determined, separately. The average stream width was found by simply measuring the stream width at two representative points in the reach and averaging them. The water surface slope was determined by finding the elevation difference at two points along the reach and dividing it by the distance between them. The values of L_o at Crab Creek and Thorne Springs Branch were 65 feet and 175 feet, respectively.

The amount of rhodamine WT 20% solution to be used in the injection at each site had to be determined. The procedures outlined by Kilpatrick and Cobb (1985) dictate the use of a 20% solution of rhodamine WT tracer dye as a basis for preparing the solution to be injected into the stream. They also provide an equation to determine the amount of the dye required to prepare the injection solution:

$$V_s = 3.79x10^{-5} \frac{QL}{v} C_p \quad (3.2)$$

Where:

V_s = volume of rhodamine WT 20% solution, in ml,

Q = stream discharge, in cfs,

L = measurement reach length, in ft.,

v = average stream velocity, in fps, and

C_p = desired peak concentration at sampling section, in μg/l.

The recommended peak concentration of rhodamine WT at the sampling section is 10 to 20 μg/l (Kilpatrick and Cobb, 1985).

At first, an attempt was made to use Figure 4 presented by Kilpatrick and Cobb (1985), but the small size and relatively low discharge of the streams used in this study resulted in a QL/v value too low for this procedure. Figure 4 is a graphical solution of Equation 3.2, and relates the volume of 20% rhodamine WT solution used to the estimated stream discharge, average stream velocity, and measurement reach length. Instead, Equation 3.2 was used to determine the amount of rhodamine WT 20% solution to be used. The discharge value was estimated using the rating values for the current flow conditions at each site. The desired peak concentration chosen for this study was 20 μg/l to maximize the resulting dye volume, V_s. The resulting volumes of rhodamine WT 20% solution to be injected into the stream at Crab Creek and Thorne Springs Branch were 0.14 ml and 0.47 ml, respectively.

When conducting the dilution discharge measurements at the sites, the first step in the procedure was to sample the stream water at the sampling sections. This is done to account for any background fluorescence in the stream, and is performed prior to touching the dye so there is no chance of contaminating the samples.

The injection solution is prepared by extracting about 10 liters of stream water, measuring the calculated volume of rhodamine WT 20%, and mixing the two. Using a graduated cylinder, the operator carefully measured 10 L of stream water into a large container; a 5 gal. bucket in this case. The dye was measured using a 1 ml pipette and was added to the water in the bucket. The amount of dye actually used did not always exactly match the calculated amount due to the method used to measure and dispense it, so the actual dye volume was recorded. The actual amount of dye used did not vary from the calculated volume by more than 0.05 ml, except when the volume was reduced in an attempt to lower the peak measured concentration. The solution was thoroughly mixed, and a sample of 60 ml was collected for future reference. The 60 ml extracted was also noted as this slightly reduced the amount of solution injected into the stream.

The previously designated reach lengths were measured and marked on the stream bank using stakes. The injection solution was poured into the stream at the upstream end of the designated reach. The solution was poured in the approximate centroid of flow in one slug. The time at which the solution was poured into the stream was recorded, and all sampling times were recorded relative to this time.

Once the dye solution has been injected into the stream, personnel at the sampling section should be ready to sample. The dye cloud was visible in the stream, which aided the hydrographers in determining the sampling rate during the experiment. As the dye cloud approached the sampling section, sampling began in order to ensure the complete recovery of the tracer. Samples were collected in translucent 20 ml vials to provide a sufficiently large sample with room for sediment to settle, if necessary. About 12 or 13 samples per sampling point are to be collected, with the sampling interval larger at the tails of the cloud and smaller toward the peak. The sampling was performed at three points across the measurement section representing approximately one-third of the discharge in the stream. Two people are recommended to sample the stream as the cloud passes (Kilpatrick and Cobb, 1985). One person was located in the stream just downstream of the sampling section to collect the samples. At least one other person was stationed on the adjacent stream bank to label the samples and record the time at which each sample was collected. Samples were collected at three points in the stream cross-section, representing the center of approximately one-third of the discharge. The sampling proceeded in the same order with each round of samples, starting with the left partial section and moving to the right. Samples were collected very frequently (1 sample every 5 seconds) until the peak of the dye cloud had passed. The high sampling frequency was used to make sure the peak concentration of the tracer cloud at each of the sections was measured. After the peak of the dye cloud had passed, sampling frequency was reduced to about 1 sample every 10-20 seconds. Once the dye concentration in the stream was reduced, the time interval between samples was increased to about 25-45 seconds. Sampling continued after the peak of the dye cloud passed for a period of about 2-3 times the time it took the peak to arrive at the sampling section. This ensured the total recovery of the dye by fully accounting for the low concentrations of the concentration-time curve. Once all the samples were collected, the tray of samples was placed in a covered box to prevent exposure to sunlight, which may degrade the fluorescent dye.

The samples were transported in covered boxes to the Land and Water Resources Laboratory at Virginia Tech, to prevent degradation of the dye in the sample. Once the samples were in the laboratory, they were allowed to reach room temperature. This practice made it unnecessary to account for temperature differences in samples since all samples were analyzed at the same temperature. Prior to analysis, the fluorometer was started and allowed to run for 2 hours to stabilize the lamp. The cuvette was filled with the desired sample. After filling, any excess liquid was wiped from the cuvette and it was placed in the sample holder in the door of the fluorometer. The door was closed and the dial was read and recorded when it stopped advancing. Any additional movement of the dial after initially stopping was ignored. If the sample exhibited more fluorescence than the dial allowed (off scale), the sensitivity was adjusted down to accommodate the sample. The dial reading was recorded for each sample along with the sensitivity setting used in the analysis.

After analyzing the samples for a given discharge measurement, the resulting elapsed times and florescence readings were recorded. The fluorescence readings were converted to dye concentrations using the calibration equations derived previously. The dye concentrations for each of the three points were plotted against elapsed time, resulting in time-concentration curves. Figure 3.6 displays the time-concentration curves for dilution run 3 at Crab Creek., where sections 1-3 represent the three sampling points. The mean area under the three time-concentrations must then be determined to calculate stream discharge.

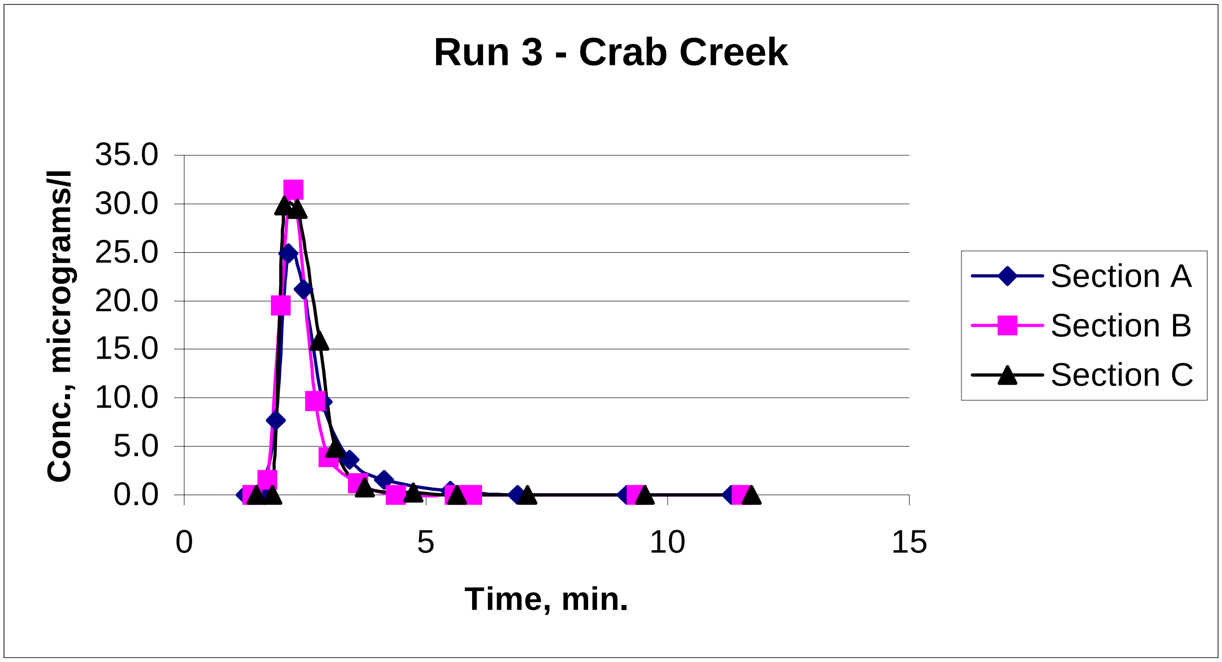


Figure 3.6 - Time-concentration curves for three points in dilution run 3 at Crab Creek.

The trapezoid method of integration was used to find the area under each of the time-concentration curves representing the three sections used in sampling the stream (Chapra and Canale, 1988). The incremental areas under the curve are calculate using:

$$I = (b - a)\frac{f(a) + f(b)}{2} \tag{3.3}$$

Where: I = the incremental area under the curve

a, b = x-coordinates comprising the left and right edges of the trapezoid

$f(a)$ = y-coordinates corresponding to a

$f(b)$ = y-coordinates corresponding to b

The incremental areas were summed to find the area under the response curve for each section of the stream. The mean of the areas under the curves was calculated for each measurement. The average area under the response curves was used with the dye concentration, volume, and specific gravity to calculate the discharge using Equation 2.18.

Use of Pressure Transducers in the Field Investigations:

A pressure transducer was used at each site to compare the accuracy of the flow depth measurements with those obtained with an FW-1 stage recorder equipped with a potentiometer. Prior to being placed in the field, the pressure transducer, FW-1, and potentiometer were all calibrated in the laboratory using a water level test stand. The pressure transducer and potentiometer were each connected to a Campbell CR-10 datalogger, which was programmed to measure the relevant parameters associated with each device. The devices were installed in the test stand in the same fashion they are used in the field. The water level was increased in random increments to obtain corresponding voltage or resistance values for the potentiometer and transducer, respectively. The water level was read from two manometers installed on either side of the test stand as shown in Figure 3.7. The two water level readings were averaged when processing the data for regression analysis. A regression analysis was performed between the resistance or voltage values and the water depths to obtain a transformation equation. This equation was used in the programming of the datalogger to transform device readings to water level values.

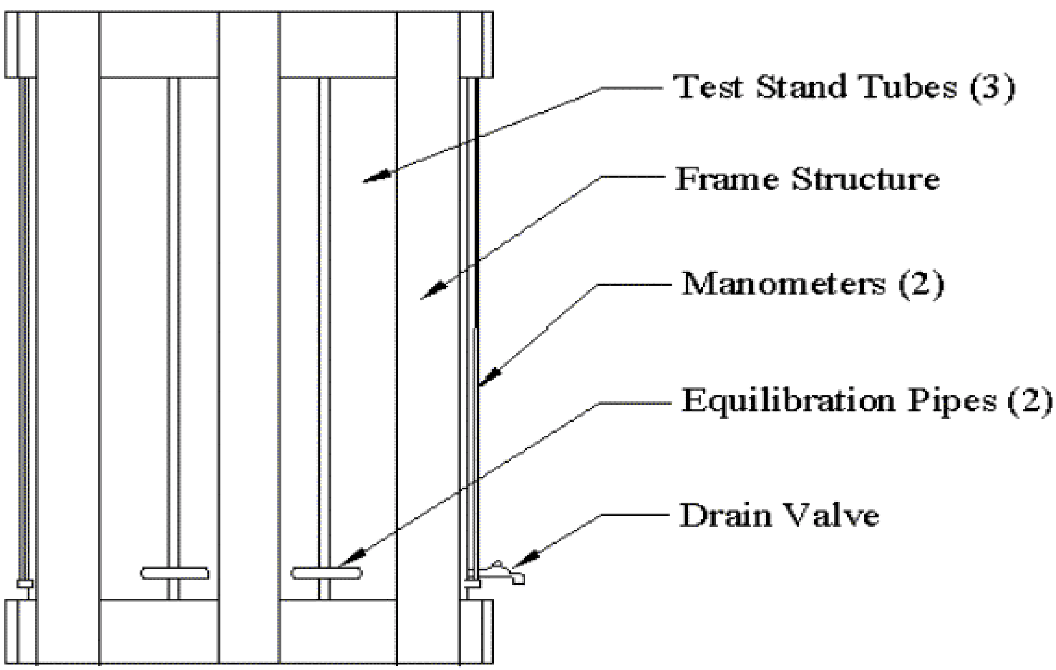


Figure 3.7 - Stage test stand used to calibrate the pressure transducer, potentiometer, and FW-1.

Two pressure transducers were installed at the Crab creek site. One transducer was placed directly in the stream adjacent to the stilling well, and the other transducer was lowered into the stilling well. The reason for using two transducers was to evaluate the effects of the stilling well in damping the change in water level. The first transducer was attached to a stream mounting plate identical to the one described for mounting the acoustic Doppler devices. A stainless steel shroud was fabricated to protect each of the pressure transducers while in service. The shroud also allowed for easy mounting to the plate by just drilling a hole in the shroud and attaching the shroud and transducer assembly to the plate with a screw. The second transducer was placed in the stilling well at the gaging station. A small cable was attached to the shroud, and the transducer was lowered into the stilling well. The stable placement of the transducer was confirmed by observing the device through an access door located in the lower end of the stilling well.

Only one pressure transducer was installed at the Thorne Springs Branch gaging station, since sediment accumulation prevented the installation of a transducer in the stream above the weir. The pressure transducer was installed in the stilling well as described for the Crab Creek gaging station.

Once the transducers were mounted in the stream and/or the stilling well, the devices were connected to the Campbell 21X datalogger located in the instrument shelter at the top of the stilling well. The potentiometer attached to the FW-1 stage recorder was also connected to the datalogger. After installation, each of these devices was field calibrated to match the stage reading of the staff gage. This was done by reading the staff gage, adjusting the intercept value in the respective transformation equations, and comparing the resulting value to the staff gage value. This process was repeated until the stage value for each device matched the staff gage reading.

The stage data were automatically recorded by the datalogger for at least a week. Data were downloaded using the PC208W software designed to interface with the Campbell dataloggers (Campbell, 1996). Since the data were already in the form of stage for each device, a sample of

30 data points was randomly extracted from the collected data for comparison. When comparing the data statistically, stage values obtained with the pressure transducers were compared to those obtained with the potentiometer attached to the FW-1 since the potentiometer was considered the standard.

Laboratory Methods:

While field investigations provide a more realistic setting for evaluating the various methods of stream flow measurement, they also expose these methods to rapidly changing velocities and flow angles. Laboratory experiments are necessary to assess the performance of all the methods under nearly identical flow conditions. All the methods evaluated in the field investigations were also studied in laboratory experiments, except for the tracer dilution method.

The laboratory trials were conducted in the Soil and Water Resources Laboratory at Virginia Tech. All devices were evaluated in a 1-foot hydraulic flume. As a control for comparison, a thin plate v-notch weir was installed at the far end of the flume to measure discharge. A point gage was used to measure the water depth in the flume during the experiment. The point gage was mounted on a bracket fabricated to fit the flume. For a given measurement section, the elevations of the water surface and the bottom of the flume were measured with the point gage. The difference between these two measurements represented the water depth at that section.

The pressure transducer, Isco acoustic doppler flow meter, and Starflow acoustic doppler flow meter were all installed in the flume using 6" x 6" steel plates fabricated for that purpose. Three positions for these devices were determined to avoid interference of one device with another as shown in Figure 3.8. The order of the placement of these devices in these positions was randomized. The section used to measure discharge in the flume with current meters is also shown in Figure 3.8. The starting and finishing points used for the one-orange method in the flume are also indicated.

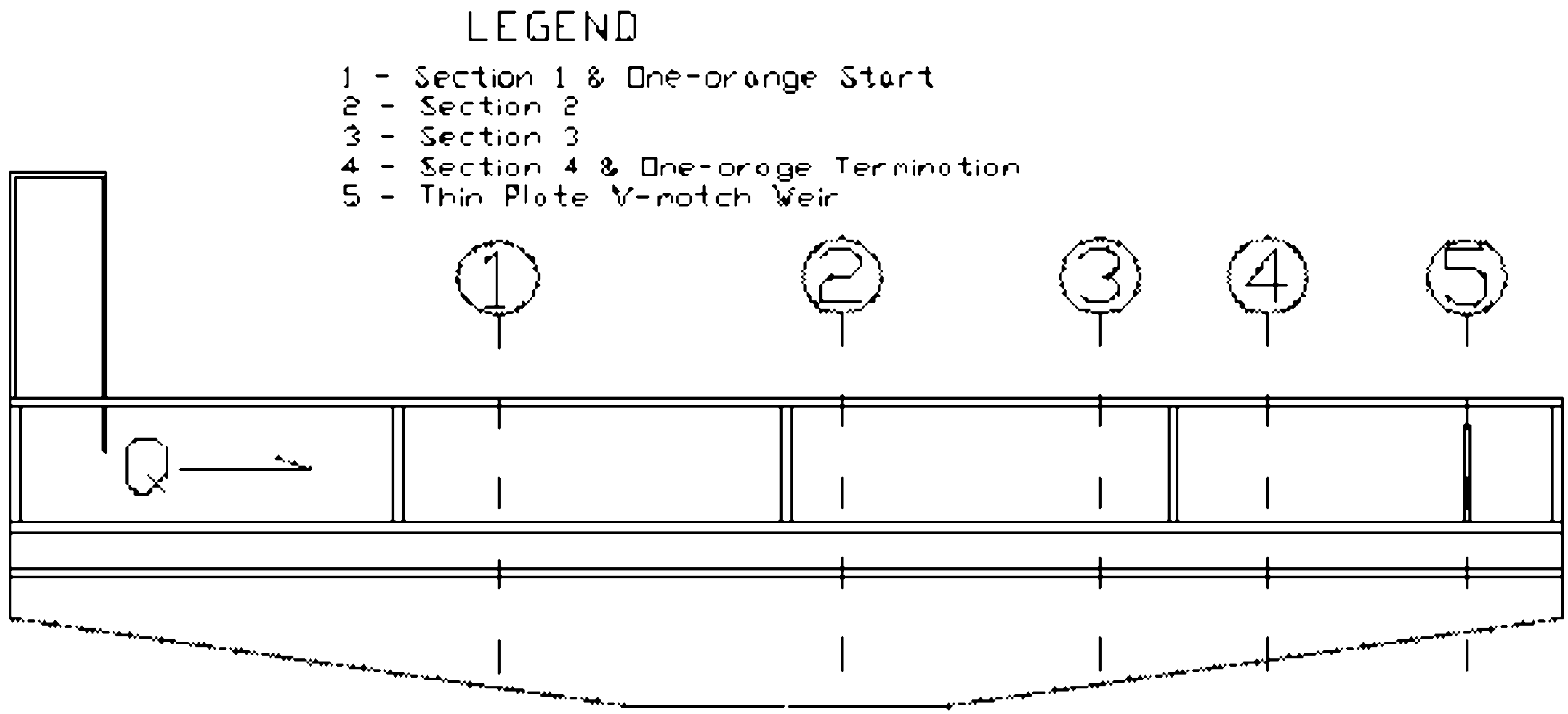


Figure 3.8 – Sketch of hydraulic flume with measurement sections.

The Statistical Consulting Center at Virginia Tech was contacted to aid in the design of the laboratory experiment. The experimental design dictated that the flume be set at a given discharge. The discharge in the flume was allowed to stabilize for about two minutes prior to any discharge measurements. After the flow had stabilized, each of the methods was employed to determine the discharge. The order in which the devices were used to measure the discharge in the flume was random. Three discharge readings were recorded for each device, and the mean of these three discharge values was used in the analysis. Only one method was used at a time to prevent the possibility of interference among them. The flow in the flume was increased at random increments fourteen times using the pump control valves until the maximum discharge of the flume was achieved. A total of fifteen discharge values, and thus mean discharge values for each method were recorded while increasing the flow rate. The process described for discharge stabilization and collection of discharge measurements was repeated at each discharge. After the maximum discharge of the flume was achieved and discharge values were recorded for each method, the discharge rate in the flume was decreased by random increments. This process was repeated for another fifteen data points until the discharge in the flume was zero cfs. The total of 30 discharge values used in the analysis included the no flow condition.

Use of Current Meters in the Laboratory Experiment:

When using current meters in the flume, the stage was determined using the point gage as previously described. The data collected for each current meter at each discharge value in the flume included:

- Three velocity measurements, or three sets of revolutions and elapsed times
- Water depth at the measurement section

The current meters were mounted on wading rods as in the field studies. The 0.6-depth method was used to determine the mean velocity in the middle of the flume, and the velocity was recorded three times for each current meter. The Aquacount device was again used with the

Price AA and pygmy current meters to count revolutions and determine velocity, respectively. The current meters averaged the velocity over a minimum 40-second period.

The front control panel of the Flo-mate model 2000 was used to interface with the electromagnetic flow sensor when using the Marsh McBirney current meter. The sensor was mounted on a USGS top set rod, and set at 60% of the water depth from the water surface. The top set rod was set in the middle of the flume at the measurement section.

When using the Valeport current meter, the control unit was used to count the number of revolutions in an elapsed time with a minimum of 50 seconds. The impeller was mounted on the accompanying wading rod, and adjusted to the 0.6-depth as described for the other current meters to measure the velocity in the middle of the flume.

Performance of the One-orange Method in the Laboratory Experiment:

To use the One-orange method for measuring the discharge rate in the flume, the following data were recorded:

- Elapsed time for the orange to emerge, T_1
- Horizontal displacement to emerge, X_1
- Elapsed time to travel a total distance, T_2
- The total distance traveled, X_2

The starting and termination sections for use in this method are indicated in Figure 3.8.
The orange was held on the bottom of the flume, then released. Upon emergence, T_1 and X_1 were measured, then the orange was permitted to continue its travel in the flume. When the orange reached the terminal section, T_2 and X_2 were recorded. This process was repeated three times to acquire three velocity values which were averaged for the analysis.

Use of the Pressure Transducer in the Laboratory Experiment:

The pressure transducer was mounted at the bottom of the flume and connected to a Campbell 21X datalogger. The program used in the field studies was used with the datalogger to measure the transducer signal and transform it to a stage measurement. The transducer was calibrated in the flume by adjusting the intercept value in the transformation equation in the program. The transducer was used to only measure stage in the flume, and the data recorded for the transducer included the transformed stage and water depth, which was determined manually with a 1-millimeter resolution measuring rod.

Use of Acoustic Doppler Devices in the Laboratory Experiment:

The two acoustic Doppler instruments were mounted in the flume as previously described. The Starflow instrument was connected to a notebook computer running the accompanying software to record the discharge readings from the device. The Isco acoustic doppler device was connected to the Isco datalogger, which was connected to a notebook computer. The Flowlink software, which is used with the Isco device, was also used to monitor the discharge readings from the device. The programs for each of these devices can be seen in Appendix A.

Data Reduction:

During the field and laboratory experiments, either velocity (rev./s or fps) or discharge (cfs) data were collected. The method of transforming these data to the form of a discharge varied depending on the discharge estimation method used. This section describes the techniques used to transform the raw data into stream flow discharge data. Also included in this section are the sources of control discharge data and methods used to interpret the weir ratings. All stream flow discharge data are included in Appendix B.

The midpoint method was used with all current meter data for calculation of discharge. This method was discussed in detail at the beginning of this chapter, so only the conversion of raw current meter data to velocity values is discussed here. To facilitate the storage and manipulation of the data, a spreadsheet program was used to construct databases.

The data directly collected by use of the Price AA current meter were rotational velocity values in rev/s. These data first were converted to velocity measurements in ft./s. The rating table accompanying the current meter was used for this purpose. A spreadsheet program was then used to calculate the incremental discharge values and sum them to obtain a cumulative discharge value for the entire stream.

A similar process was used to convert the data resulting from the use of the Valeport BFM 001 current meter. Station, revolutions, and elapsed time were recorded during the measurement. The ratio of the revolutions to elapsed time was calculated, and the resulting rotational velocity was used with the rating table for the current meter. A corresponding value of velocity was derived from the rating table in the form of m/s, which was converted to ft./s. The midpoint method was then used to calculate stream flow discharge.

The data resulting from using the Marsh McBirney and pygmy current meters were in the form of station and flow velocity. These data were converted to discharge values using the midpoint method.

Use of the Global flow probe resulted in an average flow velocity for the measurement section and a set of horizontal displacement and corresponding depth values. The horizontal displacement and depth values were converted to area using the midpoint method. As described in the User's Manual for the flow probe, the resulting area was simply multiplied by the section average velocity to yield discharge (Global Water, 1997).

The One-orange method was described at the beginning of this chapter in great detail. The calculations that yield the values used to find the values of $Q/AV_{max,o}$ are provided in that section of the Field Methods. The Figure presented by Christensen (1994), which relates the values of ω, $d_{max/k}$, and $Q/AV_{max,o}$ contains a set of curves which relate the parameters previously listed on a logarithmic scale. The figure is rather small and does not have a fine resolution, which makes it difficult to consistently interpret results from the figure. The section of the figure of interest was copied and its size increased. Lines were drawn parallel to the x-axis to allow interpolation of values between curves. These values were listed in the worksheet used for calculation of One-orange method discharge values for easy reference. With the values of $Q/AV_{max,o}$ extracted from the figure, the values of A and $V_{max,o}$ were simply multiplied by the extracted value to yield the discharge.

All the equations used to derive the discharge from the time-concentration data resulting from these experiments are contained earlier in this chapter, and in Chapter 2. Sample identifications, elapsed times, and fluorescence readings were the data resulting from the dilution experiments. The background fluorescence readings were subtracted from the raw fluorescence values, resulting in the net fluorescence. Using the linear equations resulting from the simple linear regressions used during the fluorometer calibration, the fluorescence values were converted to dye concentration values. The dye concentration values and corresponding elapsed times were plotted, forming a time-concentration curve for each of the three sampling points in the section. The trapezoidal rule was used to integrate the area under the time-concentration curve as described in the Field Methods (Chapra and Canale, 1988).

The acoustic Doppler devices yielded discharge values, along with stage and velocity values. Only the discharge and stage values were recorded during these experiments. These data required no reduction for analysis. Similarly, the data resulting from the experiments using pressure transducers yielded comparable stage data, which required no reduction or transformation for analyses.

The purpose of the experiments in this study was to compare discharge values resulting from these various methods of stream-gaging to simultaneous values obtained using a weir as a control. The field investigations compared the performance of these methods to existing broad-crested weirs that were accompanied by established ratings relating stage and discharge at the site.

The depth-discharge rating curve for the weir at the Thorne Springs Branch gaging station was in the form of an equation, which directly transformed the depth of the water over the notch of the weir to a discharge value. The gage heights at this site did not directly represent the depth of water, so the staff gage and water surface were surveyed to establish the relationship between gage height and water depth.

The depth-discharge rating curve for the Crab Creek gaging station was in the form of stage and discharge data. Like the rating chart for the Price AA current meter, this rating table only gave discharge values for certain stage values. Therefore, not all possible values of stage were listed with corresponding discharge values. To solve this problem, a transformation was performed on the data to linearize the relationship. First, the stage and discharge data covering the range of interest were plotted and examined. Since the data displayed an upward trend, a square root transformation on the discharge was performed, but a regression between the stage and the transformed discharge data resulted in a low correlation coefficient. This indicates a weak linear relationship between the independent and dependent variables in the regression (Ott, 1988). Next, a cube root transformation was used on the discharge data. The subsequent regression between the stage and transformed discharge data resulted in a correlation coefficient of 0.9998, indicating a strong positive linear relationship between the data. The regression equation was then used to complete the depth-discharge rating table.

Statistical Methods:

Statistical methods are necessary to draw any meaningful inferences about the experimental data resulting from this study. Due to the differences in variability of control flow between the field and laboratory investigations in this study, the data collected from each were analyzed differently. The analyses performed in this study encompass both established techniques used in studies that were reviewed, and procedures suggested by the Statistical Consulting Center at Virginia Tech.

Field Investigation Data Analyses:

The field investigation data were collected over a three-month period, including one month at Crab Creek and two months at Thorne Springs Branch. However, during that time period, due to a lack of significant rainfall, little variation in discharge was observed. This caused the majority of the data points to fall into a relatively narrow band of discharge range, especially the data collected at Thorne Springs Branch. For this reason, data analyses conducted on the field trial data mainly dealt with estimating the % relative error. This facilitated the comparison of the performance of the various methods to the control discharge at each site, even in this limited range of control discharge values. The % relative error was calculated as:

$$\% \text{ Relative Error} = \frac{Q_{obs} - Q_{control}}{Q_{control}} \qquad (3.2)$$

Where: Q_{obs} = observed discharge, in cfs

$Q_{control}$ = control discharge, in cfs

Descriptive statistics were also calculated for the % relative error values. These statistics included the mean, median, standard deviation, and range of the % relative error values for each stream-gaging method at each field investigation site. The mean % errors for each device at both field study sites were plotted for visual comparison. A confidence interval for the population % relative error was also included in the plot. The confidence interval for the population mean is defined as:

$$\overline{Y} \pm z_{\alpha/2}\sigma_{\overline{Y}} \qquad (3.3)$$

Where: $z_{\alpha/2}$ = value of z with a tail area of $\alpha/2$

$\sigma_{\bar{Y}}$ = sample mean standard error = $\sigma / \sqrt{n}$

The range of a sample of data is the difference between the largest and smallest values in the sample. It is used to indicate the variation of the data. It is the least useful of the indicators of variation of data, but was included due to the number of positive and negative % error values associated with some of the methods (Ott, 1988). To maximize the information that can be derived from this statistic, the minimum and maximum values were tabulated to represent the range for each method.

The standard error of estimate was calculated for each method at both field study locations. This statistic is normally used with a linear regression to indicate variation of the data from the regression equation. Since the stream-gaging methods were being compared to the weir values as a statistical control, the standard error of estimate was calculated using the gaging site rating rather than a regression equation. The standard error of estimate is defined by the following equation (Herschy, 1985):

$$S_e = \left(\frac{\sum d^2}{N - 2} \right)^{1/2} \tag{3.4}$$

Where: d = deviation of an observation from the control discharge

S_e = standard error of estimate

N = number of observations

ANOVA and Duncan’s Test:

The Statistical Consulting Center, operated by the Statistics department at Virginia Tech was utilized to investigate the use of other statistical methods to analyze the data in this study. The staff of the center suggested a one-way analysis of variance combined with Duncan's multiple range test for use with the field trial data, and an analysis of covariance to be used on the laboratory data.

The purpose of the analysis of variance is to test the equality of n population means. The same purpose could be achieved using a t-test to compare each pair of means, but this method is very laborious and could result in the possibility of falsely rejecting the equality hypothesis (Type I error) (Ott, 1988). As applied to this study, the analysis of variance is testing whether the mean % error, and consequently the accuracy, of all the methods tested are significantly different. The null hypothesis in this procedure is $\mu_1 = \mu_2 = . . . \mu_n$. In this test, one must assume that all the samples of data are normally distributed, and that they have a common variance. The analysis of variance considers the means of all the samples being tested, along with their within-sample and between-sample variability.

While the analysis of variance is very useful for evaluating the equality of a group of population means, the utility of the results of that test are somewhat limited. One can only determine whether or not all the means are statistically the same. In this study, I was interested in determining which methods of discharge measurement performed best under the conditions encountered in the field trials. For this reason, the analysis of variance was coupled with Duncan's multiple range test for use with the field trial data in this study.

Duncan's multiple range test allows one to compare the means of the samples to determine if they are statistically different in terms of sample pairs. In this procedure, the sample means are first ranked in order of mean value. Population means are then declared significantly different if the value of the sample differences exceeds a threshold value. The threshold value is a function of the number of observations in each sample mean, the mean square within sample variance (from the analysis of variance), and the critical value of the Studentized range. The analysis was performed using the statistical analysis software, SAS.

Laboratory Experiment Data Analyses:

The result of the laboratory experiment was a set of discharge measurements taken with each device at a steady discharge in a flume. The mean of three discharge estimates from each device at a given discharge was used for the analyses, along with a corresponding control discharge. This sample of discharge values for each device encompassed a broader range of discharge and velocity values than the field investigations yielded. This allowed for a slightly different analysis of the data from laboratory experiments than was performed on the data from the field investigations.

The fact that all the devices were used to measure discharge at a given control discharge allowed comparison of typical measurements at low, medium, and high discharge rates. Control discharge values in the low, medium, and high range were randomly selected. The control discharge and measured discharge values for each of the selected control discharge values were plotted on a single graph for visual comparison.

The % relative error was calculated for each measurement, and descriptive statistics were calculated for the % relative error values of the laboratory data, just as for the field investigation data. Once again, the mean % error values were plotted for visual comparison, including a 95% confidence interval for the population mean displayed using error bars.

Under ideal conditions, the control discharge and the measured discharge would be equal. The resulting trend line would have a slope of one and an intercept of zero. To visually assess the accuracy of the laboratory data, the measured discharge data were plotted against the corresponding control discharge values. To make the plots more readable, the more similar methods were grouped together in a series of three plots. The “ideal” trend line was displayed in the plot.

To further illustrate the comparison of the measured discharge values to the ideal trend line, regressions were performed between the measured and control data. While looking at the data, it was observed that some devices did not measure the discharge at some of the very low discharge conditions due to insufficient flow velocity. To evaluate each method in its particular operating range, data pairs were omitted where the estimated discharge was zero and the control discharge was not. Statistics describing the regressions were listed in a table for comparison. Those statistics included the Y-intercept, intercept p-value, slope, and standard error.

The intercept and slope describe the regression line, and constitute the regression equation. If the random error is ignored, the regression equation is that of a straight line in the form:

$$y = \beta_0 + \beta_1 x \tag{3.5}$$

Where: β_0 = y-intercept

β_1 = slope

The regressions were performed using a spreadsheet, and the theoretical details of the derivation of these constants will not be covered here. The p-value indicates the level of significance of a statistical test. The statistical test in this instance has a null hypothesis of: the intercept is equal to zero. The standard error is identical to the standard error used with the field trial data, except the regression was used rather than the site rating. It is an indicator of the variation of the data with regard to the regression.

Analysis of Covariance:

As previously mentioned, the data resulting from the laboratory experiment encompassed a broader range of control flows, and thus were subjected to different analyses. Analysis of covariance was suggested by the Statistical Consulting Center for use with this data to determine which methods were most accurate in the conditions experienced in the experiment. The concept of this analysis is similar to the performance of regression between the measured and control discharge data previously described in this section. In fact, the analysis of covariance combines regression and analysis of variance. One advantage of this analysis is that it allows one to make more robust inferences about the relationships, and thus the relative accuracy of these methods. Unlike simply comparing regressions of measured and control discharge data, the analysis of covariance adjusts the error terms in the regression models to account for differences in the values of the covariate.

This procedure is used to compare the means of different treatments, while accounting for a second variable. The second variable is called a covariable, or covariate (Ott, 1988). The covariate is an independent variable, which may have an effect on the response variable. In this laboratory experiment, the response variable was the discharge measured using each of the methods at a given control discharge in the flume. The covariate in this experiment was the control discharge.

Some assumptions must be made about the data before using this procedure. The response variable was assumed to be linearly related to the covariate. The slope of the regression line for all treatments was assumed to be equal. Like the Duncan's multiple range test performed on the field trial data, this analysis was performed using the statistical analysis software, SAS.

CHAPTER 4
RESULTS AND DISCUSSION

Field Trials:

Laboratory investigations provide a measure of the accuracy of the various devices under controlled conditions. The field trials are often necessary to determine the relevance of the laboratory experiment (Fulford et al., 1994). Data collection began in January, 1999 and continued until the end of March, 1999. Approximately one month was spent collecting data at Crab Creek, and the other two months were spent collecting data at Thorne Springs Branch. During this time, there was very little precipitation. Consequently, the flow in the streams at the field investigation sites was very low for most of the data collection period. A broader range of control flows would have been desirable, but the dry conditions resulted in a somewhat limited range.

The field sites and experimental procedure used in this study are described in detail in Chapter 3. Each of the methods investigated in this study was used in random order at each field site. A total of 30 discharge measurements were taken with each device. The control discharge for field trials was the discharge measured for the same time period by the weir/stilling well structure at each site. In the following analyses, the difference between the measured and control discharge values (% error) is examined for the various devices at each site.

The mean control discharge measured at the Crab Creek gaging station was 0.402 cfs, with the individual discharge rates ranging from 0.182 cfs to 1.196 cfs. The average velocity measured with the methods investigated in this study at Crab Creek ranged from 0.104 fps to 0.403 fps. At Thorne Springs Branch, the mean control discharge was 0.377 cfs, ranging from 0.348 to 1.198 cfs. The average measured velocity for the various methods at Thorne Springs Branch ranged from 0.075 fps to 0.563 fps. The maximum value of average measured velocity at each site was registered by the Global flow probe. The similar discharge rates obtained for the two field sites would seem to indicate that the streams were practically identical. However, the stream cross section at Thorne Springs Branch was much larger than that of Crab Creek. This created considerably lower flow velocity at Thorne Springs Branch compared to Crab Creek.

The data did not encompass a sufficiently broad range of control discharge values to allow a meaningful regression between measured and control discharge values. The % error was, thus, calculated for each discharge measurement in the field trials as a means of comparison of the different methods. To investigate the possible correlation between % error and control discharge, the values of % error were plotted against the control discharge for visual examination.

The stream-gaging guidelines caution against using mechanical current meters to measure discharge in velocities lower than 0.5 fps, and other methods have minimum flow velocity requirements. Yet, these methods are often the only ones available for measuring discharge in streams with small flow rates. The various methods investigated in this study have different recommended operating requirements related to the stream they are used in. Application limits have been recommended in the stream-gaging guidelines for some methods, and in user's manuals for others. These guidelines are usually conservative estimates, and caution is suggested when using the devices in streams with velocities below these limits. Rantz et al. (1982) stated that neither the Price AA nor the pygmy current meters should be used to measure velocity below 0.2 fps, unless necessary. Table 4.1 lists the suggested velocity operating ranges for each method used in the laboratory experiment.

Figures 4.1 through 4.3 show the % relative error data for Crab Creek, plotted against the control discharge, for the various methods. One can see that the data are mostly concentrated at control discharge values below 0.5 cfs. The % relative error is higher at the very low control discharge values (0 cfs to 0.3 cfs), which may be the result of low discharge values. The data shown in Figures 4.1 through 4.3 indicate a lower % relative error at the higher control discharge values, though the number of data points in the higher control discharge range is somewhat limited. This trend of decreasing % relative error with increased control is very noticeable in Figures 4.1 and 4.3. The % relative error data resulting from use of the Starflow and Isco devices seem to decrease with an increase in control discharge, as do the Price AA current meter data. The Global flow probe consistently resulted in overestimation of discharge values, as almost all the data collected by this device indicate a relative error of over 100%. While using this device in the field, it was noted that the probe only registered velocity in very fast flow. The average velocity measured in the section was estimated using only the registered velocities. Since the device only registered the higher velocities, this resulted in a gross overestimation of the average velocity in the entire cross-section. The other data that seem to indicate extreme overestimation are those resulting from the use of the Isco acoustic Doppler. With the exception of three observations, these data indicate a relative error of 109 % to 146 % as well. The method prescribed by the manufacturer for use with the Isco device directs the user to create a table relating stage to the total area of the measurement section. The velocity read by the sensor is then multiplied by the total area for the measured stage. In natural streams, the edges often contain "dead" spots where there is no flow velocity. This would cause an overestimation of the discharge.

Table 4.1 – Suggested minimum and maximum operating flow velocities for each method.

Method	Minimum Velocity (ft/s)	Maximum Velocity (ft/s)
Marsh McBirney	-0.5[a]	19.99[a]
Price AA	0.2[b]	*
Pygmy	0.2[b]	*
Valeport BFM-001	0.5[c]	16.4[c]
Global flow probe	0.3[d]	*
One-orange method	*	*
Isco acoustic Doppler	*	*
Starflow acoustic Doppler	0.066[e]	16.4[e]

* - A velocity value could not be found.

[a]Unidata, 1995 [b]Rantz et al., 1982 [c]Valeport, 1995 [d]Global Water, 1997 [e]Unidata, 1995

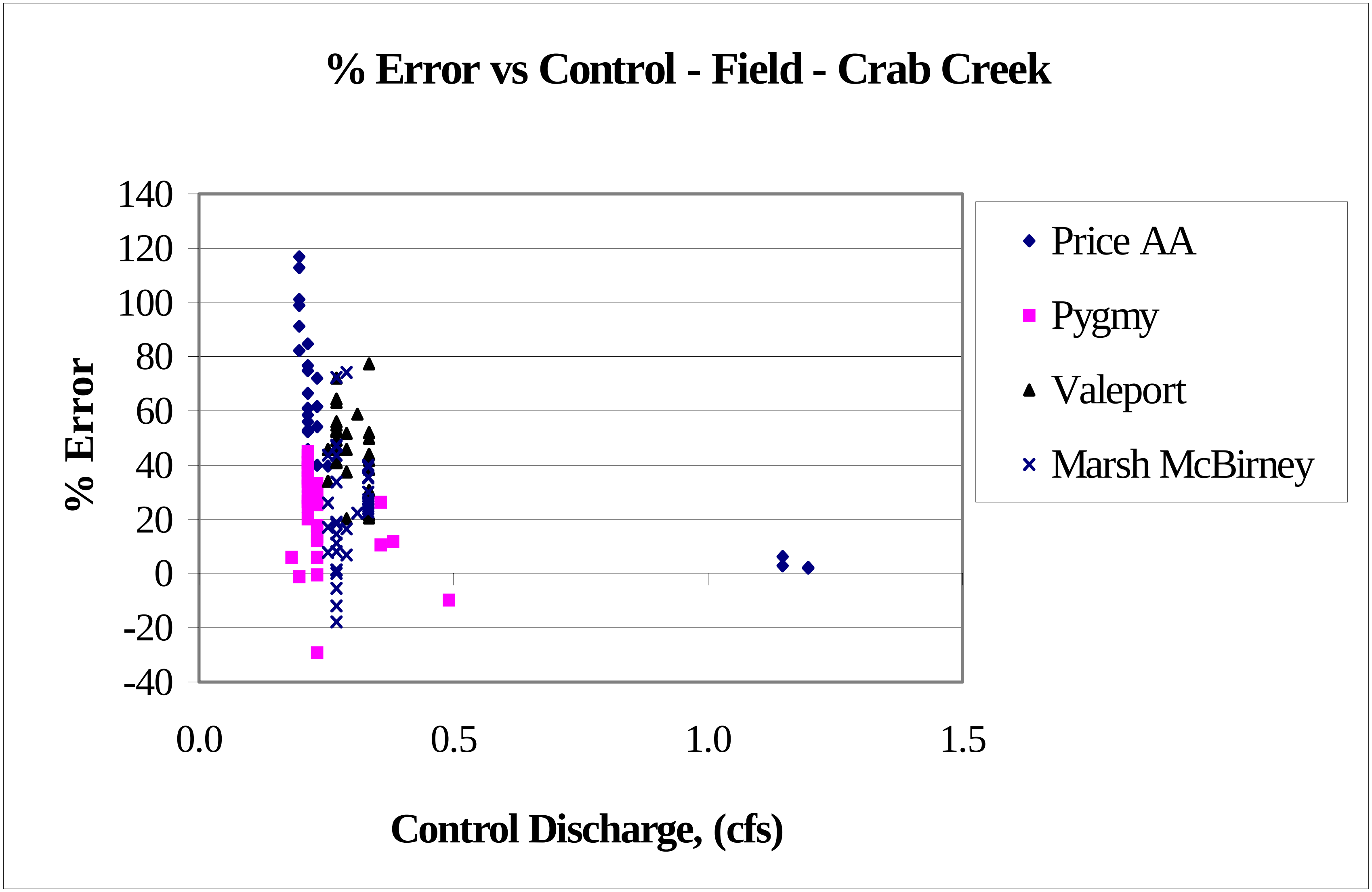


Figure 4.1 – Current meter % error plotted against control discharge for Crab Creek field data.

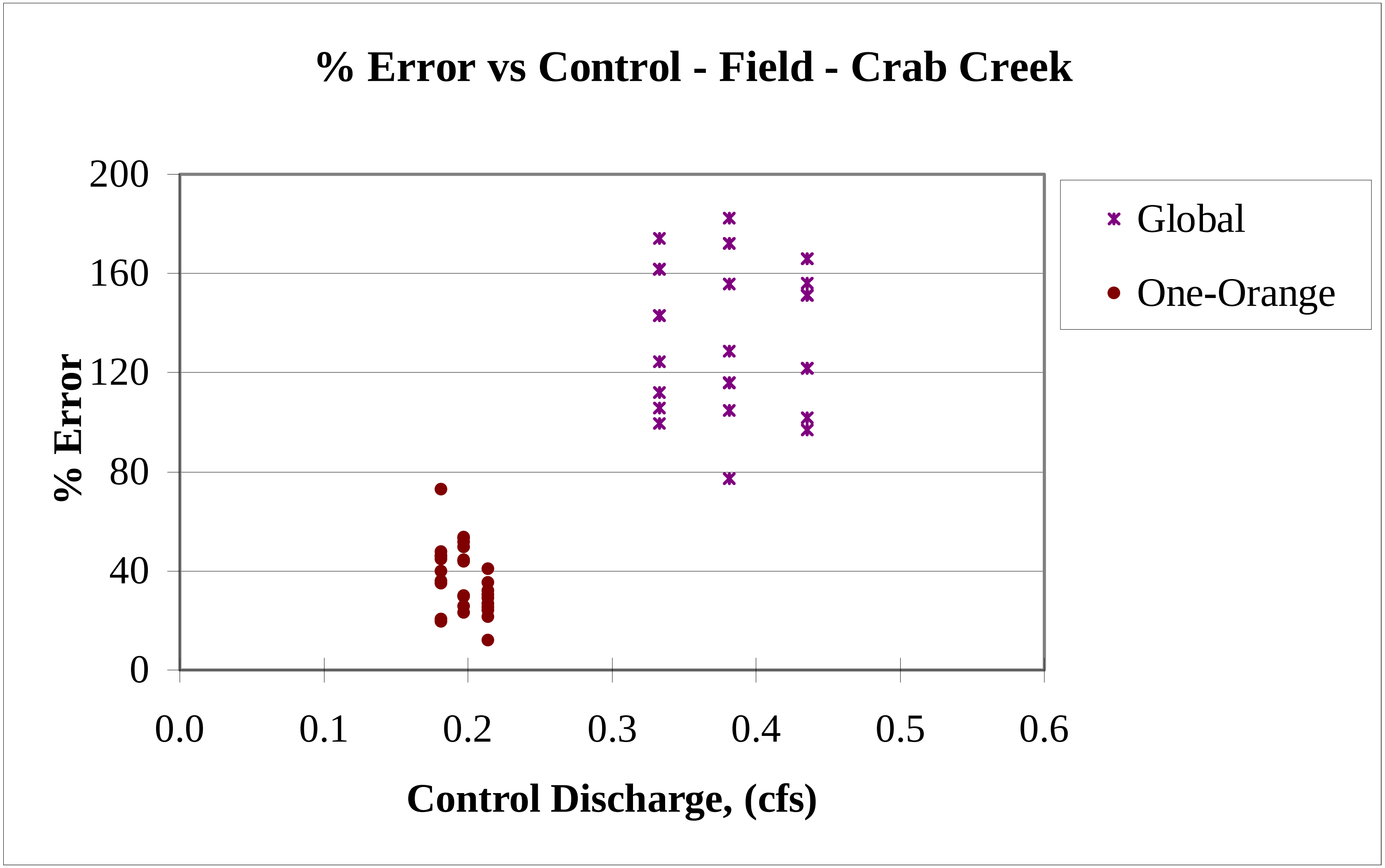


Figure 4.2 – Global flow probe and One-orange method % error plotted against control discharge for Crab Creek field data.

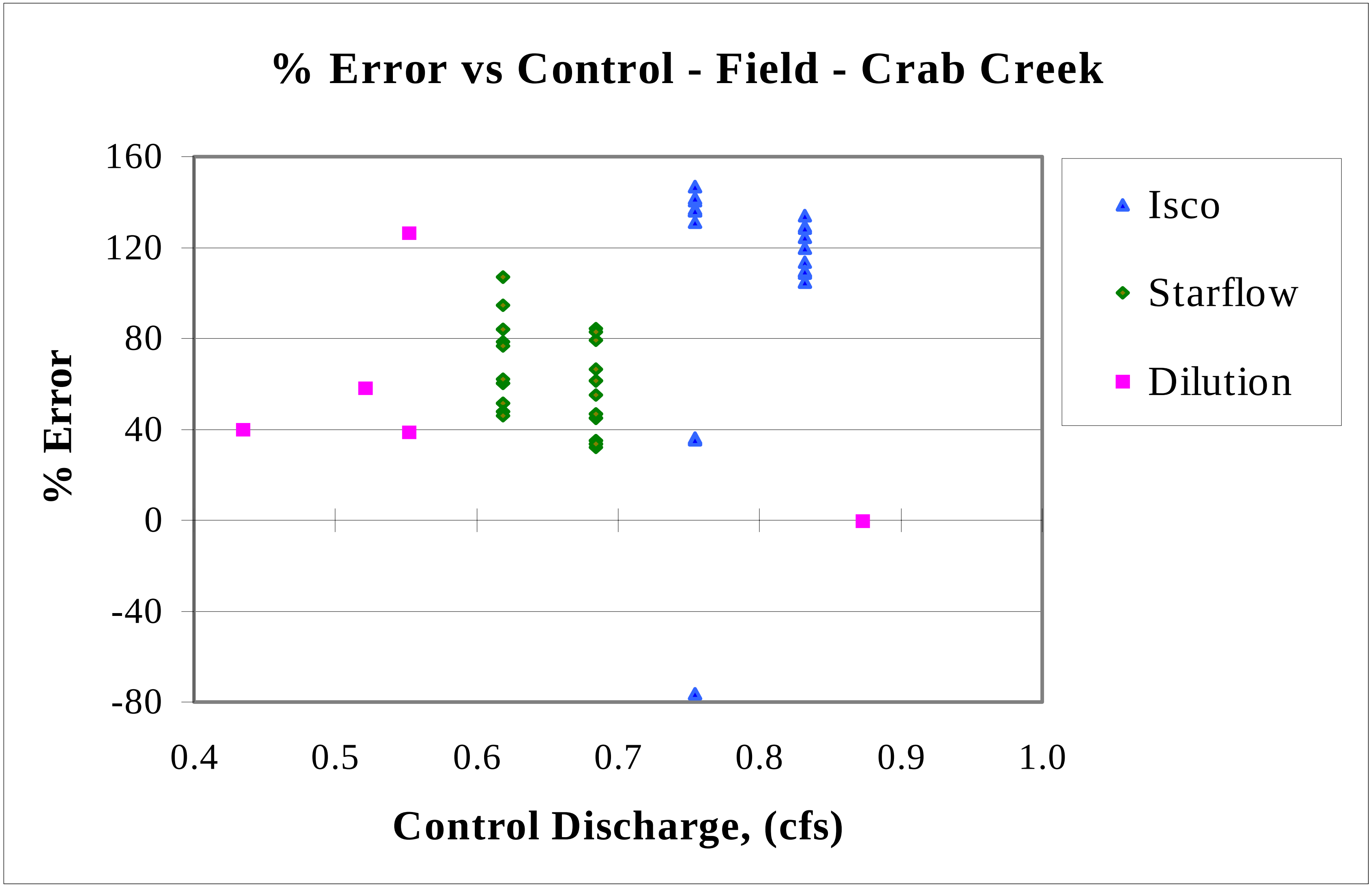


Figure 4.3 – Acoustic Doppler and dilution method % error plotted against control discharge for Crab Creek field data.

The % relative error data resulting at Thorne Springs Branch are displayed in Figures 4.4 through 4.6. Though the period of data collection was twice that of the Crab Creek, the data are still clustered at the lower control discharge range. The few data points that were taken at higher control discharge rates do posses a lower % relative error, but not enough data points exist in this range to draw a meaningful conclusion. There are more negative % relative error values with lower values at this site compared to those at Crab Creek. This may be due to the lower velocities encountered at the Thorne Springs Branch site. The close proximity of data points makes it difficult to distinguish one point from another by visual inspection. One can observe that there was considerable underestimation of discharge at the Thorne Springs Branch site using the mechanical current meters. The Global flow probe overestimated the discharge at Thorne Springs Branch (Figure 4.5).

Descriptive statistics were calculated and tabulated as described in Chapter 3 of this document. All the descriptive statistics are included in Appendix C, and Table 4.2 summarizes selected descriptive statistics associated with the % relative error data for the field data. The mean and median give an idea of the central tendency of the data, while the standard deviation and range indicate the degree of scatter the data exhibited. The mean and median of the % relative error data for the Global meter is higher than the other mechanical current meters at both sites. The low value of the minimum % relative error of most mechanical current meters can be attributed to the low flow velocities encountered at the site. This often resulted in the meters not registering any velocity in some measurement subsections.

Figures 4.7 and 4.8 show the mean % relative error for each method used at each watershed. The bars in each of these figures represent the mean sample relative error (%) for each method at each field study site. The error bars represent the 95 % confidence interval for the population mean of the same. Figure 4.9 displays the standard error of estimate for each method at each site to visually evaluate the consistency in the error encountered from one site to another. The calculation of the standard error of estimate is also described in Chapter 3.

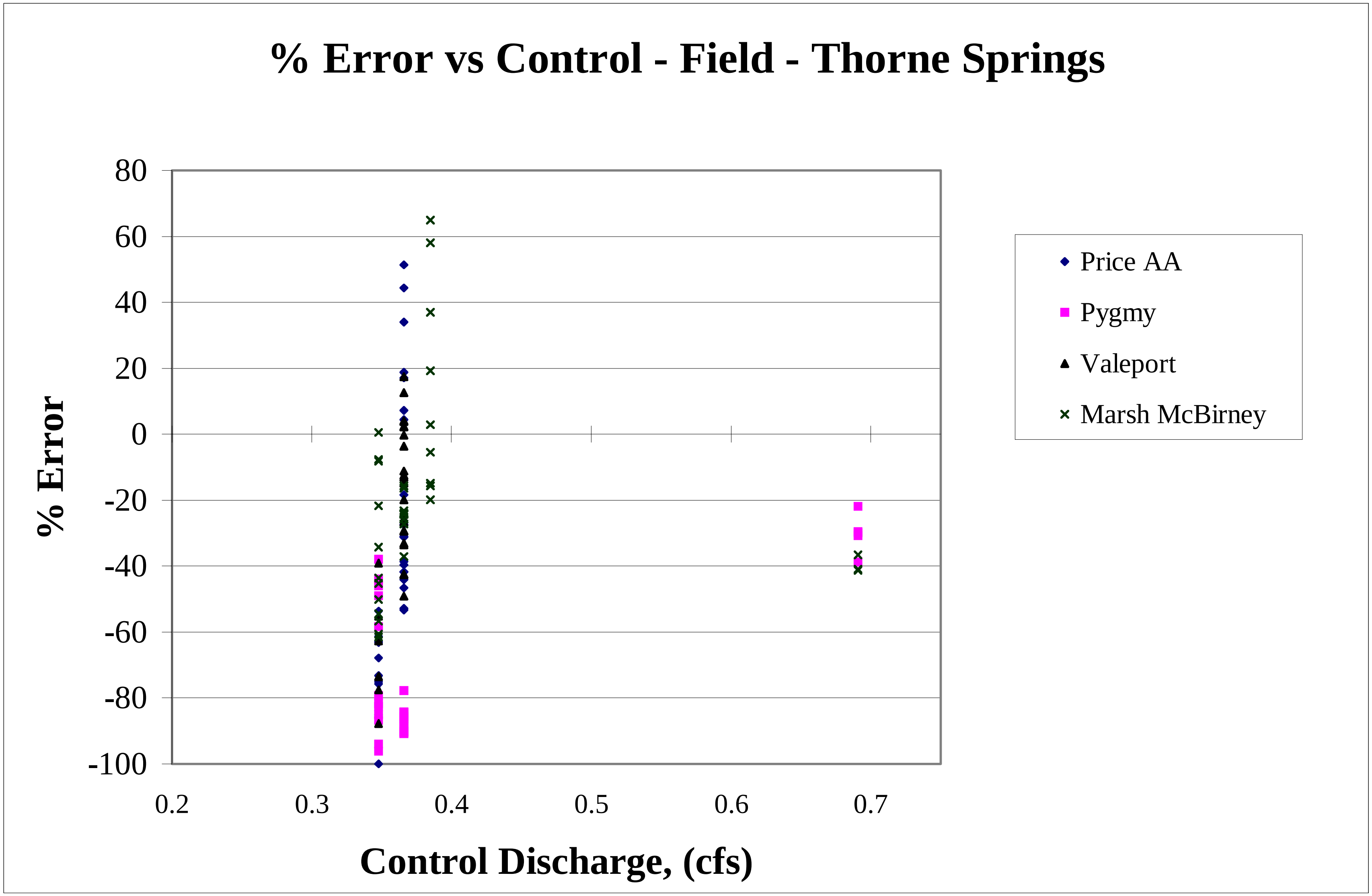


Figure 4.4 - Percent relative error plotted against control discharge for Thorne Springs Branch field data for current meters.

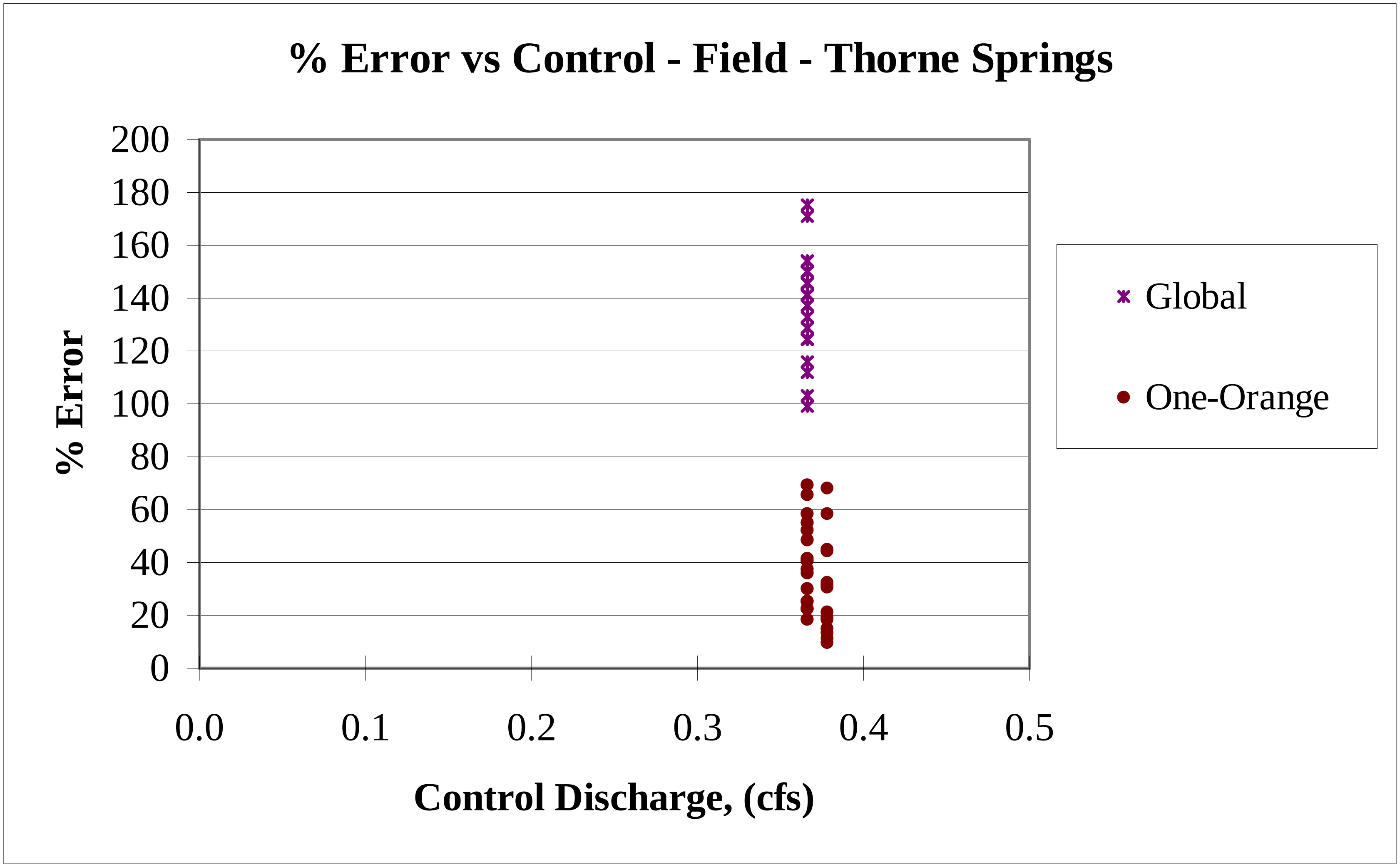


Figure 4.5 - Percent relative error plotted against control discharge for Thorne Springs Branch field data for various flow measuring methods.

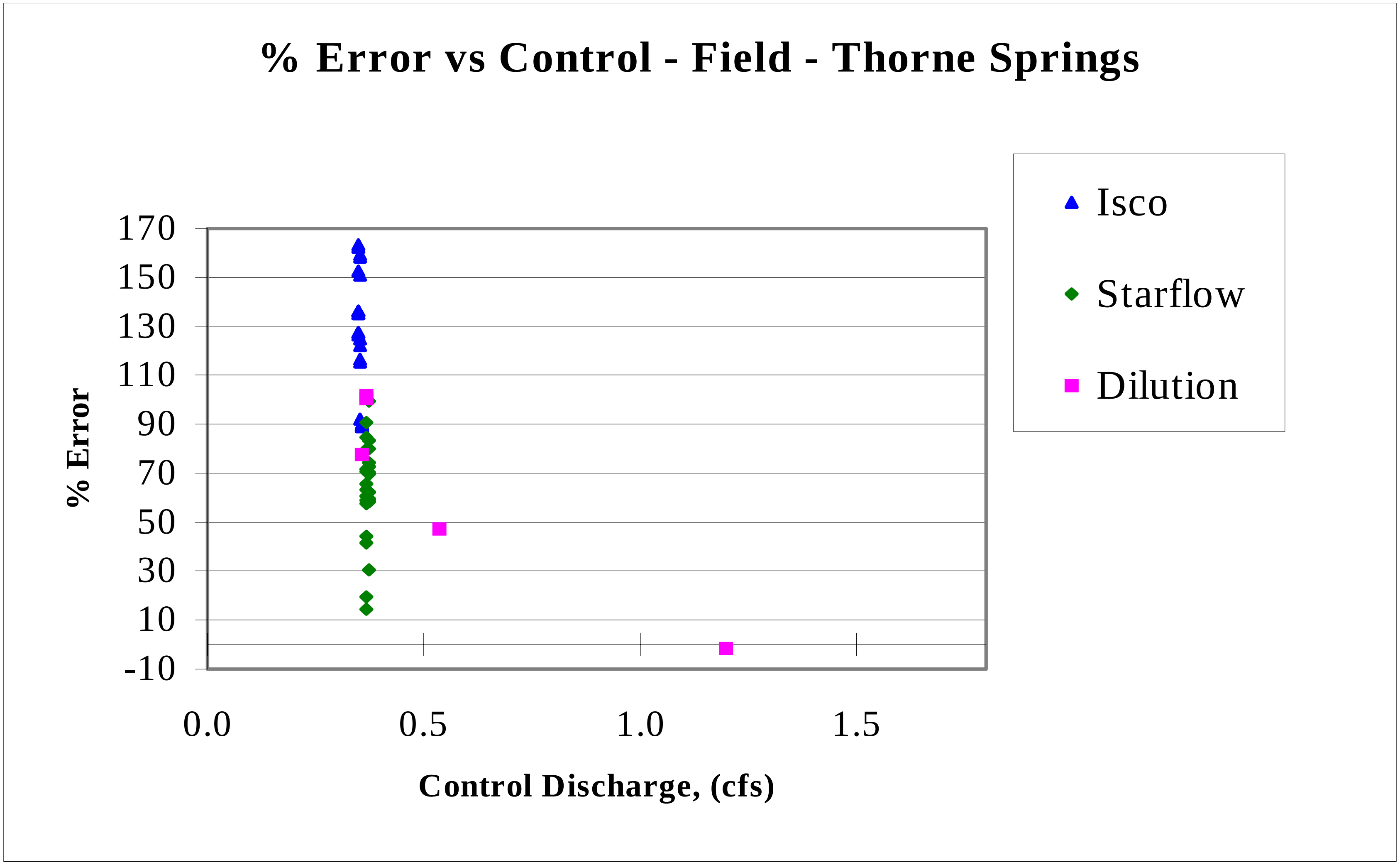


Figure 4.6 - % relative error plotted against control discharge for Thorne Springs Branch field data for various flow measuring methods.

Table 4.2 – Descriptive statistics of % relative error data in field trials listed by site and method.

Thorne Springs Branch	Mean	Median	Standard Deviation	Range	
				Min.	Max.
Price AA	-36.4	-43.0	40.1	-100.0	51.4
Pygmy	-70.7	-84.4	24.2	-96.2	-21.9
Braystoke	-27.9	-26.2	28.3	-87.8	17.4
Marsh McBirney	-19.8	-24.0	30.3	-61.5	65.0
Global	138.3	141.4	17.1	99.0	175.3
One-orange	35.6	32.0	17.7	9.6	69.2
Isco	117.2	122.2	26.7	89.1	163.3
Starflow	64.2	64.5	19.3	14.3	99.5
Dilution	65.0	77.6	43.4	-1.8	101.3
Pres. Transducer	10.1	3.3	15.5	-3.1	40.0
Crab Creek					
Price AA	60.1	60.9	30.7	1.9	116.9
Pygmy	21.0	25.9	16.9	-29.3	45.0
Braystoke	46.9	46.3	13.5	20.3	77.4
Marsh McBirney	23.7	24.0	20.5	-17.7	74.2
Global	137.0	143.0	28.4	77.1	182.3
One-orange	36.5	35.1	13.2	12.2	73.0
Isco	109.3	116.7	43.3	-76.4	146.8
Starflow	59.9	57.7	19.9	32.2	107.1
Dilution	52.6	39.8	46.5	-0.2	126.5
Pres. Transducer 1	3.5	0.0	5.3	-2.6	11.8
Pres. Transducer 2	-3.9	-4.2	1.1	-5.7	-1.6

*Positive values indicate overestimation of discharge, and negative (-) values indicate underestimation of discharge.

The mean % error values for each method used at the Crab Creek gaging station are shown in Figure 4.7. The 95 % confidence interval for the dilution method is very broad. This can be attributed to the small sample size associated with the dilution method in the field trials. The sample mean used in calculation of the confidence interval (Equation 3.3) is inversely proportional to the square root of the sample size. Therefore, a smaller sample size results in a wider confidence interval under otherwise identical conditions. The Isco and Global devices have the largest sample mean relative errors (%) among all devices. At Thorne Springs Branch (Figure 4.8), the mean % relative error values for each of the current meters is negative, whereas the mean % relative error for the other devices is positive. This means the current meters generally underestimated the discharge at this site. This underestimation of discharge was noted previously and was attributed to low flow velocities at Thorne Springs Branch. In contrast, the current meters overestimated the discharge at the Crab Creek gaging station, which exhibited higher flow velocities. All other methods overestimated the discharge for both watersheds, and resulted in similar sample means and population mean confidence intervals. As shown in Table 4.2, the mean and median values for the methods other than current meters at Crab Creek are very close to those at Thorne Springs Branch. This would imply that, except for the sign of the errors for the current meters, the performance of each method was consistent from site to site. Figure 4.9 confirms this assertion, which indicates that, except for the Isco device, the standard errors for the various methods at each site are very similar. No explanation was found for the difference in standard error for the Isco device.

The range of % relative error values for all the methods is fairly large, except for the pressure transducers. Almost all the velocity-area methods of discharge measurement exhibited a % relative error of at least 50%. The only exception is the pygmy current meter used at Crab Creek, with a maximum value of 45% relative error.

The pressure transducers installed at each site exhibited a very small relative error (%). Two pressure transducers were installed at the Crab Creek site to assess the difference in accuracy between a transducer installed in a stilling well and one installed in the stream itself. Figure 4.7 indicates that the pressure transducer installed in the stilling well slightly overestimated the stage compared to the float and weight recorder equipped with a potentiometer. The transducer installed in the stream underestimated the stage, with a small % relative error. The pressure transducer in the stilling well had a mean % relative error of 3.5 (Table 4.2), while the transducer in the stream had a mean % relative error of –3.9. The median % relative error value for each transducer was 0.0 and –4.2, respectively. Due to complications associated with installing a transducer in the stream at Thorne Springs Branch, only one transducer was installed at this site in the stilling well. It can be seen in figure 4.8 that the transducer error at Thorne Springs Branch was slightly higher than those at Crab Creek, though still very low. The data in Table 4.2 confirm that the error exhibited by this pressure transducer was very low, but the range of % relative error at Thorne Springs Branch had a maximum of 40%. This is considerably higher than the range of % relative error values for the pressure transducers installed at Crab Creek. Figure 4.9 also indicates very low standard errors for the pressure transducers installed at each watershed.

Fulford et al. (1994) reported a maximum mean discharge residual of about 6% for all current meters tested. However, this residual is the difference between the discharge measured with each device and the mean value obtained with all devices at a given study site. Therefore, their results can not be directly compared with those of this study. It should be noted that some current meters were evaluated in both the Fulford et al. study and this research. The current meters common to both studies listed in order of increasing absolute value of residual are: Price AA (-)Marsh McBirney (-)Valeport BFM001 (+)Price pygmy (-). The symbol next to the current meter name indicates whether the device underestimated (-) or overestimated (+) discharge in the Fulford study, relative to the mean for the study site.

These results do not correlate with those of this study, which could be due to differences in site conditions. The minimum discharge measured by Fulford et al. was 27 cfs, and the minimum mean velocity in the measurement sections was 1.14 fps. This is in contrast to the conditions encountered at the field trial sites in this study which typically flowed at less than 0.5 cfs with measured velocity for most methods (other than the Global flow probe) well under 0.4 fps (usually less than 0.3 fps).

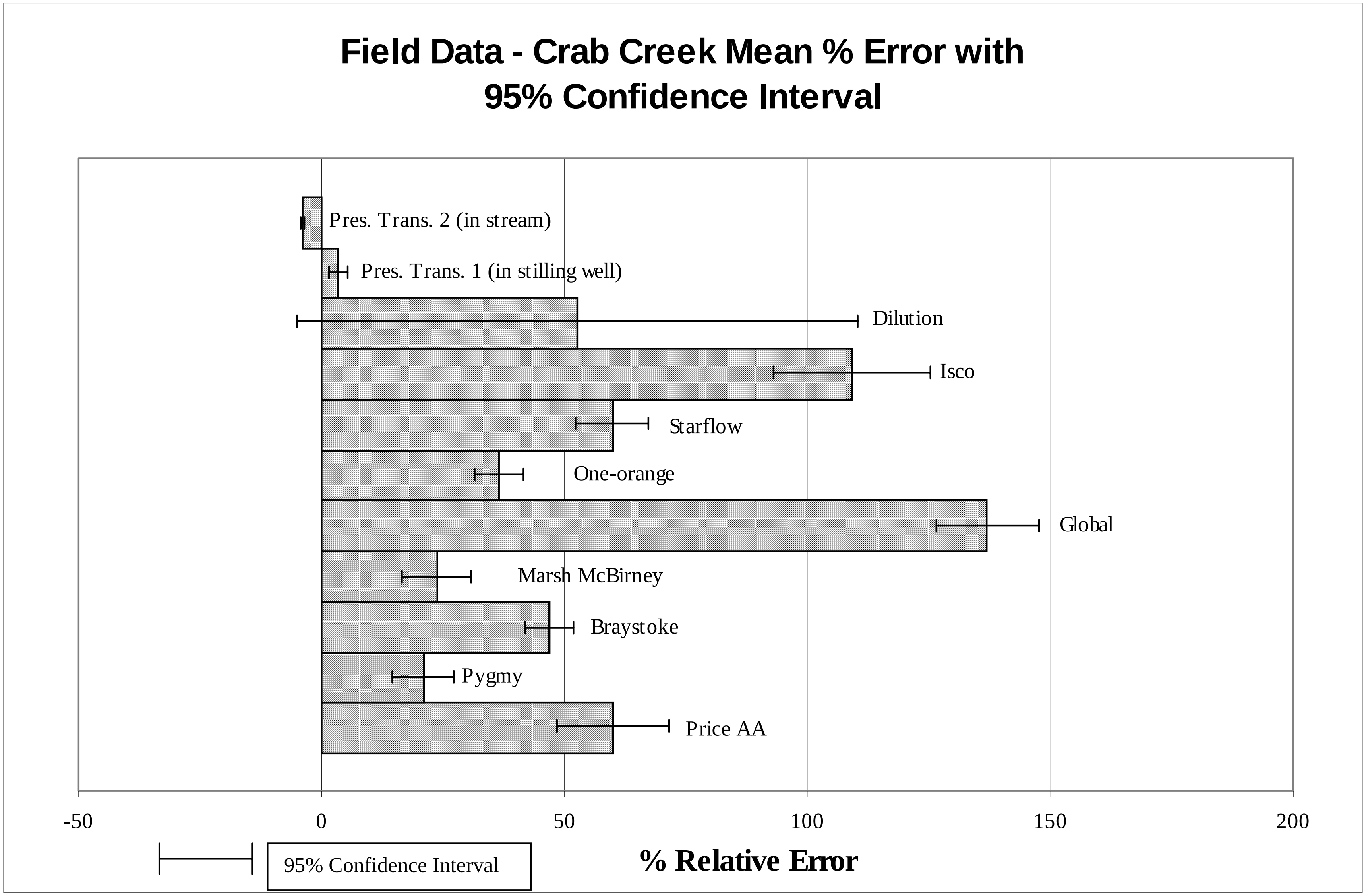


Figure 4.7 – Mean sample % relative error with 95% confidence interval of population mean at Crab Creek.

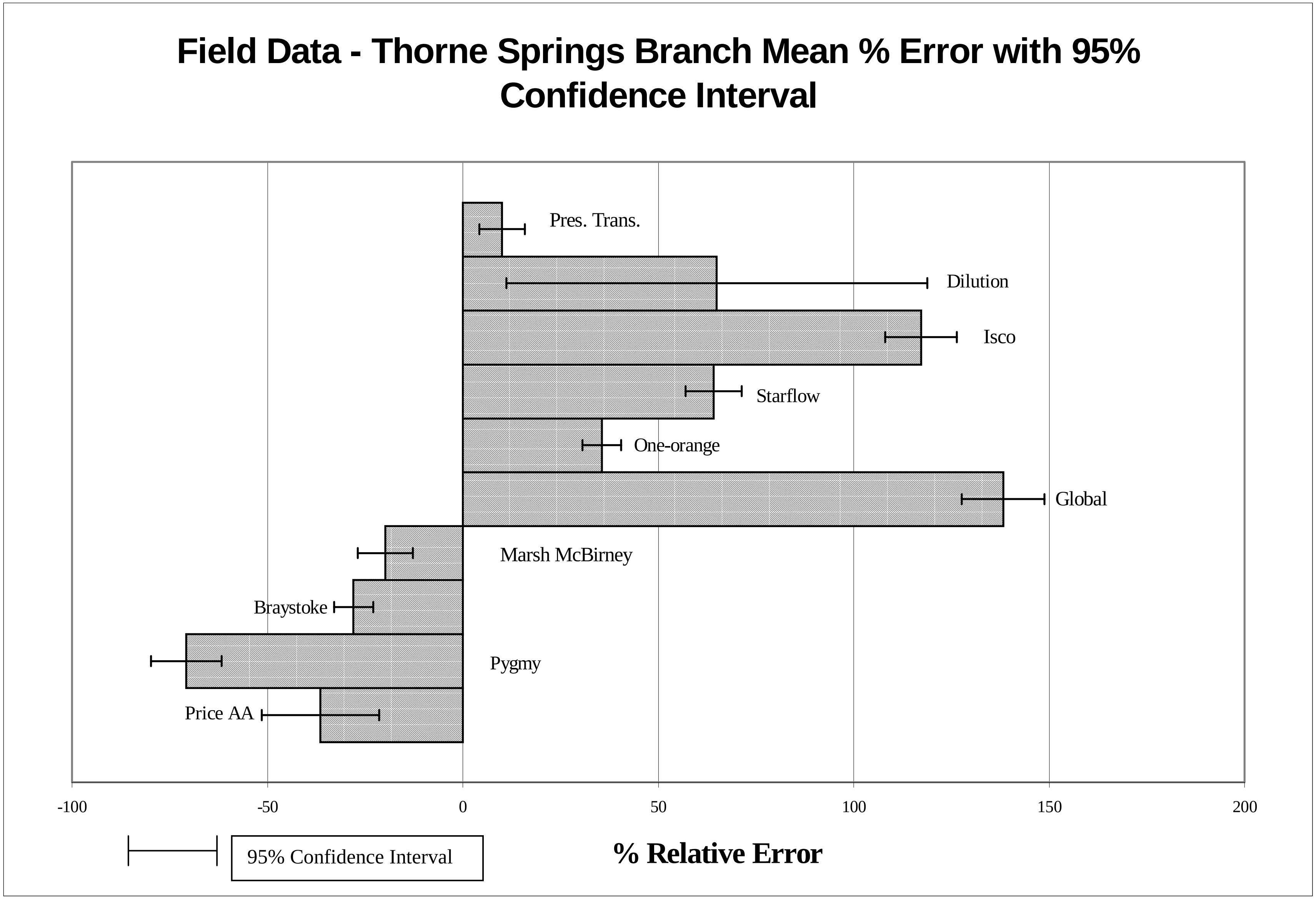


Figure 4.8 – Sample mean % relative error and 95% confidence interval of population mean for Thorne Springs.

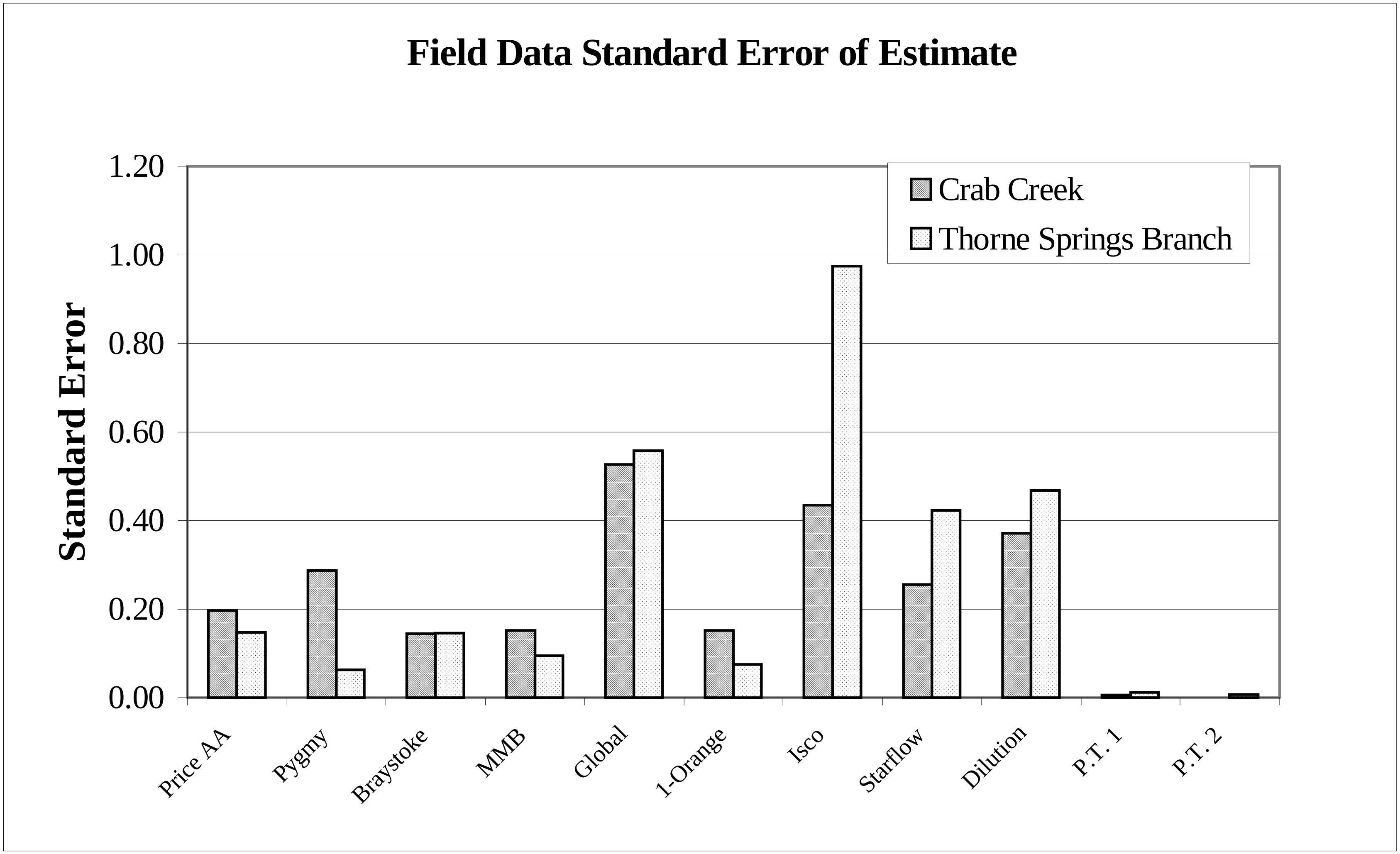


Figure 4.9 – Standard error of estimate for field measurements listed by site and method.

Field Trial Statistical Analyses:

Analysis of variance was performed on the absolute values of the residuals for discharge estimation techniques at Crab Creek and Thorne Springs Branch, as well as the pressure transducer data at both sites. In this application, the residual used was the difference between the estimated discharge and the control discharge. The Analysis of Variance allows one to conclude if the population means of all the treatments are equal. The null hypothesis of this test is that there is no difference in the treatment means, implying the accuracy of the methods under the test conditions. The alternative hypothesis is that there is at least one difference in treatment means.

Table 4.3 summarizes the results of the Analysis of Variance performed on the field study data. The critical F-value for both field sites is 1.98, which is considerably lower than the calculated values listed (245.09 and 100.34). The p-values for both sets of data are very close to zero, which constitutes strong evidence in favor of the alternative hypothesis. Therefore, the null hypothesis is rejected.

Table 4.3 - Analysis of Variance results for % relative error data.

Data	df1	df2	F-value	p-value
Crab Creek	8	241	245.09	0.0001
Thorne Springs	8	244	100.34	0.0001
All Pres. Trans.	1	60	0.59	0.4466

The critical F-value for the comparison of the all the pressure transducer data (both sites together) was 4.00. This is much higher than the calculated value of 0.59, listed in Table 4.3. The corresponding p-value of 0.4466 implies weak evidence in favor of the alternative hypothesis. This implies that one must fail to reject the null hypothesis of equal means. Therefore, it can not be said that the pressure transducer measures stage with more or less accuracy when placed in a stream as compared to when it is placed in a stilling well.

Since the mean residuals among all the velocity-area discharge measurement methods were found to be significantly different, the next step was to determine which method or methods functioned best under the test conditions. This was accomplished using Duncan's multiple range test (Ott, 1988). In this test, all the means were ranked in order of descending value, then each mean was compared in pairwise fashion to determine if they were significantly different. Groups of treatments that were not significantly different were identified. The complete results for Duncan's multiple range test are contained in Appendix C, and are summarized in Table 4.4.

Table 4.4 – Summary of the results of Duncan's Multiple Range Test.

Crab Creek Data:

Duncan Grouping				Mean Residual	Method
A				0.934	Isco
	B			0.525	Global
		C		0.389	Starflow
			D	0.278	Dilution
	E			0.135	Valeport
	E			0.131	Price AA
	E	F		0.075	Marsh McBirney
	E	F		0.071	One-orange
		F		0.055	Pygmy
			Z	0.008	Pres. Transducer 1
			Z	0.007	Pres. Transducer 2

Thorne Springs Branch Data:

Duncan Grouping			Mean Residual	Method
A			0.506	Global
	B		0.412	Isco
		C	0.317	Dilution
D		C	0.270	Pygmy
D			0.237	Starflow
		E	0.171	Price AA
F		E	0.132	One-orange
F		E	0.124	Marsh McBirney
F			0.110	Valeport

For the data collected at Crab Creek, the pygmy current meter, Marsh McBirney current meter, and One-orange method were found not significantly different from one another. These methods were also considered the most accurate since each exhibited a mean difference of under 0.08 cfs.

The Price AA and Valeport BFM001 current meters were considered not significantly different from the One-orange method and the Marsh McBirney current meter, but had mean residual values of 0.131 cfs and 0.135 cfs, respectively. The mean residuals for the other methods were substantially higher, and significantly different from the other methods. The pygmy current meter, along with the other mechanical current meters, performed rather well at the Crab Creek site because the velocities encountered there were suitable for their use. The One-orange method performed very well, given the level of technological sophistication associated with the method. The Marsh McBirney current meter also performed well at the Crab Creek site, and seemed to be more sensitive in the lower velocities encountered at the edges of the stream sections. The dilution method had the next highest mean residual value at 0.278 cfs. The reach length may have been a little too short for complete mixing, although the reach length used was calculated as prescribed. The Isco acoustic Doppler device performed worst at this site, with a mean residual value of 0.934 cfs. The Global flow probe exhibited a mean residual value of 0.525 cfs, indicating this device also did not perform well at the Crab Creek site.

At Thorne Springs Branch, the best-performing group of velocity-area methods of discharge measurement included the Valeport BFM001 current meter, the Marsh McBirney current meter, and the One-orange method. Each of these devices had a mean residual of slightly over 0.1 cfs (0.11 cfs to 0.13 cfs). The Price AA current meter was not significantly different from the One-orange method and Marsh McBirney current meter, but had a mean residual value of 0.17 cfs. These four were significantly different from the remaining methods. The Starflow and pygmy current meter were not significantly different, but had means of 0.23 cfs and 0.27 cfs, respectively. The dilution method, with a mean residual value of 0.31 cfs, was not significantly different from the pygmy current meter. The Isco and Global devices were each significantly different from the other methods, and had mean residual values of over 0.40 cfs. The low flow velocity at Thorne Springs Branch had a significant effect on the performance of the pygmy current meter, drastically increasing the mean residual compared to Crab Creek. The measurement section used at the Thorne Springs Branch site was also less desirable than the ones used at Crab Creek, which also could have contributed to the higher mean residual values for some methods. This does not apply to the acoustic Doppler devices, which had lower mean residual values. These devices did not perform well at either field study site, which was probably the result of the method prescribed for their use. The measured parameters (depth and mean vertical velocity) seemed accurate based on measured depths and velocity values measured with other devices, but resulted in overestimation of the discharge when the mean velocity was applied to the entire cross section corresponding to the measured stage. The measurement section had little effect on the Global meter, which was used upstream of the control structure (Figure 3.4). This meter did not register lower velocity values, which usually resulted in an overestimation of discharge. The dilution method resulted in a higher mean residual value at Thorne Springs Branch than at Crab Creek, probably due to the irregular stream bank shape caused by cattle entering and exiting the stream. This irregular bank may have caused small eddies that impeded the travel of the dye.

Considering the data collected at both sites, the Marsh McBirney and One-orange methods performed with the most accuracy under the conditions encountered. These two streams were smaller and slower than most streams one would encounter in stream-gaging applications other than NPS pollution studies. However, these are the types of streams one occasionally has to deal with in NPS pollution studies such as TMDL development. If such a small stream has sufficient flow velocity, the pygmy current meter would be preferred over these two methods based on the results of the field investigations. The Valeport BFM001 current meter would be the preferred mechanical current meter under conditions of extremely slow flow, since it performed so well in the slow flow at Thorne Springs Branch. The Marsh McBirney current meter exhibited the best accuracy at both field study sites. The One-orange method also performed very well at both sites. Neither of the acoustic Doppler devices seemed to perform well in the field study, but that was more a reflection of the procedure used with them than the instruments themselves. However, the procedure prescribed by the manufacturer dictates that the measured velocity be applied to the entire cross-section corresponding to the measured depth. The sensor is positioned in the middle of the section, where velocity is the highest. The result is a consistent overestimation of discharge by the device.

Laboratory Investigations:

The laboratory procedures used for evaluation of the stream-gaging methods in this study are explained in detail in Chapter 3. All methods were used to measure discharge in a one-foot recirculating flume in the Land and Water Resources Laboratory in the BSE department at Virginia Tech. A thin-plate v-notch weir was mounted in the far end of the flume to measure the control discharge while creating a backwater condition. The backwater condition was necessary to reduce the mean section flow velocity, which simulated conditions at the field trial sites. The discharge measured by the weir was used as the control when analyzing the data from each method, much like the broad-crested weirs were used as statistical controls in the field investigations. The discharge in the flume was allowed to stabilize, then each of the nine methods was used to measure the flow velocity and/or depth. After measurements were taken, the discharge was increased by a random increment and the procedure was repeated. Fifteen measurements were recorded for each method while randomly increasing discharge, and another fifteen measurements were taken while randomly decreasing discharge. The control discharge values ranged from 0 cfs to 0.591 cfs, while the average velocity in the flume ranged from 0 to 0.498 fps.

The result of this experiment was thirty sets of control and measured discharge values by each method. Figure 4.10 displays the control and the corresponding measured discharge values for one low (0.105 cfs, 0.106 fps), medium (0.316 cfs, 0.282 fps), and high (0.591 cfs, 0.483 fps) control discharge.

The various methods investigated in this study have different suggested operating requirements with regard to the flow conditions in the stream. Table 4.1 lists the suggested velocity limitations for each method used in the laboratory experiment. Four of the methods (Price AA current meter, pygmy current meter, Valeport BFM001 current meter, and the Global flow probe) registered no discharge at the low control discharge. In addition, the Global flow probe measured no flow at the medium control discharge. This lack of operation at very low velocity and low discharge rates was also observed in the field, which confirms the assertion that slow flow at the

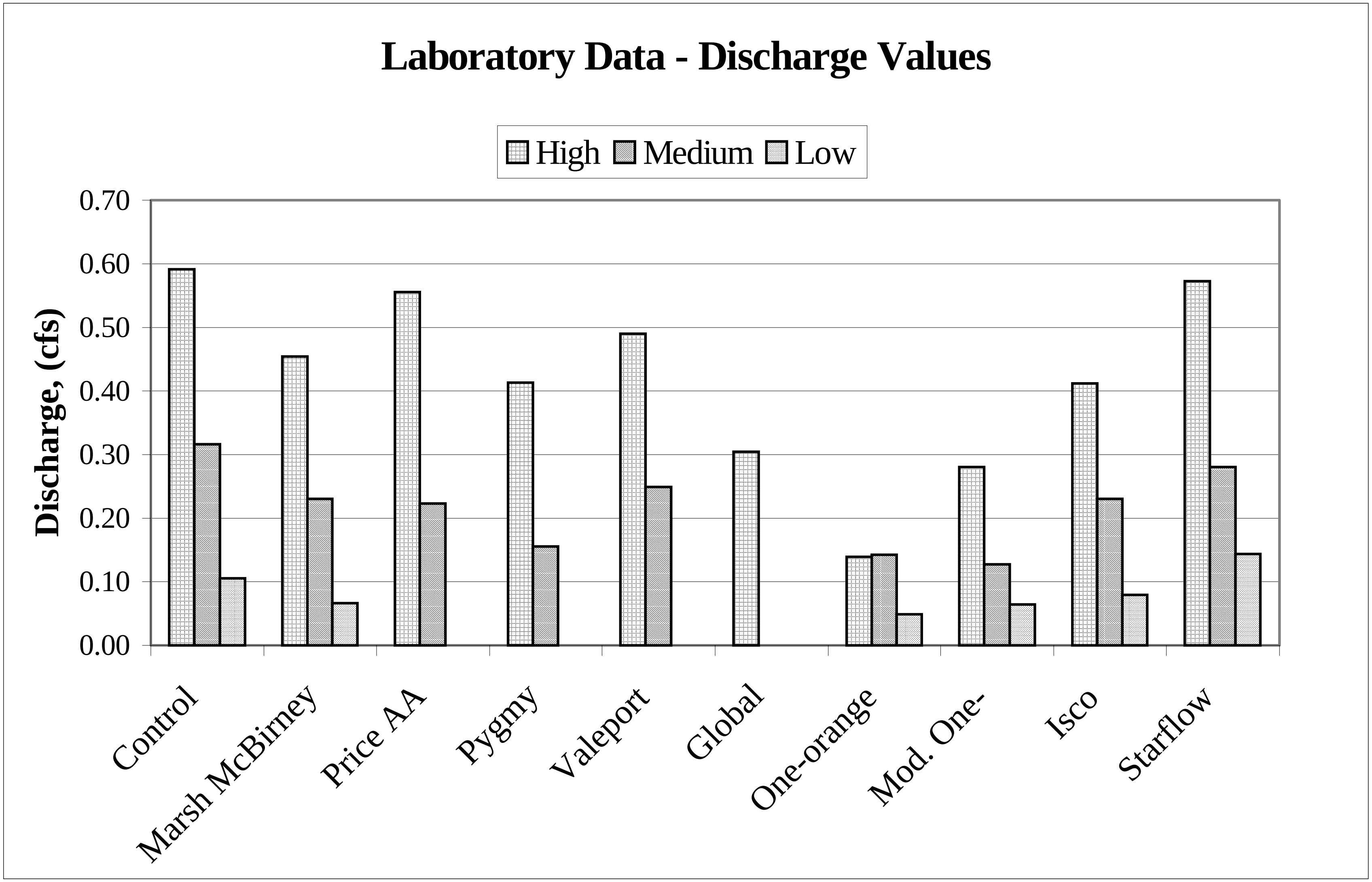


Figure 4.10 – Discharge values measured in the laboratory by various methods. A missing bar implies no flow was measured at that control (weir) discharge.

Thorne Springs Branch site was responsible for underestimation of discharge by the current meters.

The % relative error values were calculated for each measurement and descriptive statistics were prepared and tabulated for the % relative error data from each method (including non-registering data). The % relative error values represent the difference between the discharge estimate obtained by a given method and the corresponding control discharge. Calculation of all statistics is discussed more thoroughly in Chapter 3. The laboratory experiment data are contained in Appendix B, and a complete list of descriptive statistics can be found in Appendix C. Table 4.5 contains a summary of the descriptive statistics of the % relative error values. The mean and median % relative error values were negative for all the devices, indicating that all these methods underestimated the discharge in the flume. In fact, there were very few overestimations of discharge by any method. The mean and median % relative errors were probably artificially high due to the lower discharge values in the flume. A high occurrence of unregistered velocity by some devices resulted when the control discharge was very low.

Figure 4.11 shows the mean % relative error for each device in the laboratory trial, along with the 95% confidence interval for the population mean % relative error. The 95% confidence interval for the population mean % relative error was calculated using Equation 3.3. Most, but not all % relative error values were lower than those obtained in the field trials. The mechanical current meters exhibited a higher % relative error in the laboratory experiment compared to those obtained for the field investigations. This is most likely due to the instances in the laboratory where they did not register at lower velocities (29 times out of a total of 240 measurements). The Valeport BFM001 failed to measure the velocity less often than the other mechanical current meters. It registered a false zero seven times, compared to at least ten times for the other mechanical current meters. The One-orange method also had a higher % relative error in the laboratory experiment, compared to the field investigations. There is no clear reason for the higher % error associated with the use of the One-orange method in the laboratory. This method does involve characterization of the stream cross-section, and the flume has a simple rectangular profile. Estimation of the discharge using the One-orange method was improved by using the

Table 4.5 – Descriptive statistics for laboratory data % error (including non-registering values).

Method	Mean	Median	Standard Deviation	Data Range	
				Min.	Max.
Marsh McBirney	-23.1	-27.5	14.7	-37.2	26.5
Price AA	-59.3	-47.6	35.5	-100.0	0.0
Pygmy	-62.0	-50.8	30.1	-100.0	0.0
Valeport	-42.6	-29.6	33.0	-100.0	0.0
Global	-87.4	-100.0	23.5	-100.0	0.0
One-orange	-58.9	-60.2	23.9	-100.0	3.32
Mod. One-orange	-51.1	-53.0	20.9	-100.0	0.0
Isco	-29.8	-29.4	21.6	-100.0	46.9
Starflow	-13.9	-11.8	39.7	-100.0	104.1
Pres. Transducer	-0.635	-0.638	0.700	-2.10	0.509

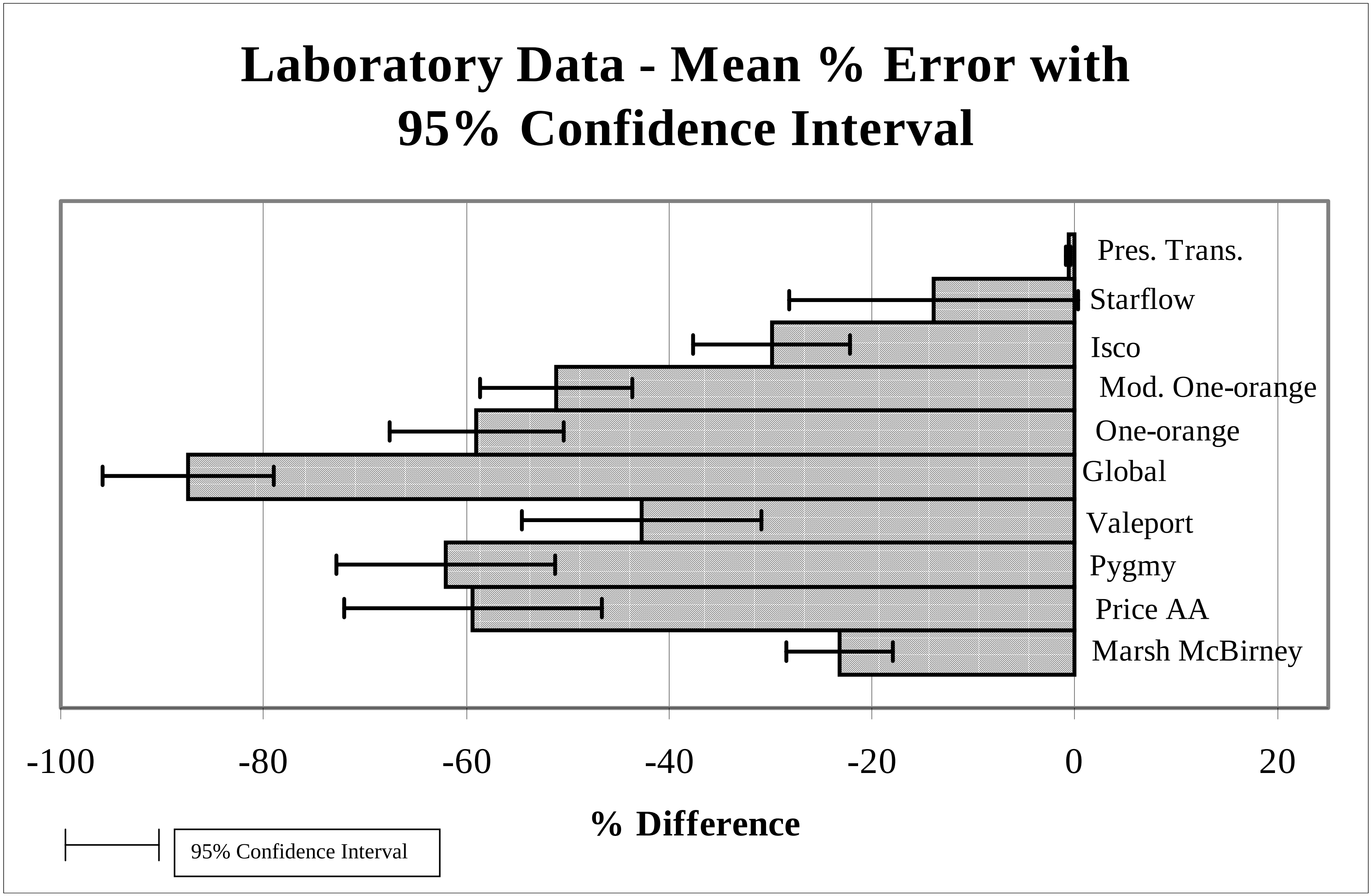


Figure 4.11 – Sample mean % error and 95% confidence interval of population mean % error for laboratory data.

calculated mean velocity to find the discharge in the flume, but the error remained relatively high. The pressure transducer, as in the field trials, exhibited a very low % relative error.

The standard deviations of the % relative error data indicate a fairly similar degree of variability among the various methods tested in the laboratory (Table 4.5). The ranges of the data listed in Table 4.5 imply there is a higher degree of variability associated with the laboratory data than the field trial data. However, the devices not measuring the very low velocity during the experiment inflated the variability of some methods. All methods, except the Marsh McBirney current meter, failed to measure flow velocity at least once during the course of the experiment. The Global flow probe failed to measure flow velocity seventeen times, while the Price AA current meter did not measure the existing flow velocity eight times. The pygmy current meter and Valeport BFM001 did not measure flow velocity seven and six times, respectively. The One-orange method failed twice to measure flow velocity. The acoustic Doppler devices errantly registered zero velocity once (Isco device) and twice (Starflow).

The standard errors were calculated for each device in the laboratory experiment, with the non-registering data points included. Figure 4.12 shows the standard error values for the laboratory data. With few exceptions, the standard error was lower in the laboratory than at either of the field study sites. Those exceptions include the Price AA, pygmy, and Marsh McBirney used at Thorne Springs Branch, and the One-orange method used at both sites.

Most methods investigated in this study have a minimum operating flow velocity as presented in Table 4.1. Still, the use of these methods below the stated minimum operating flow velocity is discretionary. In some small, slow-moving streams associated with NPS pollution studies, the investigator has no choice but to use a method in measuring discharge below its minimum operating flow velocity. There was an effort in the laboratory experiment to identify the lowest flow velocity each method is capable of measuring. This made it necessary to operate each method at discharges (and flow velocities) very near to zero. As previously mentioned, this resulted in several instances of devices not registering flow velocity in the flume. To better

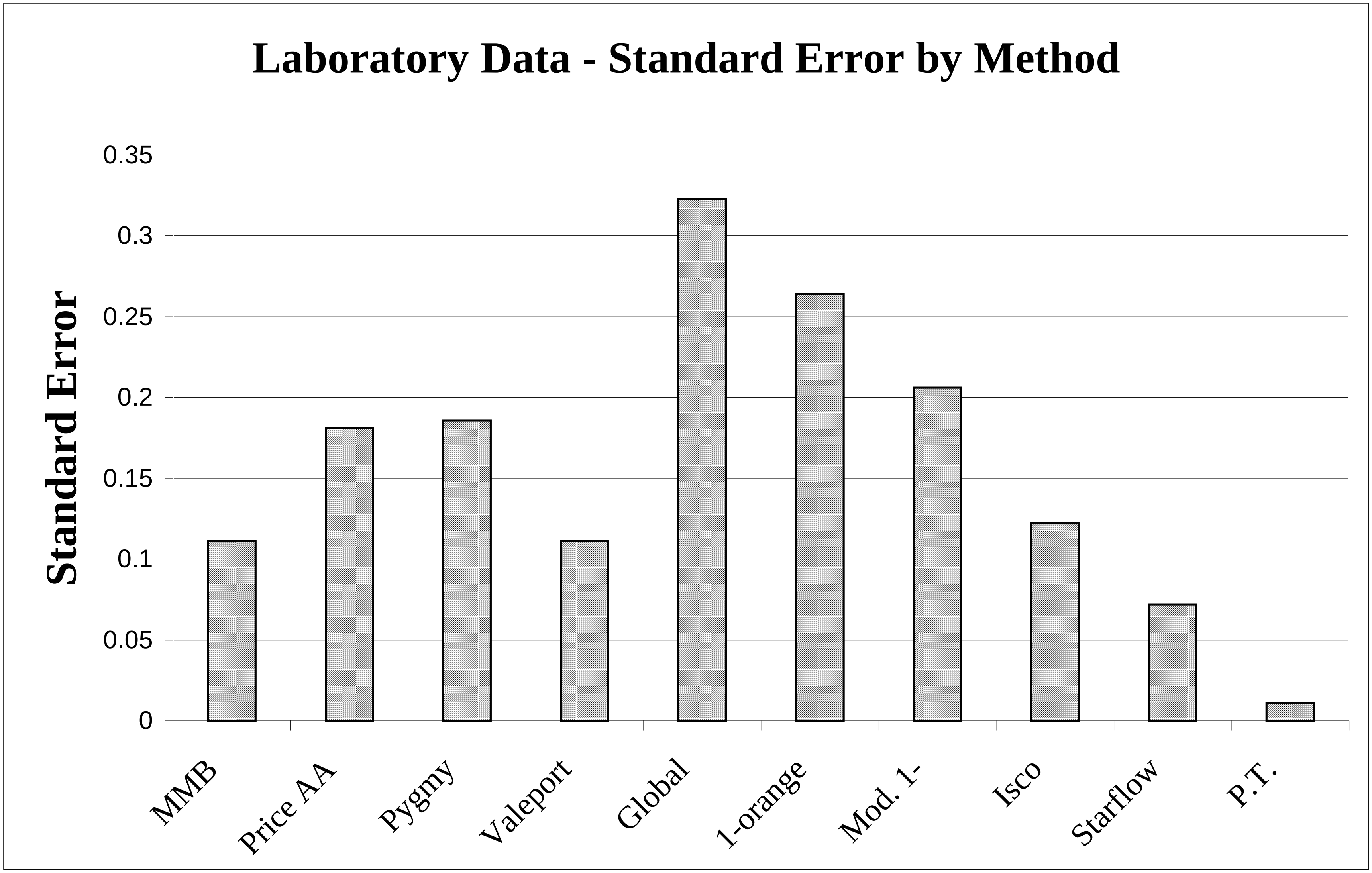


Figure 4.12 – Standard error values for various methods used in laboratory experiment.

evaluate the performance of these methods in their extended operating range, the % relative error analysis was repeated. For the second analysis, the data points were omitted if the method did not measure flow velocity. The results of this second % relative error analysis are summarized in Table 4.6. Almost all mean and median % relative error values were lower in the second analysis than in the first. Standard deviations were decreased, and ranges for the data were narrowed for most methods by omitting the non-registering data points.

As with the first % relative error analysis, which included the non-registering data points, the mean % relative error values were plotted for visual comparison. Figure 4.13 shows the mean % relative error for each method. Brackets were once again added to the plot to represent the 95% confidence of the population mean % relative error for each method. The Starflow acoustic Doppler device is the only velocity-measuring method whose 95% population mean confidence interval contains the zero value (Figure 4.13). The fact that only the Starflow confidence interval contains the zero value implies this device is the only one tested that is capable of estimating the discharge with minimal error under the given flow conditions.

Laboratory Investigation Statistical Analyses:

Since the data from the laboratory experiment contained measured discharge values for each method corresponding to a common flow discharge, different statistical analyses were performed on the data compared to those performed on the field data. The rest of the analyses in this section deal with correlation between the control and measured discharge values. Specifically, I performed linear regressions between the control and measured flow data collected by each method.

Under ideal conditions, the methods used to measure discharge would result in the same value as the control discharge. Assuming the ideal conditions existed, a plot of the measured discharge values against the corresponding control discharge values should result in a line with a slope of 1

Table 4.6 - Descriptive statistics for laboratory % relative error data with non-registering data points omitted.

Method	Mean	Median	Standard Deviation	Data Range	
				Min.	Max.
Marsh McBirney	-23.2	-27.5	14.7	-37.3	26.6
Price AA	-32.3	30.0	14.5	-54.0	0.0
Pygmy	-43.1	-45.2	15.8	-67.9	0.0
Valeport	-25.2	-27.3	8.7	-37.1	0.0
Global	-58.1	-62.1	25.1	-90.8	0.0
One-orange	-56.1	-58.1	22.0	-84.9	3.3
Mod. One-orange	-47.7	-50.4	16.8	-68.0	0.0
Isco	-27.5	-29.2	17.4	-67.4	47.0
Starflow	-4.4	-11.2	28.5	-29.0	104.1
Pres. Transducer	-0.6	-0.6	0.7	-2.1	0.5

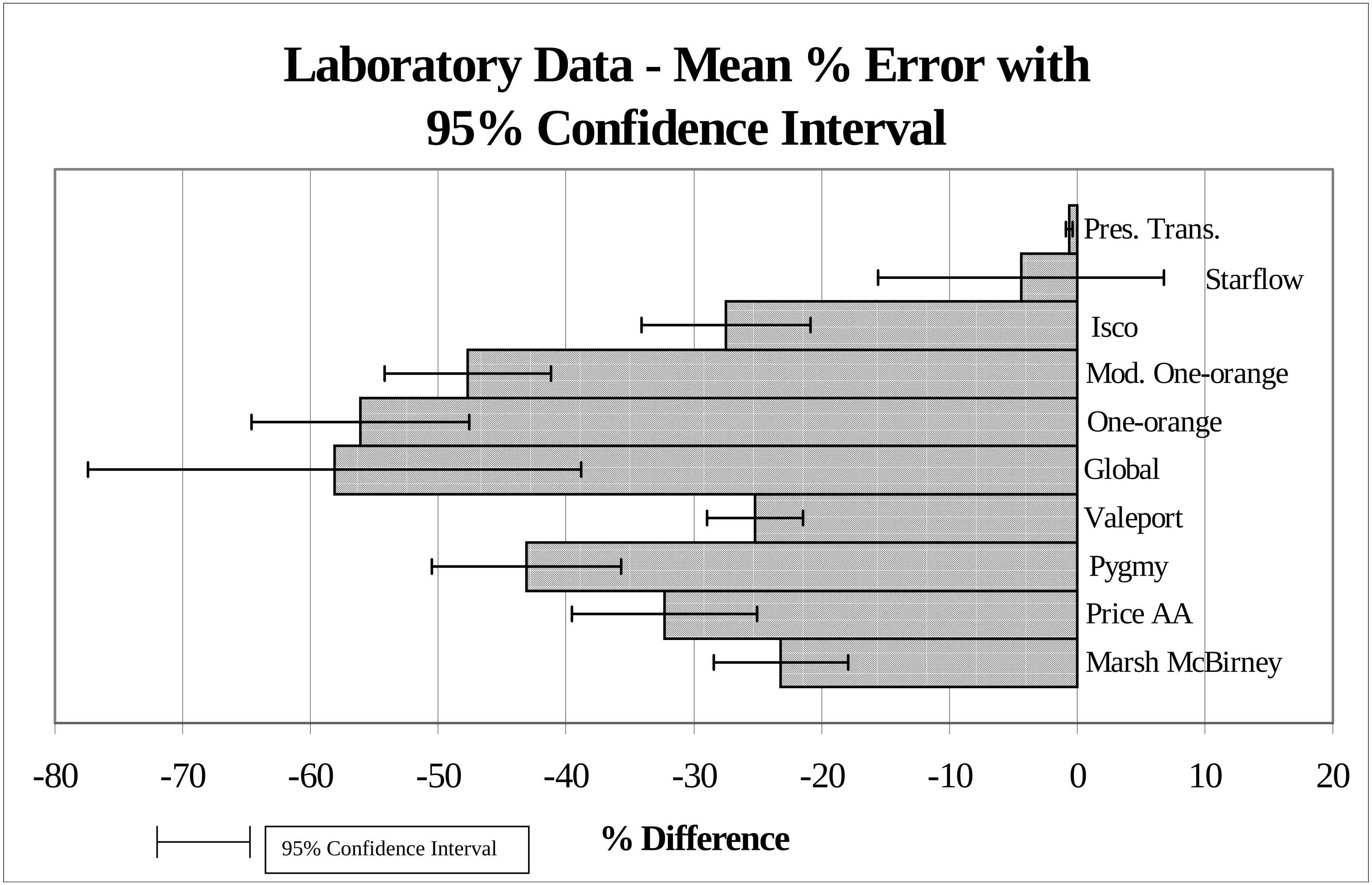


Figure 4.13 – Sample mean % relative error and 95% confidence interval of population mean for laboratory data with non-registering data omitted.

and an intercept of 0. The plots (Figures 4.14 – 4.16) of the laboratory investigation data include the ideal trend line (slope of 1 and intercept of 0) to provide a visual comparison of the data with ideal conditions.

Figure 4.14 shows the measured discharge values plotted against the control discharge for all the current meters used in this study. All the current meters underestimated the discharge in the flume when the control discharge was between 0.3 cfs and 0.55 cfs. The data exhibit a more linear trend in the higher discharge range, and more closely approximate ideal conditions. One can also see that none of the current meters, except the Marsh McBirney, were able to measure any discharge until the control discharge exceeded 0.2 cfs.

Figure 4.15 displays control and measured discharge values for the Global flow probe, One-orange method, and the modified One-orange method. As the discharge rates increased, the variability in the discharge data collected by the One-orange method and modified One-orange increased, as did the gap between the data and ideal trend line. Most of the data points for the Global flow probe lie on the y-origin, indicating the device did not measure flow velocity for most of the control discharge range. The minimum recommended operating velocity of this device is 0.3 fps (Table 4.1). The majority of the flow velocity values in this experiment were below 0.3 fps, which explains the Global flow probe's failure to register velocity for much of this experiment. When the probe did register velocity, the variability was still quite large.

Figure 4.16 contains similar discharge data for the two acoustic Doppler devices. The data for the Starflow device seem to follow the 1:1 trend line better than any other method used in the study. The Starflow data points fell on both sides of the line for the majority of the control discharge range. The data for the Isco device diverge from the ideal trend line as the control discharge increased. The Isco data exhibited a linear trend with little variability, but the slope of the trend line was less than 1.

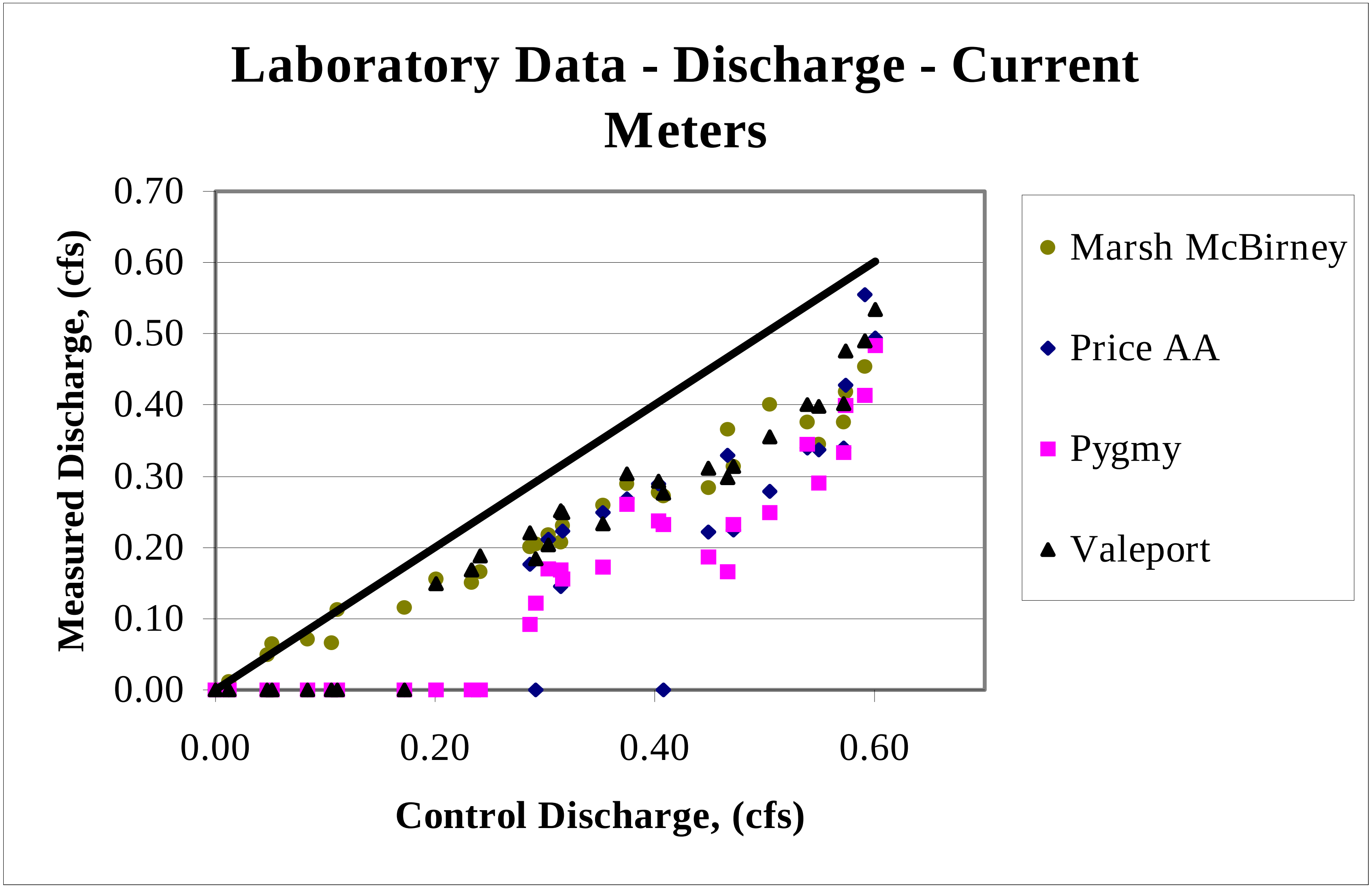


Figure 4.14 – Laboratory current meter and control discharge data with ideal trend line.

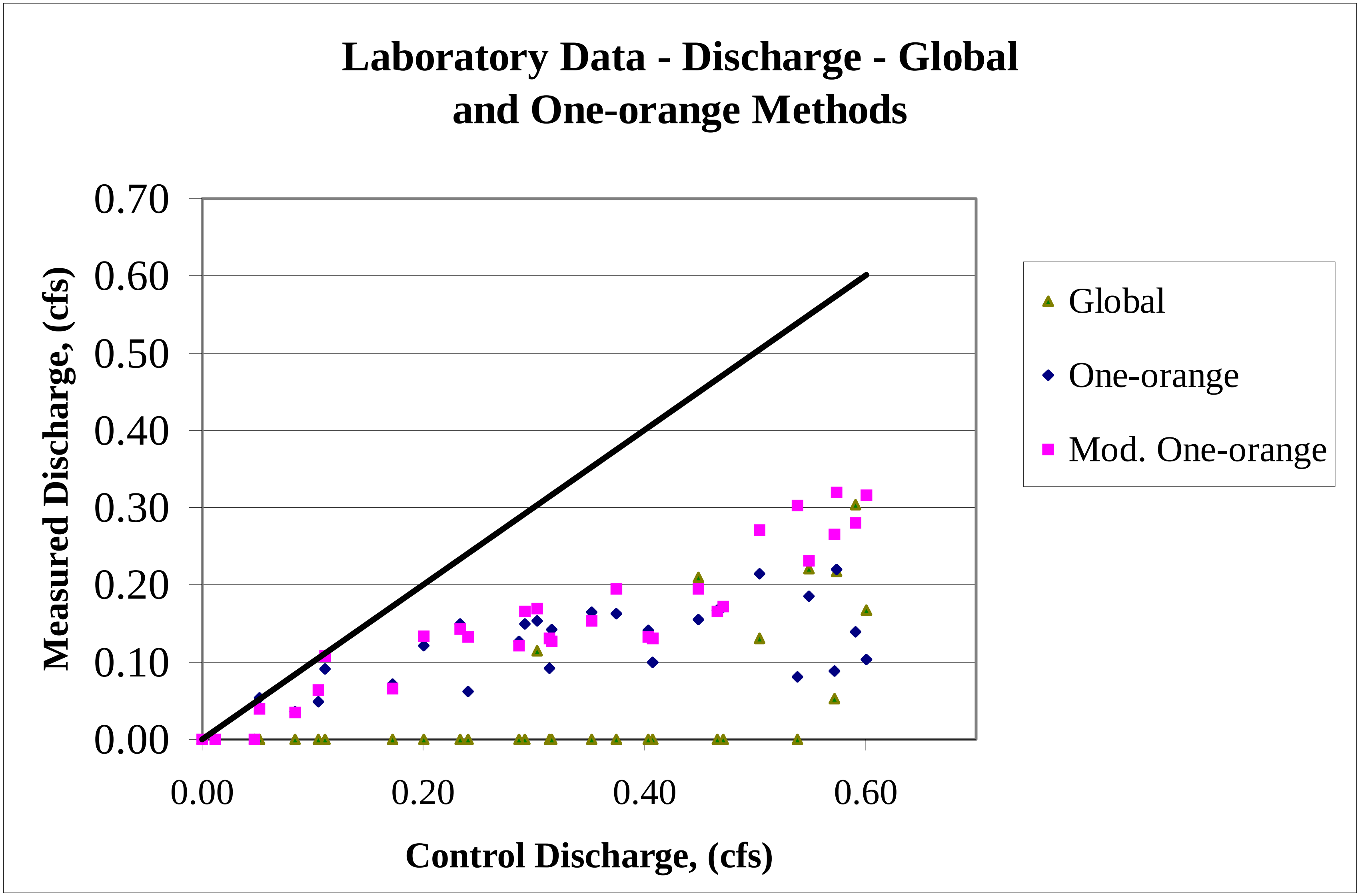


Figure 4.15 – Laboratory Global flow probe, One-orange method, and control discharge data with ideal trend line.

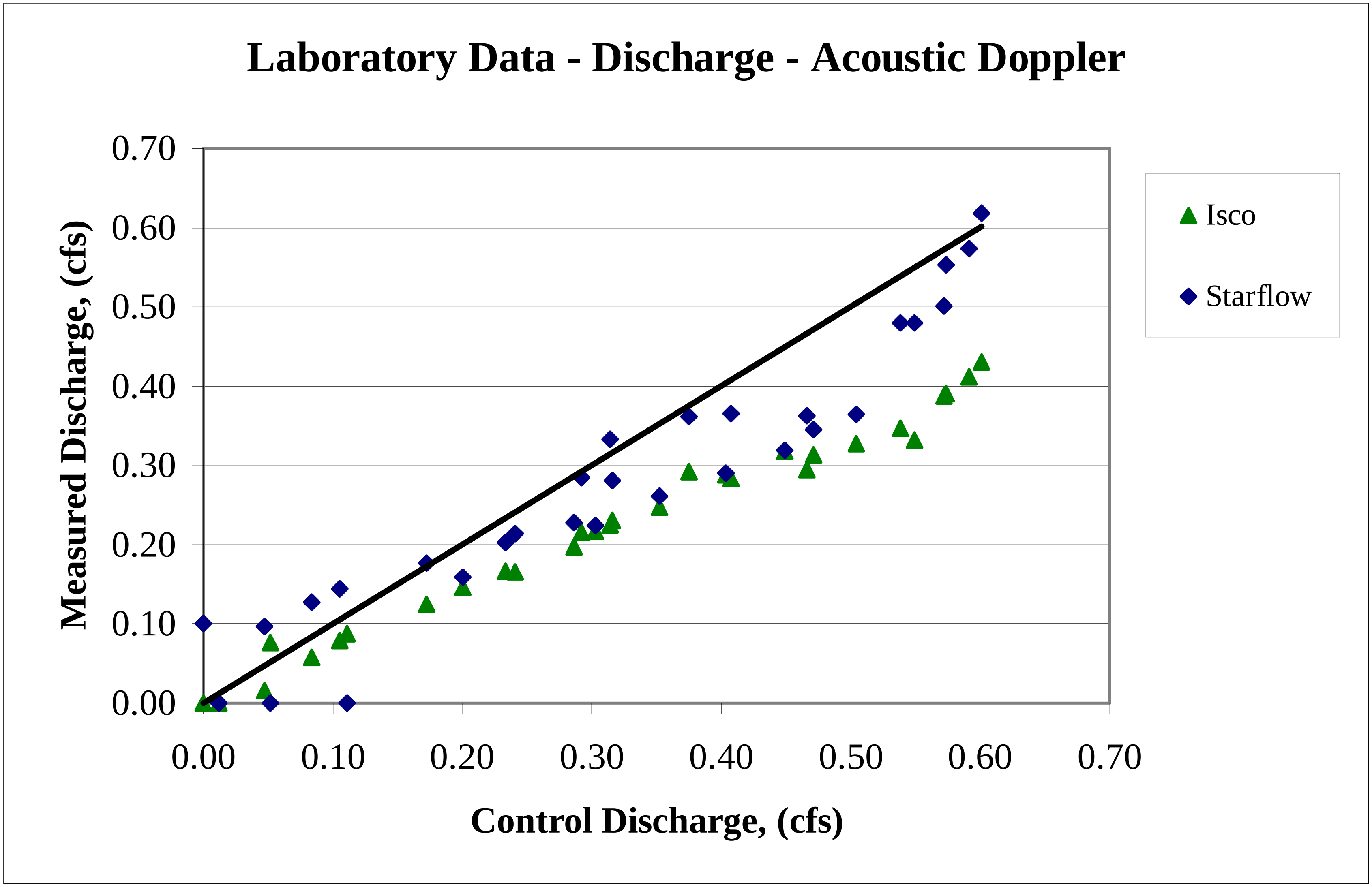


Figure 4.16 – Laboratory acoustic Doppler device and control discharge data with ideal trend line.

In an attempt to determine the minimum average velocity below which the methods used in this study are not applicable, the flume was operated at very low discharge values approaching zero flow. The control and measured discharge values were converted to mean velocity values using the cross-sectional area of the flow. The average velocity values were calculated by dividing the discharge by the flow depths in the flume at the various measurement sections. The flume is 1 ft wide, so the depth equals the area. Mean velocity for the One-orange method was calculated using Equation 2.7. The velocity data are plotted in Figures 4.17, 4.18 and 4.19.

Figure 4.17 shows the average velocity data for the current meters. The Marsh McBirney current meter did not fail to measure velocity at any point in the experiment. The Valeport BFM001 current meter appears to stop registering velocity at a mean control velocity below 0.19 fps. Both the Price AA and pygmy current meters seem to stop measuring velocity below 0.26 fps. Figure 4.18 includes velocity data for the Global flow probe and the One-orange method. The Global flow probe does not appear to consistently register velocity until almost 0.5 fps, but the results under higher flow velocity are still not satisfactory. The One-orange method failed to measure mean velocity only at the very lowest control mean velocity (0.051 fps). Figure 4.19 shows data for both of the acoustic Doppler devices. The Starflow was very effective in the lower velocity range in this experiment, except for one data point below 0.15 fps. The Isco device measured velocity during the entire range of control average velocity.

Regression analyses were conducted between the measured discharge data by each device and the corresponding control discharge data. Since the lack of flow measurements at low velocity might skew the regression results, measurements where no flow velocity was registered were omitted from the data prior to the regression analysis. This omission was intended to create a regression that is representative of the operating range of each method. The desired result for each analysis was a linear equation with an intercept of zero and a slope of 1.

The results of the regressions performed on the discharge data are presented in Table 4.7. The data for the pressure transducer are also included in Table 4.7. The p-value listed pertains to the possible rejection of the null hypothesis of Y-intercept being equal to 0. A very low p-value

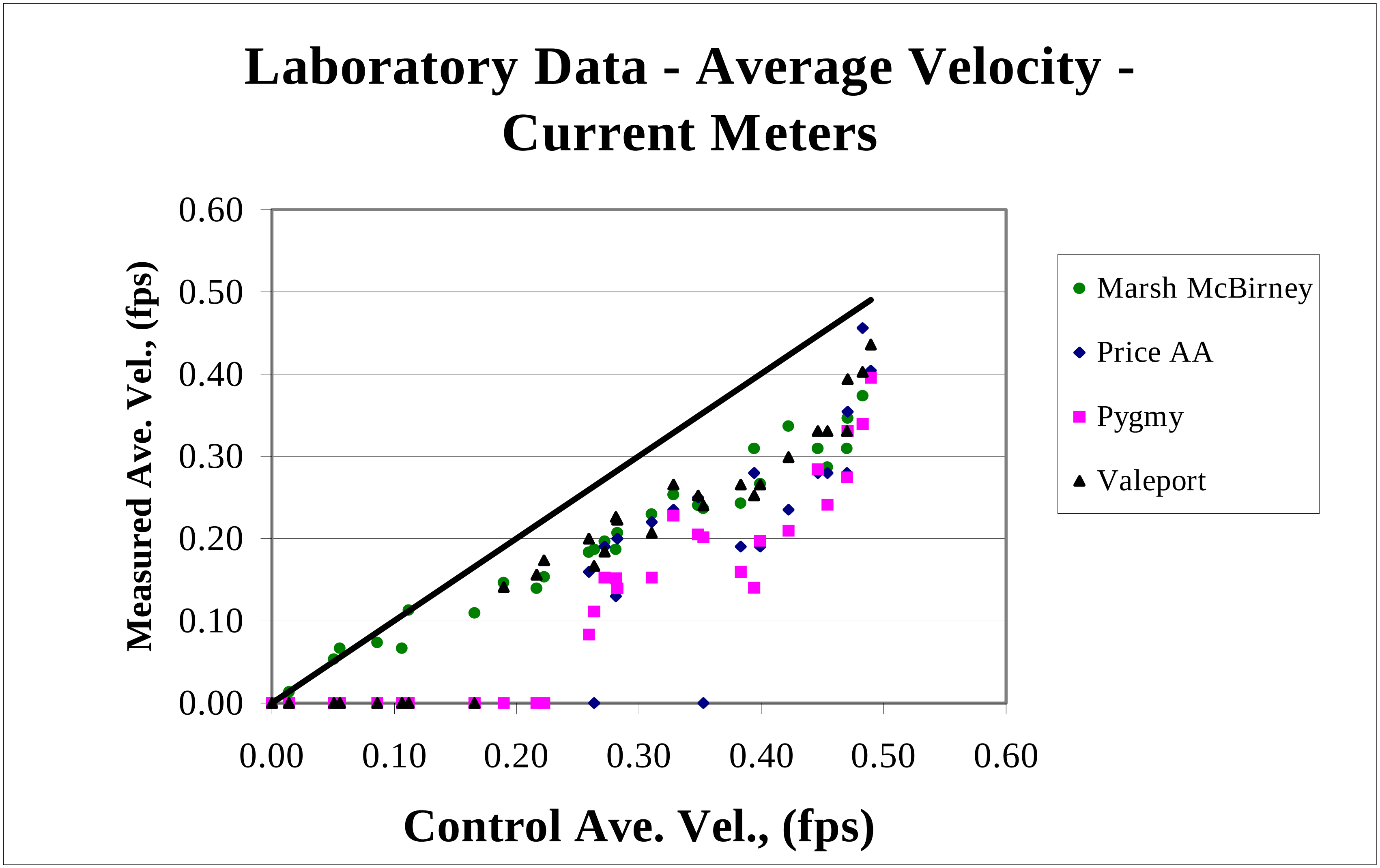


Figure 4.17 – Laboratory current meter and control average velocity data with ideal trend line.

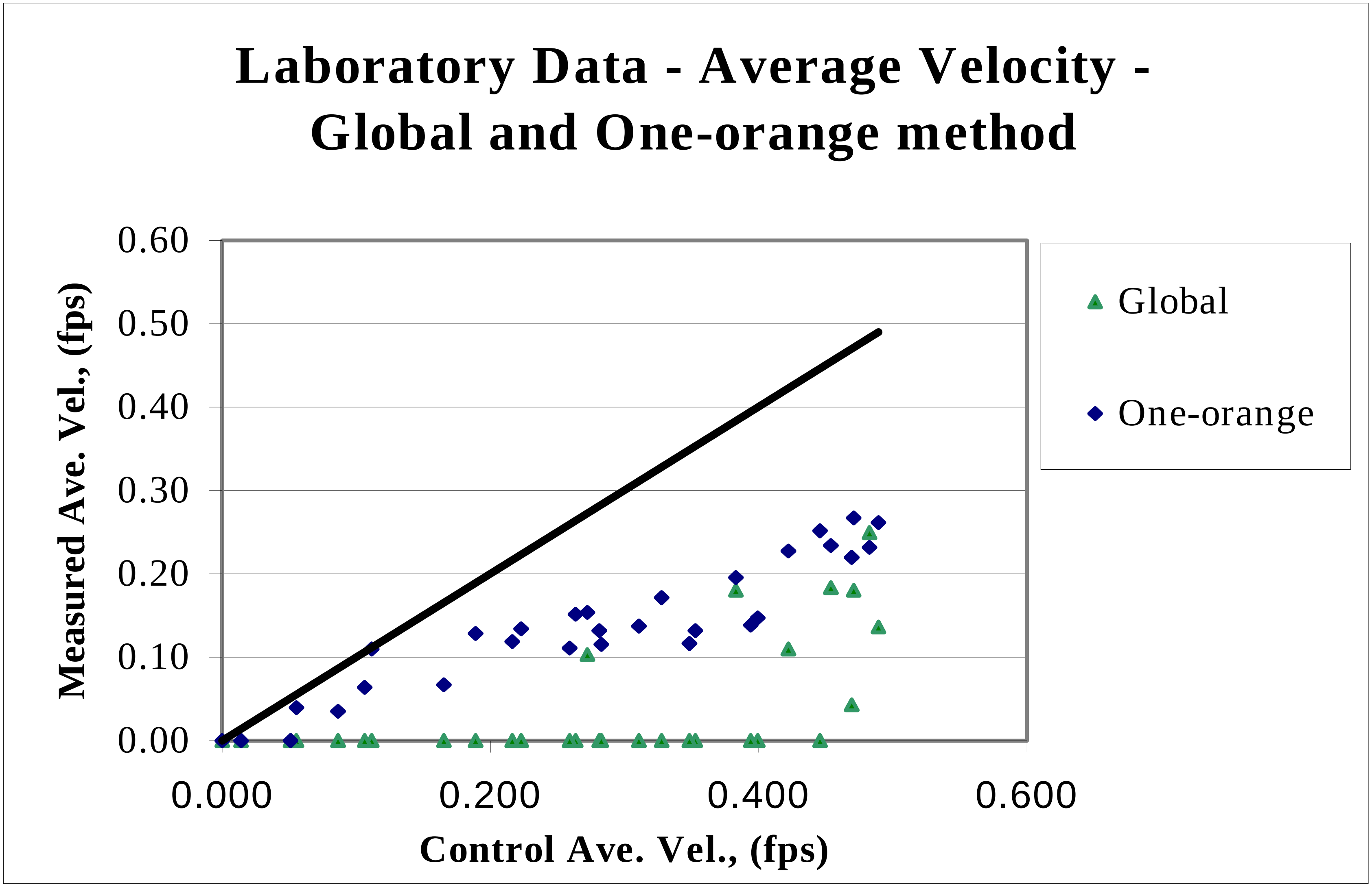


Figure 4.18 – Laboratory Global probe, One-orange method, and control average velocity data with ideal trend line.

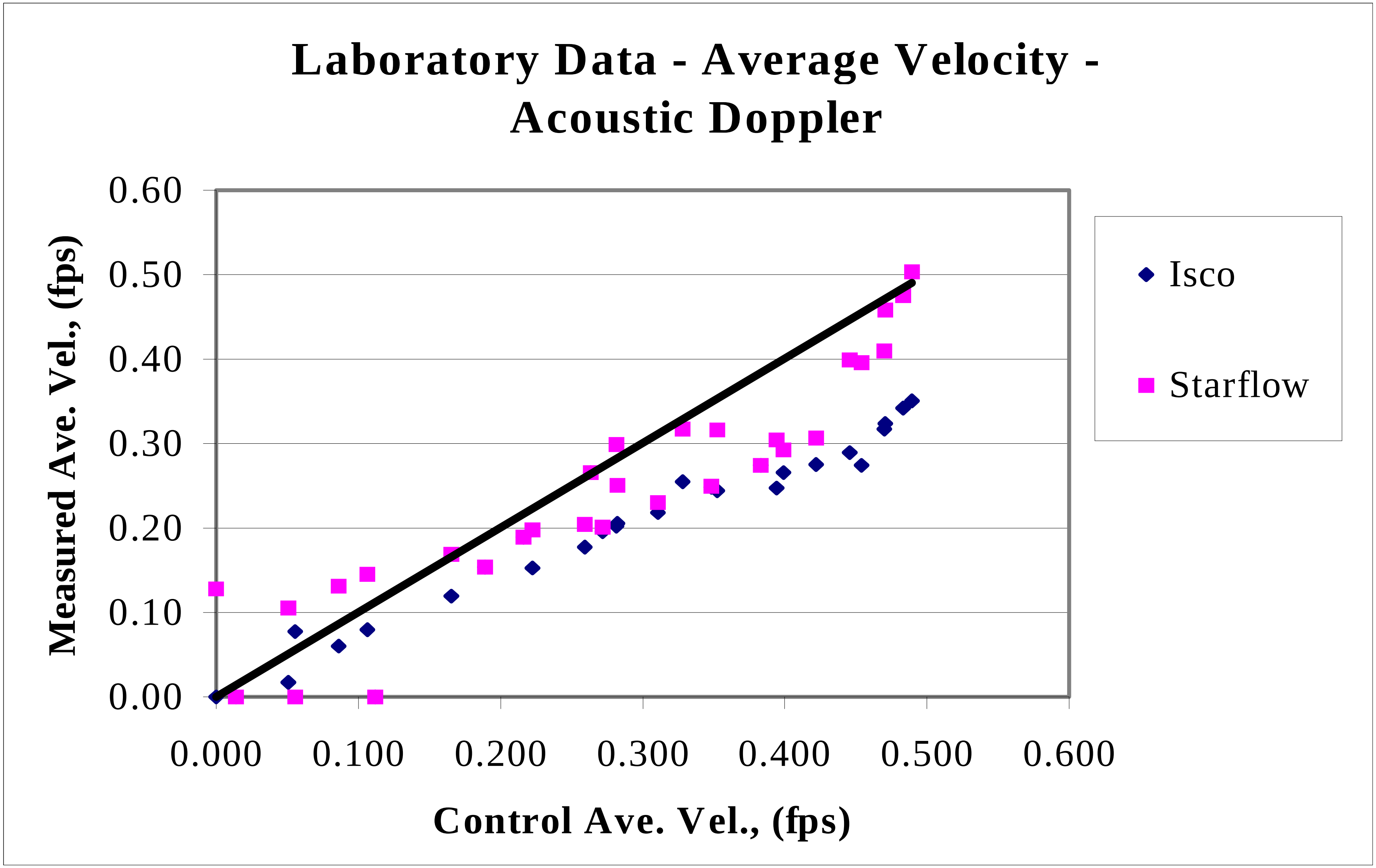


Figure 4.19 – Laboratory acoustic Doppler and control average velocity data with ideal trend line.

(<0.10) implies statistical significance, and that the hypothesis should be rejected. A higher p-value, on the other hand, indicates a greater chance that the Y-intercept is equal to 0, and a failure to reject the null hypothesis. The standard error in the table gives an indication of the reliability of the regression, and is a measure of the scatter of the data about the regression line. A higher standard error implies more variability of the data about the regression.

Table 4.7 – Data describing regressions between measured and control discharge by method.

Method	Y-intercept	p-value	Slope	Standard Error
Marsh McBirney	0.005	0.559	0.705	0.137
Price AA	0.129	0.007	1.044	0.024
Pygmy	0.156	0.000	1.114	0.132
Valeport	0.048	0.035	1.186	0.067
Global	0.239	0.059	1.402	0.588
One-orange	0.082	0.218	2.144	0.489
Mod. One-orange	0.030	0.301	1.907	0.157
Isco	-0.013	0.207	1.498	0.039
Starflow	-0.004	0.896	1.130	0.078
Pressure Trans.	-0.004	0.802	1.010	0.013

The pressure transducer data resulted in a practically ideal regression with a Y-intercept of -0.004, a slope of 1.010, and a standard error of 0.013. Among the velocity-area methods of discharge measurement, the Starflow acoustic Doppler device exhibited a trend closest to the ideal conditions. This confirms the visual observations made in Figure 4.16. The following methods also have a Y-intercept equal to 0: Marsh McBirney current meter, both versions of the One-orange method, and the Isco acoustic Doppler device. The high p-values (>0.5) of the Marsh McBirney current meter, Starflow acoustic Doppler device, and pressure transducer provide strong evidence to fail to reject the null hypothesis of a Y-intercept equal to 0. All the current meters evaluated exhibited a regression slope close to 1, ranging from 0.705 to 1.186. Aside from the current meters and the Starflow acoustic Doppler device, the remaining velocity-area methods resulted in a slope greater than 1.4. The One-orange method exhibited the highest slope value (2.144). Among the velocity-area discharge measurement methods, the lowest standard error values resulted from the Price AA current meter (0.024), and the Isco acoustic

Doppler device (0.039). The Global flow probe and the One-orange method also had the highest values of standard errors (0.588 and 0.489, respectively), indicating high variability in the data about the regression line.

To more thoroughly assess the relative accuracy of the methods tested in the laboratory experiment, the statistical consulting center staff (Steeno, 1999) suggested using an analysis of covariance using the control discharge values as the covariate. Details of these methods were discussed in Chapter 3. The results of these analyses can be found in Appendix C. This procedure is intended to compare multiple treatment means, and is a combination of a linear regression and analysis of variance (Walpole and Myers, 1993). The experiment was a completely randomized design with multiple treatments and a single covariate, the control discharge. The result provides an improved evaluation of the regressions between the measured and control discharge values previously discussed in this chapter.

Prior to performing the analysis of covariance, the statistical consulting center staff assisted with regressions of the treatment (methods) data and the control (weir) data. The program also compares the regression parameters of the various treatments to the ideal conditions (slope of 1, intercept of 0). Included in the results for this procedure were the 95% confidence intervals for the differences between the treatment regression parameters and the ideal regression parameters. The methods for which the confidence intervals include a zero value for the difference between the treatment and control slope parameter include the Price AA , pygmy, and Valeport BFM001 current meters, and the Starflow acoustic Doppler device. Similarly, the methods whose 95% confidence intervals for difference of intercept include the value of zero include Marsh McBirney current meter, Valeport BFM001 current meter, both acoustic Doppler devices, and the modified One-orange method. This implied that these methods could have the ideal regression parameters stated.

Also included in the analysis was the test of fixed effects, and the solution for fixed effects. Included in the solution for fixed effects was an estimation of the slope of the regressions between the treatment and control data. The Price AA current meter, pygmy current meter, Valeport BFM001 current meter, and the Starflow acoustic Doppler device exhibited slopes nearest to one among the methods tested. Thus, these methods most closely reflect the performance of the thin-plate weir used as the control in this experiment. The results of the tests of fixed effects also implies the slopes of these methods most closely match the slope of the control. In this test, the null hypothesis is that there is no difference in the treatment and control slopes. The alternative hypothesis is that the two slopes are not equal. The p-values of these methods (Price AA, pygmy, Valeport, and Starflow) indicate a failure to reject the null hypothesis.

To further compare the regressions for these four methods (Price AA, pygmy, Valeport, and Starflow), the analysis of variance for the equations was printed and reviewed. Through the comparison of the regression parameters to those of the control regression parameters and ideal regression conditions, the Price AA current meter, pygmy current meter, Valeport BFM001 current meter, and the Starflow acoustic Doppler device were considered to have estimated the discharge in the flume more accurately than the other methods. Emphasis was placed on the regression slope for each method, or the difference between the slopes of the method and control regressions.

The next criterion used to determine which method performed best in the laboratory experiment was the evaluation of the Y-intercept and its p-value. Using this criterion, the Valeport BFM001 current meter and the Starflow acoustic Doppler device performed better than the other two.

As a final criterion to establish which method best estimated the control discharge, the R^2values were investigated. A high value of R^2 implies a strong relationship between the two variables in the regression (measured and control discharge). The R^2 values for the Valeport and Starflow devices were 0.917 and 0.874, respectively. While these values are very close, when considered with the previous two criteria, they do not distinguish the two devices from one another.

Table 4.8 contains a summary of the data considered for the three criteria (slope, Y-intercept, and R^2). Data for a given criterion were not listed in Table 4.8 for methods that were eliminated from consideration as the most accurate using the previous criterion (reading the table from left to right).

Table 4.8 - Analysis of covariance summary.

Method	Difference in slope (method-control)	Y-intercept	p-value	R^2
Marsh McBirney	-0.256	---*	---	---
Price AA	0.074	-0.209	0.003	---
Pygmy	-0.051	-0.176	0.000	---
Valeport	-0.187	-0.030	0.223	0.917
Global	-0.507	---	---	---
One-orange	-0.929	---	---	---
Mod. One-orange	-0.541	---	---	---
Isco	-0.369	---	---	---
Starflow	-0.056	-0.033	0.345	0.874

*Data were not listed for methods eliminated from consideration as "most accurate" using the previous criterion (reading the table left to right).

Based on the three criteria indicated (slope, Y-intercept, and R^2), among the velocity-area discharge measurement devices tested, the Starflow acoustic Doppler device is the best-performing method for measuring discharge. The Y-intercepts and R^2 values are practically the same for the Starflow and Valeport devices, but a higher slope (0.94) was obtained using the Starflow, compared to the 0.81 slope for the Valeport device.

From the results of this laboratory experiment, a few observations can be made. The Marsh McBirney performs very reliably, even in extremely slow-moving flows. However, for the flow velocities in the range of those seen in this experiment (<0.50 fps), the Valeport BFM001 current meter and the Starflow acoustic Doppler device are the most accurate of the devices tested. Some devices, such as the Starflow acoustic Doppler device, can safely be used below their recommended minimum flow velocities. Other devices, like the Global flow probe, should not be used below their recommended minimum velocities.

The Marsh McBirney current meter and One-orange method exhibited the highest accuracy in the field study, while the Starflow acoustic Doppler and Valeport BFM001 current meter performed best in the laboratory experiment. The Marsh McBirney, while not the most accurate, did perform well in the laboratory experiment. Similarly, the Valeport BFM001 current meter performed well in the field study, though it was not the most accurate method. The pygmy and Price AA current meters performed well in both the field and laboratory. The One-orange method did not perform well in the laboratory experiment, and the Starflow acoustic Doppler device did not estimate discharge well in the field. Considering the overall accuracy in both field and laboratory, the Marsh McBirney and Valeport BFM001 current meters performed the best among the methods evaluated. Conversely, the Global flow probe provided the least accuracy under the conditions encountered in both the field study and laboratory experiments.

CHAPTER 5
COST ANALYSIS

Introduction:

A cost analysis was conducted to provide information on the initial and annual costs associated with each of the methods investigated. Cost of various methods is included in the USBR Water Measurement Manual, but the manual only advises the user whether or not cost should be a significant consideration when choosing a particular stream-gaging method (USBR, 1998). The cost factor is designated by a “+”, “-“, or “0” indicating a positive, negative, or no negative effect on the decision to employ a given method.

For each method evaluated in this study, the equipment required to collect continuous record of flow data was included in the analysis. It is impossible to provide the user with a cost analysis applicable to all stream-gaging situations, given the variations encountered in the field. As an example, excavation costs associated with installing a stilling well can vary widely depending on the type of soil material encountered while digging. For this reason, some assumptions were made in the process of the cost analysis to evaluate each method under the same conditions. The assumptions made produce a hypothetical application scenario similar to the sites in the field investigations in this study. The hypothetical site that was considered in this cost analysis was assumed to be located in a stream similar in size and configuration to the Crab Creek and Thorne Springs Branch sites.

This analysis is intended only as a guideline to aid the hydrologist in selecting a suitable and cost-effective flow measurement method for a given situation. The nature of this analysis is very simple. There are no benefit-cost ratios, annualized costs, or other such economic tools utilized in this cost analysis.

Methodology:

The major cost categories and brief explanations of their constituents are listed in Table 5.1. The initial costs listed under the name of each method include the purchase costs of the devices themselves, along with any peripherals that may be required for their implementation. For example, when using a current meter, this category would include the purchase and maintenance of the current meter, wading rod, and any electronics (headset or digital display interface) associated with the current meter. The annual costs listed under the method consist of maintenance costs, such as battery replacement, associated with the particular equipment used with that method.

For all methods, except acoustic Doppler devices, a stilling well may be necessary to create a continuous flow record. However, the cost of a stilling well is not included in the cost analysis for each method, as it is common to so many methods. The initial and annual costs have been listed separately in the analysis for reference only. A stilling well is neither required nor included for the acoustic Doppler methods, but an instrument shelter was included in these estimates for security purposes. The stilling well is commonly a 24-inch corrugated metal pipe equipped with a 3-inch diameter intake pipe. The stilling well is typically equipped with a small instrument shelter and a float and weight type stage recorder. The cost of a staff gage is included for all stream-gaging methods considered.

Initial operation costs include the costs associated with establishing the gaging site. This includes identification of the gaging site, any construction costs necessary to operate the gaging station, and development of the stage-discharge relationship for the site. This relationship is used to transform stage data collected at the site to discharge records. This relationship must be refined throughout the operation of the gaging site to reflect any changes in the flow characteristics of the stream. Installation of the staff gage is an example of construction-type initial operation costs. Once established, the gaging station must be maintained. The annual operation costs resulting from maintenance of the gaging station include tree-trimming, cleaning the staff gage, and refining the stage-discharge relationship.

Table 5.1 – Major cost categories and their initial and annual constituents.

Cost Category	Initial Costs Considered	Annual Costs Considered
Device and required accessories	Purchase of current meter, sensor, or other equipment that constitutes each method	Maintenance of equipment, batteries, etc.
Operation	Developing and refining the stage-discharge relationship	Maintaining the site rating, collecting and processing flow data
Heavy duty measuring tape	Purchase of the measuring tape, which is to be used as a tag line	Maintenance and replacement of the tape
Installation and/or extraction	Installing a given device, such as an acoustic Doppler, into the stream (or extracting it)	N/A
Shelter	Construction and installation of an instrument shelter without a stilling well	Maintenance of the instrument shelter
Laptop computer and accessories	Hardware/software purchase	Maintenance of hardware and software upgrades

A heavy duty measuring tape is listed separately in the cost analysis, though it could be considered peripheral equipment needed for operation of current meters. The tape measure is used in place of a tag line in this analysis because the tape measure is sufficient to measure the cross-section in smaller streams such as those considered in this study. The initial and annual costs simply relate to the purchase and maintenance or replacement of the tape.

The installation and extraction costs associated with each method include the described costs associated with the specific method used. There are no annual costs, as installation and extraction of the method should be considered before the method is employed. An example of such costs is the installation of an acoustic Doppler sensor in a stream. This requires the fabrication or purchase of a mounting plate suitable for use in the stream, among other details associated with such a method. Establishment of the gaging site is not accounted for in this category, as it has already been considered in the initial operation costs.

Some methods require an instrument shelter, as described earlier. The initial costs associated with such a shelter include the construction and installation of such a structure. The annual costs include routine maintenance, such as painting.

The cost of a personal computer was included only for those methods that required one to operate in the field environment. This condition is limited to the acoustic Doppler devices in this study. The initial costs associated with this cost category are the purchase cost of a laptop computer and any required software. The software for these devices is typically included with the purchase of the sensor. Annual costs include the maintenance of the computer, and any possible software upgrades. Once again, the software upgrades are typically free with ownership of the sensors.

Equipment costs used for each device represent current purchase cost with no allowance for taxes or other such costs. Most prices were obtained from the manufacturer or a retail catalog provided by an equipment distributor. Necessary items such as rechargeable batteries, wading rods, tag lines, etc. were included in the initial costs of the method and were obtained from the same sources.

Maintenance and annual operating costs of the equipment used in this analysis were derived using the prescribed maintenance procedures for each device as outlined by the USGS (Rantz et al., 1982) or the individual manufacturer. Maintenance and annual operating costs of the stilling well and associated equipment were estimated by interviewing staff of the Watershed Monitoring Project in the Biological Systems Engineering department at Virginia Tech (McClellan, 1999). The values used in these analyses are cost estimates for application of the various methods under the hypothetical “average condition” described previously, and were estimated by the staff based on their experience with a wide variety of sizes of research watersheds.

The final result consists of a table listing each of the methods used in this study and its categorized initial and annual costs as determined by these analyses. Contingency costs were not added to the estimates resulting from this study.

Results of the Cost Analysis:

The costs associated with each of the methods investigated in this study were evaluated to provide hydrologists with means to assess the relative costs of the methods for stream flow monitoring. This analysis is intended merely as a guide, and is based on the hypothetical scenario described in the previous section. Careful analysis of costs associated with use of any method at a particular site should be made before the final selection of the method. Other criteria such as accuracy, site conditions and potential debris accumulation should also be considered when deciding on a stream-gaging method.

The results of the cost analysis are displayed in Table 5.2. Description of the various cost categories can be found in Table 5.1. The initial costs for both Price-type current meters (Price AA and pygmy) are practically the same. Similarly, the initial costs of the Marsh McBirney and Valeport current meters are very similar. The difference in cost between the Marsh McBirney and Valeport current meters and the Price-type current meters is about $2,000, however. This difference in cost is directly related to the difference in the price of the current meters themselves and required accessories. The total initial costs associated with the first six methods (Price AA, pygmy, Marsh McBirney, Valeport, Global flow probe, and One-orange method) of discharge measurement vary by $4,242. The major initial cost associated with these six methods is the operation cost. The operation cost is comprised of the costs of gaging site and development of the stage-discharge relationship required for use with each of these methods. The estimated costs of the initial operation of the gaging site for these methods is $3,000, more than half of the total initial costs of the majority of these six methods. Since the initial operating costs of these six methods is equal, the difference in initial costs lies in the initial costs associated with each method. One can simply refer to these initial method costs to decide which is most cost-effective.

Table 5.2 – Cost analysis data with initial cost and annual cost totals for each method.

Cost Category	Price AA			Pygmy			Marsh McBirney		
	Initial	Annual	Total	Initial	Annual	Total	Initial	Annual	Total
Device and required accessories	$2,050	$102	$2,152	$1,898	$102	$2,000	$3,894	$125	$4,019
Heavy duty measuring tape	$25	$5	$30	$25	$5	$30	$25	$5	$30
Operation	$3,000	$3,000	$6,000	$3,000	$3,000	$6,000	$3,000	$3,000	$6,000
Datalogger	-	-	-	-	-	-	-	-	-
Shelter	-	-	-	-	-	-	-	-	-
Top-set wading rod	-	-	-	-	-	-	$395	-	$395
Installation/extraction	-	-	-	-	-	-	-	-	-
Laptop computer and accessories	-	-	-	-	-	-	-	-	-
Site survey and initial investigation	-	-	-	-	-	-	-	-	-
Gaging station instrumentation	-	-	-	-	-	-	-	-	-
TOTAL	$5,075	$3,107	$8,182	$4,923	$3,107	$8,030	$7,314	$3,130	$10,444

Cost Category	One-orange			Isco Doppler			Starflow Doppler		
	Initial	Annual	Total	Initial	Annual	Total	Initial	Annual	Total
Device and required accessories	$47	$10	$57	$4,075	-	$4,075	$1,878	-	$1,878
Heavy duty measuring tape	-	-	-	-	-	-	-	-	-
Operation	$3,000	$3,000	$6,000	$504	$648	$1,152	$504	$648	$1,152
Datalogger	-	-	-	-	-	-	-	-	-
Shelter	-	-	-	$150	$20	$170	$150	$20	$170
Top-set wading rod	-	-	-	-	-	-	-	-	-
Installation/extraction	-	-	-	$141	-	$141	$141	-	$141
Laptop computer and accessories	-	-	-	$1,400	$125	$1,525	$1,400	$125	$1,525
Site survey and initial investigation	-	-	-	-	-	-	-	-	-
Gaging station instrumentation	-	-	-	-	-	-	-	-	-
TOTAL	$3,047	$3,010	$6,057	$6,270	$793	$7,063	$4,073	$793	$4,866

Table 5.2 (continued) – Cost analysis data with initial cost and annual cost totals for each method.

Cost Category	Pres. Transducer			Global Probe			Stilling Well		
	Initial	Annual	Total	Initial	Annual	Total	Initial	Annual	Total
Device and required accessories	$608	$550	$1,158	$709	$90	$799	$15,000	$250	$15,250
Heavy duty measuring tape	-	-	-	-	-	-	-	-	-
Operation	$4,200	$4,200	$8,400	$3,000	$3,000	$6,000	-	-	-
Datalogger	$1,100	-	$1,100	-	-	-	-	-	-
Shelter	$150	$20	$170	-	-	-	-	-	-
Top-set wading rod	-	-	-	-	-	-	-	-	-
Installation/extraction	$141	-	$141	-	-	-	$1,500	-	$1,500
Laptop computer and accessories	-	-	-	-	-	-	-	-	-
Site survey and initial investigation	-	-	-	-	-	-	-	-	-
Gaging station instrumentation	-	-	-	-	-	-	$2,500	$504	$3,004
TOTAL	$6,199	$4,770	$10,969	$3,709	$3,090	$6,799	$19,000	$754	$19,754

Cost Category	Valeport			Dilution		
	Initial	Annual	Total	Initial	Annual	Total
Device and required accessories	$3,628	$115	$3,743	$4,073	-	$4,073
Heavy duty measuring tape	$25	$5	$30	-	-	-
Operation	$3,000	$3,000	$6,000	$4,300	$4,300	$8,600
Datalogger	-	-	-	-	-	-
Shelter	-	-	-	-	-	-
Top-set wading rod	-	-	-	-	-	-
Installation/extraction	-	-	-	-	-	-
Laptop computer and accessories	-	-	-	-	-	-
Site survey and initial investigation	-	-	-	$144	-	$144
Gaging station instrumentation	-	-	-	-	-	-
TOTAL	$6,653	$3,120	$9,773	$8,517	$4,300	$12,817

For example, the initial costs for the One-orange method and the Marsh McBirney method are $72 and $4,314, respectively. Still, one must remember that cost is only one of several considerations when selecting a stream-gaging method.

The initial cost of using the dilution method is higher than that of all other methods, primarily due to the cost of the fluorometer and time-consuming sample analyses of samples, as well as data reduction and processing requirements. The initial costs of the pressure transducer without a stilling well and the Starflow acoustic Doppler device are among the lowest in the analysis. This low initial cost is mostly due to the relatively low cost of the sensors used by these methods. A small shelter is required to secure and protect the equipment used for these methods, but the cost of building such a shelter is very low ($150). The use of a stilling well significantly increases the initial costs of any method for which it is required. Cost analysis data have been included in Table 5.2 for reference only. The installation of a stilling well requires considerable excavation, erosion and sediment control, concrete, and similar costs.

The Isco acoustic Doppler device is considerably more expensive than the similar Starflow device. The power source, microcomputer, mounting plate, and maintenance costs are identical. Therefore, the difference in cost is due to the fact that the Isco system has more components than the Starflow. The Starflow combines the sensor and the logger functions, whereas the logger is separate from the sensor in the Isco acoustic Doppler system. Data storage requirements should also be considered with both of these instruments.

The annual costs, as listed in Table 5.2, follow the same pattern as the initial costs, although the annual costs for all the methods are much lower than the initial costs. The annual costs for each method reflect the expense of maintaining the operation of data collection at the gaging site for each method. Further explanation of the annual cost categories can be found in Table 5.1. It should be noted that the hypothetical gaging site is assumed to be located in close proximity to the investigator, so the travel costs associated with maintenance and data collection are negligible. These expenses could rise significantly when personnel are required to travel long distances and possibly seek lodging near the site in order to maintain the gaging site and collect data.

The data collection, data processing, and maintenance costs associated with the current meters, Global flow probe, and One-orange method are very similar, as reflected in the annual cost listed for each method. These costs are dominated by the development of the stage-discharge relationship and instrumentation maintenance.

The annual costs of the Isco and Starflow acoustic Doppler devices, each less than $1,000, are by far the lowest among the methods listed. This can be attributed to the fact that no maintenance of the stage-discharge relationship is needed for these methods. Rather than developing a stage-discharge relationship for the site, the measurement section containing the area-velocity sensor must be surveyed. To account for the changes in stream bottom geometry that can drastically impact the stage-area relationship, this section should be surveyed regularly. The frequency of these surveys depends on the streambed conditions and the type of storms encountered. For the hypothetical gaging site, a surveying frequency of once every other month was assumed.

Dilution and pressure transducer methods have relatively high annual costs associated with them. The high annual costs of using the dilution method are due to the high cost of refining the site stage-discharge relationship. The cost of refining the stage-discharge relationship using the dilution method is much higher than for other methods. This is caused by the higher cost per discharge measurement created by the large volume of sample and data analyses required for the dilution method. The stage-discharge relationship refinement costs for the pressure transducer are higher than for the current meter. This is because some other means of measuring the discharge for development of the stage-discharge relationship is required since this technique only measures stage.

Overall, the Starflow acoustic Doppler device has the lowest costs (initial and annual) in this analysis while the dilution method has the highest total cost. The range of the total costs for all the methods investigated was $4,866 for the Starflow acoustic Doppler device, to $12,817 for the dilution method. The current meters are all expensive, once again due to the high cost developing the stage-discharge relationship.

CHAPTER 6
SUMMARY AND CONCLUSIONS

Summary:

A total of ten stream-gaging methods were evaluated for their field performance, laboratory performance, and costs in this study. These nine methods included four current meters, two acoustic Doppler devices, a flow probe, an improved float method, and a pressure transducer. In both the field and laboratory investigations, special consideration was given to conditions often encountered in NPS studies such as TMDL development. Field sites featuring small, often slow-flowing streams were used in this investigation. These conditions were duplicated in the laboratory experiments. The cost analysis was a simple comparison of basic costs associated with the implementation of each method.

Laboratory experiments provide an assessment of the accuracy of the methods evaluated in this study under controlled conditions. The field investigations are necessary to validate the laboratory findings, as well as to test the accuracy of the methods under more realistic conditions. The field and laboratory experiments compliment one another in studies such as this.

The field investigations were performed at two separate gaging stations: one in Montgomery County, Virginia, and the other in Pulaski County, Virginia. Both of these watersheds have a drainage area under 3100 acres, and the land use in each watershed is dominated by agriculture. Each gaging station was already equipped with a control structure to accurately measure discharge in the stream. To reliably measure the stage in each stream, an FW-1 chart stage recorder (with potentiometer) was installed in the existing stilling well. At least 30 measurements were taken with each device at each of the gaging stations during the field investigations. The discharge or stage measured using each method was then compared to the discharge or stage measured using the control structure and FW-1 as a standard. This approach differs greatly from those used by other investigators, where measurements from different devices are lumped together, then results for each device are compared to the mean discharge of all the devices combined.

Similarly, the flow measuring devices were compared to a standard method in the laboratory experiment performed in a one-foot recirculating hydraulic flume. The standard for evaluation of discharge measurement in the laboratory experiment was a thin-plate v-notch weir, and the stage measurements were compared to stage measured manually in the flume. The devices were used in random order in the laboratory experiment. Each device was used to measure stage or discharge in the flume 30 times during the course of the experiment; fifteen measurements while gradually increasing the discharge, and fifteen measurements while decreasing it.

A simplified cost analysis was performed for the methods included in this study. The cost analysis is intended to guide the user of such methods in selecting an appropriate device for stream-gaging. The cost analysis examined the initial and annual costs associated each method. The costs associated with each device were compiled from retailers, user’s manuals, and experienced users of these devices.

The data resulting from the field investigations were analyzed using an Analysis of Variance, along with Duncan’s multiple range test. From these analyses, the most accurate methods under the conditions encountered at these particular gaging stations were the Marsh McBirney current meter and the One-orange method. The Valeport BFM001 and Price AA current meters also performed well at both sites. The data from these trials were also examined using % relative error values and standard error.

Observations from these techniques confirm the results of the Analysis of Variance and Duncan's multiple range test. It should be noted that at Crab Creek, where the flow velocities were a little higher than at Thorne Springs Branch, the pygmy current meter performed very well.

The laboratory experiment data were interpreted using linear regressions and analysis of covariance. Based on these two analyses, the Starflow acoustic Doppler device is the most accurate method among those evaluated in this experiment. The Valeport BFM001 current meter also performed very well. Another objective of the laboratory experiment was to determine if these methods could be used below their recommended minimum flow velocity, without a considerable loss of accuracy. The Marsh McBirney current meter proved to be practically unaffected by extremely low flow velocities, as did the Starflow device. The Global flow probe was found to be very inaccurate at flow velocities below its recommended minimum value.

The Starflow acoustic Doppler device resulted in the lowest cost of the ten methods evaluated ($4,866.), followed by the One-orange method ($6,057) and the Global flow probe ($6,799). The most expensive method in this study was the Dilution method, with a combined (initial + annual) cost of $12,817. For all methods, annual costs were lower than the initial cost. The cost for the stilling well, which would likely be required for many of the methods in this study, was not included in this analysis. The combined (initial + annual) cost of such a stilling well is $19,754, which is higher than the combined costs for any of the individual methods considered in this study.

Conclusions:

Based on the analyses of the data collected in this study, the following conclusions can be drawn concerning the stream-gaging methods investigated:

- At the Crab Creek field trial site, the pygmy current meter, Marsh McBirney current meter, and the One-orange method measured the discharge most accurately. At the Thorne Springs Branch field trial site, the Valeport BFM001 current meter, Marsh McBirney current meter, and the One-orange method measured the discharge most accurately.

- In the laboratory experiment, the Starflow acoustic Doppler device, Valeport BFM001 current meter, pygmy current meter, and the Price AA current meter measured the discharge most accurately.

- The Marsh McBirney and Valeport BFM001 current meters exhibited the best combined field and laboratory accuracy.

- The technique used with the acoustic Doppler devices to relate stage and flow area hindered the ability of the device to measure flow. This was demonstrated by the performance of these devices in the laboratory experiment.

- Results can vary in field conditions, such as with the performance of some methods at the two field study sites in this study. Therefore, laboratory investigations are necessary to help interpret field experiment results.

- The initial and annual costs associated with the Starflow acoustic Doppler device and the One-orange method were lowest among the methods studied. The dilution method is very expensive to use on a regular basis. The combined costs of the current meters were very similar, and moderate, relative to other methods considered in this study.

- Measuring continuous stage at a gaging site with a pressure transducer mounted directly in the stream is considerably less expensive than installing a stilling well.

- The One-orange method is inexpensive and produced good results in the field investigations, but did not fare well in the laboratory experiment. A possible reason for this is the rectangular shape of the flume cross-section, which in no way resembles that of a natural stream channel.

- The moderate costs of the Marsh McBirney and Valeport BFM001 current meters, along with their accuracy, makes them a good choice for stream-gaging in conditions such as those encountered in this study. However, water depth must also be considered when using the Valeport BFM001 current meter, given the large diameter of the sensor. Minimum water depth to ensure submersion of the propellor is 6".

- Based on the study results, the Marsh McBirney electromagnet current meter is recommended for flow measurements in small order streams, due to its overall accuracy and moderate cost.

Study Limitations:

While the laboratory experiments and field studies were carefully planned, some limitations were observed. Evaluation of more methods in the field study and laboratory experiments would have allowed more meaningful comparisons. There are many more methods available for measuring stream flow, although not all are commonly used in NPS pollution studies. Evaluation of methods not normally used in such studies might result in the discovery of a new application for a given method.

Incorporating more streams in the field study and covering a broader range of flow conditions would have facilitated a more comprehensive comparison of the various methods. Not all the streams involved in NPS pollution studies are first or second order streams.

Four people performed discharge measurements in this study, but the number of measurements was not evenly distributed. It would have been useful to identify the uncertainty in the discharge data that could be attributed to human error. Incorporating users who possess a broad range of experience and ability would have made this possible.

Field data should be collected over a longer time period, to allow for measurement of discharge in a broader range of climatic conditions. The field data in this study were collected from January through March, so little variation in climate was experienced. In practical applications, flow data are collected year round.

Future Research Needs:

The results of this study do not constitute a complete assessment of stream-gaging methods as applied to NPS pollution studies. This study concentrated on the slow flow and small stream conditions often encountered in such studies. However, these are not the only types of streams in which such studies are performed. Similar studies are required to determine the applicability of these methods under other adverse conditions encountered in NPS pollution studies.

This study investigated the performance of ten stream-gaging techniques, which is only a fraction of the methods available to the stream gager today. Further studies are needed to evaluate other established techniques of measuring stage, velocity, and discharge under the adverse conditions just discussed. New technologies and improvements on old ideas are emerging constantly as well. The One-orange method is a good example of this. The approach taken, and methods used to determine accuracy, repeatability, cost, and other characteristics of stream-gaging methods vary among researchers. A uniform evaluation process for such devices in the form of a standard procedure would be appropriate. Uniform field procedures, laboratory procedures, and statistical analyses could be adopted for evaluation of stream-gaging methods with respect to various performance criteria such as response to oblique flow (vertical and horizontal), pulsation of flow, temperature, low flow velocities, and turbulence.

The following are general guidelines for comparative studies of flow measurement methods. It is essential that methods be evaluated both in the field and in the laboratory. The number of methods evaluated in a study should be maximized, so relevant comparisons of various methods can be performed. A minimum sample of 30 discharge measurements with each device at each location should be collected. Discharge measurements should be performed by multiple users; and performance of the users should be evaluated in addition to performance of the methods. In addition to descriptive statistics, robust statistical analyses should be performed to allow the researcher to draw conclusions about the relative performance of the various methods.

More research is also needed to evaluate the ability of continuously recording methods of measuring stage and discharge, such as the acoustic Doppler devices and pressure transducers, to react to changing flow. It is essential that such devices accurately capture the entire hydrograph during a storm event. Hysteresis of a stream-gaging system can have a large impact on the overall accuracy of the resulting flow data.

REFERENCES CITED

Ackers, P., W.R. White, J.A. Perkins, and A.J.M. Harrison. 1978. *Weirs and Flumes for Flow Measurement*. Chichester: John Wiley & Sons.

Appell, G.F. 1978. A review of the performance of an acoustic current meter. In *Proc.of a Working Conference on Current Measurement*, 35-58. University of Deleware, 11-13 Jan.

Abt, S.R., K. Thompson, and K. Staker. 1989. Discharge correction for longitudinal settlement of parshall flumes. *Transactions of the ASAE*. 32(5), 1541-1544.

Bobrow, L.S. 1985. *Fundamentals of Electrical Engineering*. New York: Holt, Rinehart and Winston, Inc.

Buchanan, T.J. and W.P. Somers. 1984. Discharge measurements at gaging stations. In *U.S. Geol. Survey Techniques Water-Resources Inv*., book 3, chap. A8, 64.

Campbell Scientific. 1996. *CR10 Measurement and Control Module Operator's Manual*. Logan, Utah: Campbell Scientific, Inc.

Carter, R.W., and J. Davidian. 1968. General procedure for gaging streams: In *U.S. Geol. Survey Techniques Water-Resources Inv*., book 3, chap. A6, 13.

Carr, J.C., and J.B. Burford. 1967. Descriptive notes of Crab Creek and Thorne Springs Branch watersheds.

Chapra, S.C. and R.P. Canale. 1988. *Numerical Methods for Engineers*. New York: McGraw-Hill, Inc.

Christensen, B.A. 1994. Velocity measurements by the "One-Orange Method". In *Fundamentals and Advancements in Hydraulic Measurements and Experimentation*. American Society of Civil Engineers, 76 - 85.

Derecki, J.A. and F.H. Quinn. 1987. Use of current meters for continuous measurement of flows in large rivers. *Water Resources Research* 23(9):1751-1756.

Fulford, J.M. 1990. Effect of turbulence on Price AA meter rotors.In *Hydraulic Engineering – Proceedings of the 1990 National Conference, Hydraulic Division of the American Society of Civil Engineers*, eds H.H. Chang and J.C. Hill, 909-914.

Fulford, J.M., K.G. Thibodeaux, and W.R. Kaehrle. 1994. Comparison of current meters used for stream-gaging. In *Fundamentals and Advancements in Hydraulic Measurements and Experimentation*. American Society of Civil Engineers, 376-385.

Global Water. 1997. *Global Flow Probe FP101-FP201 Instruction Manual*. Gold River, Colorado: Global Water, Inc.

Henderlite, H. 1999. Personal communication.

Herschy, R.W. 1985. *Streamflow Measurement*. Elsevier Applied Science Publishers. London and New York.

Isco. 1993. *4150 Flow Logger Instruction Manual*. Lincoln, Nebraska: Isco, Inc.

Kallio, N.A. 1966. Effects of vertical motion on current meters. USGS-Water Supply Paper 868-A. Washington, D.C.

Keeland, B.D., J.F. Dowd, and W.S. Hardegree. 1997. Use of inexpensive pressure transducers for measuring water levels in wells. *Wetlands Ecology and Management* 5(2):121-129.

Kilpatrick, F.A. and E.D. Cobb. 1985. Measurement of discharge using tracers. In *U.S. Geol. Survey Techniques Water-Resources Inv.*, book 3, chap. A16, 52p.

Kulin, G. and P.R. Compton. 1975. *A guide to methods and standards for the measurement of water flow*. Institute for Basic Standards – National Bureau of Standards. Washington, D.C.

Lentner, M. and T. Bishop. 1993. Analysis of Covariance. In Experimental Design and Analysis. 292-297. Blacksburg, VA: Valley Book Company.

Marsh McBirney. 1994. *Flo-Mate Model 2000 Portable Water Flow Meter Installation and Operations Manual*. Frederick, MD: Marsh McBirney Inc.

McClellan, P.W. 1999. Personal communication.

Ott, R.L. 1988. *An Introduction to Statistical Methods and Data Analysis*. Belmont, CA: Duxbury Press.

Pierce, C.H. 1941. Investigations of methods and equipment used in stream-gaging: part 1 – performance of current meters in water of shallow depth. USGS-Water Supply Paper 868-A. Washington, D.C.

Powell, E. 1999. Personal communication.

Rantz, S.E., and others. 1982. Measurement and computation of streamflow: volume I. measurement of stage and discharge. Geological Survey Water-Supply Paper 2175. United States Government Printing Office. Washington.

Robson, A.D. 1954. The effect of water temperature upon the calibration of a current meter. *Transactions, American Geophysical Union* 35(4):647-648.

SAS. 1985. *SAS User's Guide: Statistics, Version 5 Edition*. Cary, North Carolina: SAS Institute, Inc.

Serway, S.A. 1990. *Physics for Scientists and Engineers with Modern Physics*. Philadelphia: Saunders College Publishing.

Smoot, G.F. and C.E. Novak. 1977, Calibration and maintenance of vertical-axis type current meters: U.S. Geol. Survey Techniques Water-Resources Inv., book 8, chap. B2, 15p.

Steeno, G. 1999. Personal communication.

Thibodeaux, K.G. 1992. A brief literature review of open-channel current meter testing. In *Proc. of Hydraulic Engineering Conference 1992*, 458-463. New York, NY.

Turner Associates. 1974. *Turner Filter Fluorometer Model 111 Operating Instructions and Service Manual*. Palo Alto, CA: Turner Associates.

Turner Associates. 1977. *Manual of Fluorometric Clinical Procedures*. Palo Alto, CA: Turner Associates.

Unidata. 1995. *Ultrasonic Doppler Instrument with Micrologger-User's Manual*. Australia:Lynn MacLaren Publishing.

United States Bureau of Reclamation. 1997. USBR Water Measurement Manual, http://www.ogee.do.usbr.gov/fmt/wmm/.

United States Geological Survey. 1980. *National Handbook of Recommended Methods for Water-Data Acquisition*. Office of Water Data Coordination, 1-1 – 1-127.

Valeport. 1995. The Basic Design and Operation Instructions. Dartmouth: Valeport Developments.

Vermeyen, A.M. 1994. Laboratory and field evaluation of acoustic velocity meters. In *Fundamentals and Advancements in Hydraulic Measurements and Experimentation*. American Society of Civil Engineers, 43-52.

Walpole, R.E. and R.H. Myers. 1993. *Probability and Statistics for Engineers and Scientists*. New York: Macmillan Publishing Company.

White, R.K., D.C. Hayes, M.R. Eckenwiler, and P.E. Herman. 1997. *Water resources data Virginia water year 1997 vol. 1*.U.S. Geological Survey Water-Data Report VA-97-1.

Wilson, J.F. Jr., E.D. Cobb, and F.A. Kilpatrick. 1986. Fluorometric procedures for dye tracing. In *U.S. Geol. Survey Techniques Water-Resources Inv*., book 3, chap. A12, 34p.

Yoder, D.C., J.B. Wilderson, J.R. Buchanan, K.J. Hurley, and R.E. Yoder. 1998, Development and evaluation of a device to control time varying flows. *Transactions of the ASAE* 41(2):325-332.

APPENDIX A

Installation and Data Collection–
Calibrations
Programs
Schemes

Potentiometer Calibration for FW-1B to be placed at Thorne Springs Branch - 1/25/99

Stage, cm	Stage, ft	mV
1.9	0.06	2295.6
7.5	0.25	2249
13.5	0.44	2198.6
20.7	0.68	2139.2
30.2	0.99	2059.1
39.4	1.29	1983.7
49.2	1.61	1901.5
59	1.94	1822.8
67.3	2.21	1750.7
75.5	2.48	1682
84.3	2.77	1611.9
91.9	3.02	1566.9
81.9	2.69	1631.5
75	2.46	1686.7
66.6	2.19	1754.1
59.3	1.95	1820.1
52.15	1.71	1878
43.4	1.42	1948.7
35.2	1.15	2016.7
23.7	0.78	2113

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.99981
R Square	0.99962
Adjusted R Square	0.9996
Standard Error	0.01768
Observations	20

	Coefficients
Intercept	9.18153
X Variable 1	-0.004

Florometer Calibration - Rhodamine WT 3/29/99

Dye Conc. micrograms/l	Reading 1X	Reading 3X	Reading 10X	Regres. 1X	Regres. 3X	Regres. 10X
100	55			100.7		
50	26	66		48.3	50.2	
25	13	33	100	24.8	25.0	24.8
20	10.5	26	83	20.3	19.7	20.6
15	7.7	19.5	59.3	15.2	14.7	14.7
10	5	13.5	39	10.3	10.1	9.7
6	2.8	8	24	6.4	5.9	5.9
4		5	15.5	1.3	3.7	3.8
2	0.5	3	8	2.2	2.1	2.0
1		2.5	6		1.7	1.5
0		0	0		0.0	0.0

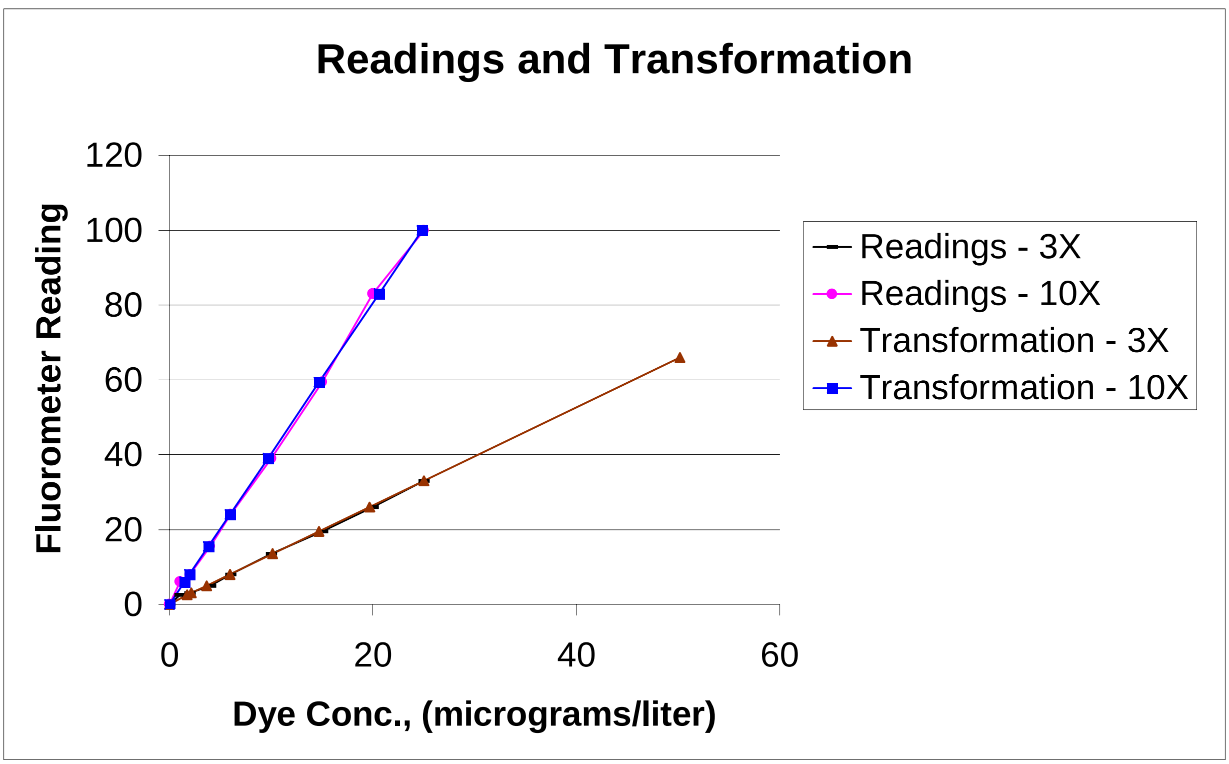


Figure A.1 - Fluorometer calibration curves.

SUMMARY OUTPUT - Conc. To 1X scale

Regression Statistics	
Multiple R	0.999709726
R Square	0.999419537
Adjusted R Square	0.999303444
Standard Error	0.87463367
Observations	7

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	6585.603651	6585.604	8608.81163	2.7568E-09
Residual	5	3.824920286	0.764984		
Total	6	6589.428571			

	Coefficients
Intercept	1.295975093
X Variable 1	1.807734786

SUMMARY OUTPUT - Conc. To 3X scale

Regression Statistics	
Multiple R	0.999774351
R Square	0.999548752
Adjusted R Square	0.999492346
Standard Error	0.347277453
Observations	10

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	2137.135187	2137.135	17720.6162	1.13396E-14
Residual	8	0.964813037	0.120602		
Total	9	2138.1			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.16413095	0.149299078	-1.099343	0.30359731	-0.50841546	0.180154	-0.508415	0.180154
X Variable 1	0.76284028	0.005730522	133.1188	1.134E-14	0.749625663	0.776055	0.749626	0.776055

SUMMARY OUTPUT - Conc. To 10X scale

Regression Statistics	
Multiple R	0.99934629
R Square	0.998693007
Adjusted R Square	0.998506293
Standard Error	0.34610256
Observations	9

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	640.7170467	640.717	5348.80365	2.35023E-11
Residual	7	0.838508874	0.119787		
Total	8	641.5555556			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.01638165	0.171075541	-0.095757	0.9263974	-0.420910736	0.388147	-0.420911	0.388147
X Variable 1	0.248349567	0.003395745	73.13552	2.3502E-11	0.240319911	0.256379	0.24032	0.256379

Discharge Measurement Notes & Raw Data
Current Meter Method

Site:______________________________ Date:____________________________
Operator:___________________________ Current Meter:_____________________
Stream Condition:_____________________ Serial Number:_____________________
Water Temperature:____________________ Flow Condition:____________________
Air Temperature:______________________ Weather:__________________________
Gage Height:_________ Time:__________ Other:____________________________
Gage Height:_________ Time:__________ Remarks:__________________________
Gage Height:_________ Time:__________ __________________________________
Gage Height:_________ Time:__________

Dist. From Initial Point (ft.)	Width (ft.)	Depth d (ft.)	Obs. Depth (.6 or .2/.8)	Revolu-tions	Time t (sec.)	Velocity (fps)		Area A (ft^2)	Discharge Q (cfs)
						@point	Ave.		

Laboratory Experiment Data Sheet

Trial Number: Date: Time:

CONTROL DISCHARGE DATA

Measurement Number	Datum Depth (ft.)	Meas. Depth (ft.)	Time of Measurement
1			
2			
3			

CURRENT METERS

Marsh McBirney

Measurement Number	Datum Depth (ft.)	Meas. Depth (ft.)	Velocity (fps)
1			
2			
3			

Price AA

Measurement Number	Datum Depth (ft.)	Meas. Depth (ft.)	Rev.	Time (sec.)
1				
2				
3				

Pygmy

Measurement Number	Datum Depth (ft.)	Meas. Depth (ft.)	Velocity (fps)
1			
2			
3			

Valeport

Measurement Number	Datum Depth (ft.)	Meas. Depth (ft.)	Rev.	Time (sec.)
1				
2				
3				

Global

Measurement Number	Datum Depth (ft.)	Meas. Depth (ft.)	Velocity (fps)
1			
2			
3			

ACOUSTIC DOPPLER

Isco

Measurement Number	Discharge (cfs)
1	
2	
3	

Starflow

Measurement Number	Discharge (cfs)
1	
2	
3	

ONE-ORANGE METHOD

Measurement Number	Datum Depth (ft.)	Meas. Depth (ft.)	X1 (ft.)	T1 (sec.)	X2 (ft.)	T2 (sec.)
1						
2						
3						

PRESSURE TRANSDUCER

Measurement Number	Datum Depth (ft.)	Meas. Depth (ft.)	Trans. Depth (ft.)
1			
2			
3			

EXAMPLE OF STARFLOW SCHEME:

UNIDATA PDL Compiler Version 1.04

Scheme CJFLUME: STARFLOW Velocity & Depth Recording

Uses serial port COM1: at 9600 baud.

There is an unload comment.

Logger used is a 6526A - STARFLOW Ultrasonic Doppler Instrument

Logger has a scan rate of 15 seconds.

Logger has 128K bytes of memory.

The log program has a log interval of 3 minutes 45 seconds.

There is no sub interval.

The log size is 12 bytes.

The duration will be 25 days 18 hours 37 minutes 30 seconds.

PROGRAM WRITTEN FOR CAMPBELL SCIENTIFIC 21X DATALOGGER:

```
;{21X}
;Data logging routine for Crab Creek and Thorne Springs Branch
;
*Table 1 Program
  01: 5        Execution Interval (seconds)

1:  Ex-Del-Diff (P8)
 1: 2       Reps
 2: 4       500 mV Slow Range
 3: 1       DIFF Channel
 4: 1       Excite all reps w/Exchan 1
```

5: 1 Delay (units 0.01 sec)

6: 2500 mV Excitation

7: 1 Loc [rp1_1]

8: 1.0 Mult

9: 0.0 Offset

2: Ex-Del-Diff (P8)

1: 2 Reps

2: 4 500 mV Slow Range

3: 3 DIFF Channel

4: 2 Excite all reps w/Exchan 2

5: 1 Delay (units 0.01 sec)

6: 2500 mV Excitation

7: 3 Loc [rp2_1]

8: 1.0 Mult

9: 0.0 Offset

3: Excite Delay Volt (SE) (P4)

1: 1 Reps

2: 5 5000 mV Slow Range

3: 9 SE Channel

4: 3 Excite all reps w/Exchan 3

5: 10 Delay (units 0.01 sec)

6: 5000 mV Excitation

7: 5 Loc [pot]

8: .5 Mult

9: 0.0 Offset

4: Z=X*F (P37)

1: 1 X Loc [rp1_1]

2: .00955 F

3: 10 Z Loc [rp1i]

5: Z=X/Y (P38)

1: 2 X Loc [rp1_2]

2: 10 Y Loc [rp1i]

3: 11 Z Loc [p1r]

6: Z=X*F (P37)

1: 3 X Loc [rp2_1]

2: .00956 F

3: 12 Z Loc [rp2i]

7: Z=X/Y (P38)

1: 4 X Loc [rp2_2]

2: 12 Y Loc [rp2i]

3: 13 Z Loc [p2r]

8: Polynomial (P55)

1: 1 Reps

2: 11 X Loc [p1r]

3: 14 F(X) Loc [p1stage]

4: .07873 C0

5: .18192 C1

6: 0.0 C2

7: 0.0 C3

8: 0.0 C4

9: 0.0 C5

9: Polynomial (P55)

1: 1 Reps

2: 13 X Loc [p2r]

3: 15 F(X) Loc [p2stage]

4: .27064 C0

5: .18777 C1

6: 0.0 C2

7: 0.0 C3

8: 0.0 C4

9: 0.0 C5

10: Polynomial (P55)

1: 1 Reps

2: 5 X Loc [pot]

3: 16 F(X) Loc [potstage]

4: .5 C0

5: .00403 C1

6: 0.0 C2

7: 0.0 C3

8: 0.0 C4

9: 0.0 C5

11: Batt Voltage (P10)

1: 6 Loc [battery]

12: Z=F (P30)

1: 0.0 F

2: 7 Z Loc [statid]

*Table 2 Program

02: 30 Execution Interval (seconds)

1: Do (P86)

1: 10 Set Output Flag High

2: Real Time (P77)

1: 1221 Year,Day,Hour/Minute,Seconds (midnight = 2400)

3: Average (P71)

1: 3 Reps

2: 14 Loc [p1stage]

4: Average (P71)

1: 1 Reps

2: 11 Loc [p1r]

5: Average (P71)

1: 1 Reps

2: 13 Loc [p2r]

6: Average (P71)

1: 1 Reps

2: 5 Loc [pot]

7: Average (P71)

1: 2 Reps

2: 6 Loc [battery]

*Table 3 Subroutines

End Program

-Input Locations-

1 rp1_1 5 1 1

2 rp1_2 17 1 1

3 rp2_1 5 1 1

4 rp2_2 17 1 1

5 pot 1 2 1

6 battery 1 1 1

7 statid 1 0 0

8 _________ 0 0 0

9 _________ 0 0 0

10 rp1i 1 1 1

11 p1r 1 2 1

12 rp2i 1 1 1

13 p2r 1 2 1

14 p1stage 5 1 1

15 p2stage 9 1 1

16 potstage 17 1 1

17 __________ 0 0 0

18 __________ 0 0 0

19 __________ 0 0 0

20 __________ 0 0 0

21 __________ 0 0 0

22 __________ 0 0 0

23 __________ 0 0 0

24 __________ 0 0 0

25 __________ 0 0 0

26 __________ 0 0 0

27 __________ 0 0 0

28 __________ 0 0 0

-Program Security-

0

0000

0000

APPENDIX B

Data –
Field
Laboratory

Table B.1 - Thorne Springs Field Trial Data (discharge in cfs).

Price-AA		Pygmy		Valeport		Marsh McBirney	
Observed	Weir Value	Observed	Weir Value	Observed	Weir Value	Observed	Weir Value
0.382	0.366	0.042	0.366	0.259	0.366	0.266	0.366
0.393	0.366	0.050	0.366	0.211	0.366	0.272	0.366
0.435	0.366	0.036	0.366	0.243	0.366	0.281	0.366
0.429	0.366	0.049	0.366	0.186	0.366	0.277	0.366
0.491	0.366	0.039	0.366	0.210	0.366	0.277	0.366
0.266	0.366	0.052	0.366	0.245	0.366	0.306	0.366
0.205	0.366	0.057	0.366	0.272	0.366	0.278	0.366
0.196	0.366	0.082	0.366	0.268	0.366	0.309	0.366
0.213	0.366	0.036	0.366	0.258	0.366	0.230	0.366
0.252	0.366	0.034	0.366	0.278	0.366	0.527	0.385
0.213	0.366	0.057	0.366	0.375	0.366	0.608	0.385
0.225	0.366	0.035	0.366	0.319	0.366	0.635	0.385
0.171	0.366	0.053	0.366	0.312	0.366	0.328	0.385
0.221	0.366	0.064	0.348	0.365	0.366	0.460	0.385
0.173	0.366	0.072	0.348	0.353	0.366	0.396	0.385
0.253	0.366	0.052	0.348	0.374	0.366	0.309	0.385
0.299	0.366	0.061	0.348	0.325	0.366	0.325	0.385
0.135	0.348	0.216	0.348	0.430	0.366	0.364	0.385
0.087	0.348	0.195	0.348	0.381	0.366	0.151	0.348
0.052	0.348	0.178	0.348	0.293	0.366	0.229	0.348
0.085	0.348	0.188	0.348	0.412	0.366	0.272	0.348
0.049	0.348	0.145	0.348	0.380	0.366	0.134	0.348
0.129	0.348	0.046	0.348	0.320	0.366	0.173	0.348
0.161	0.348	0.021	0.348	0.156	0.348	0.190	0.348
0.000	0.348	0.013	0.348	0.043	0.348	0.350	0.348
0.093	0.348	0.487	0.691	0.092	0.348	0.322	0.348
0.128	0.348	0.539	0.691	0.212	0.348	0.137	0.348
0.112	0.348	0.479	0.691	0.130	0.348	0.196	0.348
0.528	0.366	0.423	0.691	0.078	0.348	0.319	0.348
0.554	0.366	0.484	0.691	0.092	0.348	0.158	0.348
						0.408	0.691
						0.438	0.691
						0.405	0.691

Table B.1 - Thorne Springs Branch Field Trial Data (cont'd).

Global		One-Orange Method		Isco Acoustic Doppler		Starflow Acoustic Doppler	
Observed	Weir Value	Observed	Weir Value	Observed	Weir Value	Observed	Weir Value
0.915	0.366	0.62	0.366	0.82	0.348	0.658	0.366
0.822	0.366	0.46	0.366	0.82	0.348	0.576	0.366
0.915	0.366	0.50	0.366	0.822	0.348	0.658	0.366
0.899	0.366	0.45	0.366	0.822	0.348	0.625	0.366
0.744	0.366	0.58	0.366	0.819	0.348	0.607	0.366
0.992	0.366	0.54	0.366	0.822	0.348	0.676	0.366
0.822	0.366	0.52	0.366	0.788	0.348	0.697	0.366
0.775	0.366	0.43	0.366	0.791	0.348	0.628	0.366
0.791	0.366	0.50	0.366	0.791	0.348	0.658	0.366
0.837	0.366	0.51	0.366	0.819	0.348	0.519	0.366
0.868	0.366	0.45	0.366	0.879	0.348	0.582	0.366
0.915	0.366	0.61	0.366	0.916	0.348	0.588	0.366
0.853	0.366	0.57	0.366	0.913	0.348	0.437	0.366
0.884	0.366	0.48	0.366	0.913	0.352	0.418	0.366
0.822	0.366	0.46	0.366	0.910	0.352	0.528	0.366
0.884	0.366	0.56	0.366	0.883	0.352	0.597	0.366
0.899	0.366	0.55	0.378	0.758	0.352	0.607	0.374
0.915	0.366	0.50	0.378	0.762	0.352	0.746	0.374
0.884	0.366	0.45	0.378	0.791	0.352	0.646	0.374
0.884	0.366	0.64	0.378	0.782	0.352	0.637	0.374
0.899	0.366	0.42	0.378	0.676	0.352	0.607	0.374
0.837	0.366	0.60	0.378	0.676	0.357	0.634	0.374
0.930	0.366	0.44	0.378	0.675	0.357	0.685	0.374
0.729	0.366	0.43	0.378	0.676	0.357	0.594	0.374
0.899	0.366	0.50	0.378	0.676	0.357	0.488	0.374
1.008	0.366	0.55	0.378	0.675	0.357	0.607	0.374
0.915	0.366	0.41	0.378	0.676	0.357	0.597	0.374
0.822	0.366	0.46	0.378	0.676	0.357	0.673	0.374
0.884	0.366	0.49	0.378	0.676	0.357	0.652	0.374
0.930	0.366	0.45	0.378	0.676	0.357	0.591	0.374
0.868	0.366			0.679	0.357		
				0.679	0.357		
				0.676	0.357		
				0.679	0.357		
				0.676	0.357		

Table B.1 - Thorne Springs Branch Field Trial Data (cont’d).

Dilution Method		Pressure Transducer	
Observed	Weir Value	Observed	Control
0.74	0.366	0.03	0.030
0.634	0.357	0.031	0.03
1.177	1.198	0.031	0.03
0.789	0.536	0.042	0.03
0.733	0.366	0.031	0.031
		0.042	0.03
		0.031	0.031
		0.042	0.031
		0.031	0.03
		0.031	0.031
		0.031	0.031
		0.042	0.031
		0.031	0.03
		0.031	0.03
		0.031	0.03
		0.031	0.03
		0.042	0.03
		0.031	0.03
		0.031	0.031
		0.042	0.031
		0.042	0.031
		0.031	0.031
		0.032	0.031
		0.032	0.031
		0.032	0.031
		0.032	0.031
		0.032	0.031
		0.031	0.032
		0.031	0.032
		0.031	0.031

Table B.2 - Crab Creek Field Trial Data (discharge in cfs).

Price-AA		Pygmy		Valeport		Marsh McBirney	
Observed	Wier Value	Observed	Wier Value	Observed	Wier Value	Observed	Wier Value
0.399	0.231	0.443	0.490	0.369	0.253	0.452	0.333
0.374	0.231	0.394	0.357	0.340	0.253	0.466	0.333
0.291	0.214	0.427	0.381	0.420	0.269	0.420	0.333
0.357	0.214	0.450	0.357	0.410	0.269	0.424	0.333
0.397	0.197	0.192	0.182	0.395	0.269	0.415	0.333
0.360	0.197	0.195	0.197	0.416	0.269	0.273	0.2533
0.360	0.197	0.272	0.231	0.412	0.269	0.364	0.2533
0.393	0.197	0.290	0.231	0.464	0.269	0.396	0.2692
0.428	0.197	0.308	0.231	0.393	0.269	0.299	0.2692
0.420	0.197	0.297	0.231	0.393	0.269	0.270	0.2692
0.377	0.197	0.260	0.231	0.402	0.269	0.237	0.2692
0.378	0.214	0.283	0.214	0.380	0.269	0.273	0.2692
0.395	0.214	0.306	0.214	0.410	0.269	0.222	0.2692
0.344	0.214	0.296	0.214	0.379	0.269	0.273	0.2692
0.334	0.214	0.301	0.214	0.439	0.269	0.320	0.2692
0.326	0.214	0.290	0.214	0.442	0.269	0.319	0.2692
0.345	0.214	0.271	0.214	0.436	0.333	0.360	0.2692
0.327	0.214	0.267	0.214	0.402	0.333	0.386	0.2692
0.312	0.214	0.310	0.214	0.405	0.333	0.397	0.2692
0.339	0.214	0.257	0.214	0.472	0.333	0.464	0.2692
0.374	0.214	0.297	0.214	0.507	0.333	0.464	0.333
0.357	0.231	0.274	0.214	0.479	0.333	0.450	0.333
0.324	0.231	0.287	0.214	0.461	0.333	0.434	0.333
0.374	0.231	0.300	0.231	0.591	0.333	0.409	0.333
0.397	0.269	0.272	0.231	0.499	0.333	0.419	0.333
0.354	0.253	0.292	0.231	0.494	0.311	0.413	0.333
1.219	1.196	0.263	0.231	0.348	0.290	0.381	0.311
1.179	1.147	0.230	0.231	0.439	0.290	0.505	0.290
1.221	1.147	0.164	0.231	0.398	0.290	0.338	0.290
1.223	1.196	0.245	0.231	0.422	0.290	0.310	0.290
						0.291	0.269
						0.255	0.269
						0.309	0.269
						0.319	0.253
						0.297	0.253

Table B.2 - Crab Creek Field Trial Data (cont'd).

Global		One-Orange Method		Isco Acoustic Doppler		Starflow Acoustic Doppler	
Observed	Wier Value	Observed	Wier Value	Observed	Wier Value	Observed	Wier Value
0.8715	0.333	0.22	0.1816	1.0279	0.754	1.138	0.6186
0.747	0.333	0.22	0.1816	0.1782	0.754	0.992	0.6186
0.7055	0.333	0.27	0.1816	1.742	0.754	1.281	0.6186
0.664	0.333	0.26	0.1816	1.782	0.754	1.104	0.6186
0.8715	0.333	0.27	0.1816	1.782	0.754	0.938	0.6186
0.80925	0.333	0.27	0.1816	1.0216	0.754	0.992	0.6186
0.8715	0.333	0.25	0.1816	1.8152	0.754	1.203	0.6186
0.68475	0.333	0.25	0.1816	1.8612	0.754	1.094	0.6186
0.80925	0.333	0.31	0.1816	1.8216	0.754	0.938	0.6186
0.913	0.333	0.25	0.1816	1.7881	0.754	0.914	0.6186
1.0375	0.3812	0.29	0.2139	1.782	0.754	0.914	0.6186
0.8715	0.3812	0.30	0.2139	1.7424	0.832	1.138	0.6186
1.0375	0.3812	0.28	0.2139	1.7363	0.832	0.904	0.6186
0.97525	0.3812	0.28	0.2139	1.7424	0.832	1.002	0.6186
0.8229	0.3812	0.26	0.2139	1.7028	0.832	1.138	0.6839
1.0761	0.3812	0.27	0.2139	1.7028	0.832	0.914	0.6839
0.8229	0.3812	0.27	0.2139	1.7028	0.832	0.924	0.6839
0.8229	0.3812	0.28	0.2139	1.7424	0.832	1.060	0.6839
0.6752	0.3812	0.24	0.2139	1.7363	0.832	0.992	0.6839
0.7807	0.3812	0.27	0.2139	1.7028	0.832	1.261	0.6839
1.1583	0.4355	0.26	0.1973	1.7424	0.832	0.924	0.6839
0.87945	0.4355	0.30	0.1973	1.9074	0.832	0.904	0.6839
0.96525	0.4355	0.30	0.1973	1.8676	0.832	0.992	0.6839
1.09395	0.4355	0.24	0.1973	1.8279	0.832	1.104	0.6839
1.09395	0.4355	0.28	0.1973	1.7781	0.832	1.002	0.6839
1.1154	0.4355	0.29	0.1973	1.7424	0.832	1.104	0.6839
1.1583	0.4355	0.26	0.1973	1.8279	0.832	1.002	0.6839
0.858	0.4355	0.30	0.1973	1.8676	0.832	0.914	0.6839
0.96525	0.4355	0.25	0.1973	1.9008	0.832	1.227	0.6839
1.09395	0.4355	0.30	0.1973	1.9471	0.832	1.251	0.6839

Table B.2 - Crab Creek Field Trial Data (cont'd).

Dilution Method		Pressure Transducer 1		Pressure Transducer 2	
Observed	Wier Value	Observed	Potentiometer	Observed	Potentiometer
0.871	0.873	0.190	0.190	0.182	0.190
0.608	0.435	0.190	0.190	0.182	0.190
0.766	0.552	0.190	0.190	0.182	0.190
1.25	0.552	0.190	0.190	0.182	0.190
0.824	0.521	0.190	0.190	0.182	0.190
		0.190	0.191	0.182	0.191
		0.190	0.190	0.182	0.190
		0.188	0.191	0.181	0.191
		0.188	0.192	0.181	0.192
		0.188	0.191	0.181	0.191
		0.187	0.191	0.182	0.191
		0.187	0.190	0.182	0.190
		0.187	0.190	0.182	0.190
		0.187	0.190	0.182	0.190
		0.187	0.192	0.182	0.192
		0.187	0.190	0.182	0.190
		0.197	0.192	0.183	0.192
		0.208	0.192	0.183	0.192
		0.208	0.192	0.183	0.192
		0.208	0.192	0.183	0.192
		0.208	0.189	0.183	0.189
		0.208	0.189	0.183	0.189
		0.208	0.187	0.183	0.187
		0.208	0.186	0.183	0.186
		0.208	0.186	0.183	0.186
		0.197	0.186	0.183	0.186
		0.197	0.186	0.183	0.186
		0.208	0.186	0.183	0.186
		0.197	0.192	0.183	0.192
		0.208	0.192	0.183	0.192
		0.208	0.192	0.183	0.192

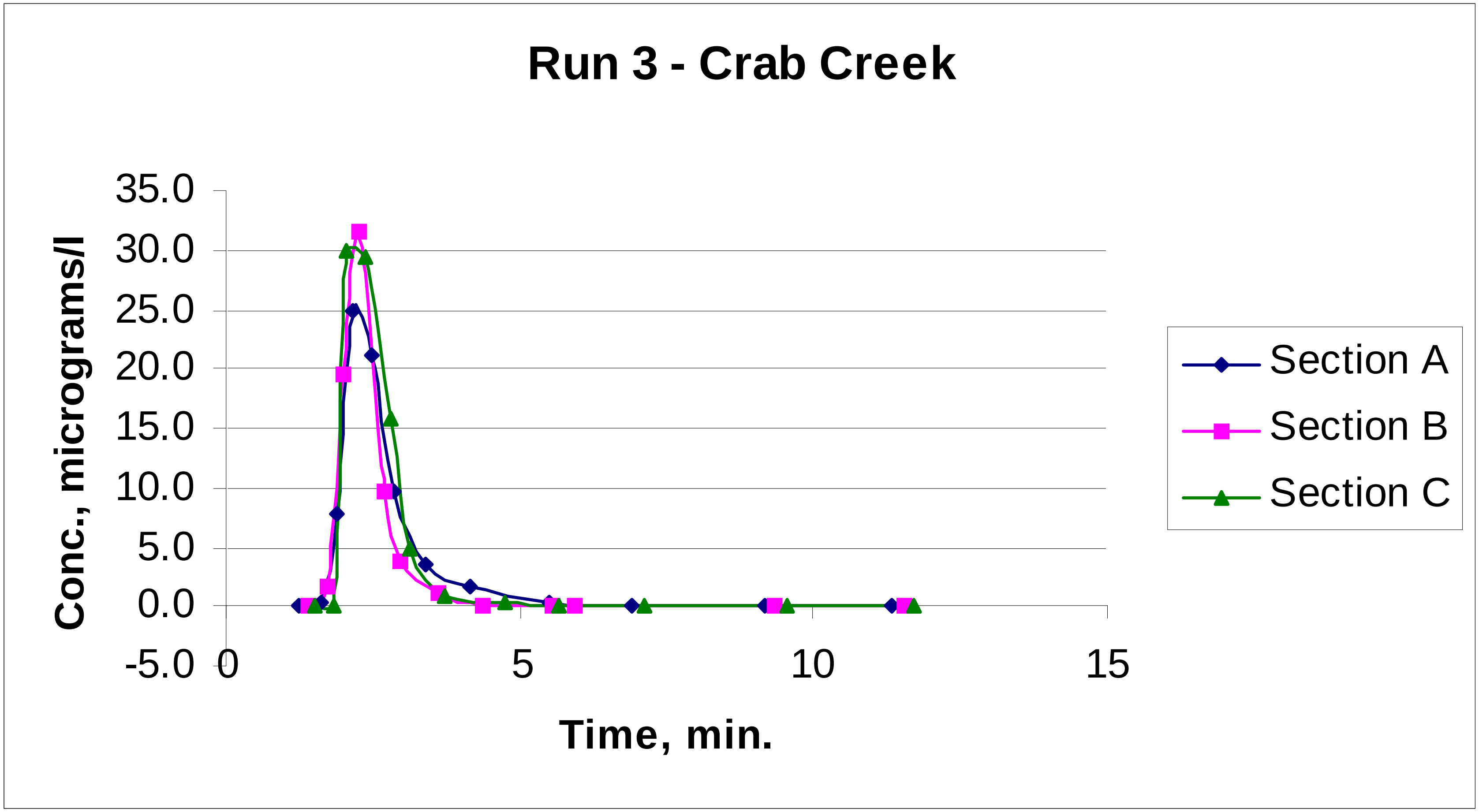


Figure B.1 – Example of time-concentration curve set from dilution method at Crab Creek.

Table B.3 - Laboratory Experiment Discharge Data.

Trial Number	Control Discharge (cfs)	Marsh McBirney (cfs)	Price AA (cfs)	Pygmy (cfs)	Valeport (cfs)	Global (cfs)
1	0.111	0.112	0.000	0.000	0.000	0.000
2	0.201	0.155	0.000	0.000	0.149	0.000
3	0.233	0.150	0.000	0.000	0.168	0.000
4	0.292	0.205	0.000	0.122	0.184	0.000
5	0.314	0.208	0.145	0.169	0.251	0.000
6	0.375	0.289	0.268	0.260	0.304	0.000
7	0.408	0.273	0.000	0.232	0.276	0.000
8	0.449	0.284	0.222	0.187	0.311	0.210
9	0.471	0.314	0.224	0.232	0.313	0.000
10	0.504	0.400	0.279	0.249	0.355	0.131
11	0.549	0.345	0.337	0.290	0.399	0.221
12	0.572	0.376	0.340	0.333	0.402	0.053
13	0.601	0.486	0.494	0.484	0.534	0.167
14	0.012	0.011	0.000	0.000	0.000	0.000
15	0.052	0.065	0.000	0.000	0.000	0.000
16	0.591	0.454	0.555	0.413	0.490	0.304
17	0.574	0.418	0.427	0.400	0.476	0.217
18	0.538	0.375	0.339	0.344	0.401	0.000
19	0.466	0.365	0.330	0.165	0.298	0.000
20	0.403	0.278	0.290	0.237	0.293	0.000
21	0.352	0.260	0.248	0.173	0.234	0.000
22	0.316	0.230	0.223	0.156	0.249	0.000
23	0.303	0.218	0.211	0.170	0.204	0.115
24	0.286	0.201	0.176	0.092	0.220	0.000
25	0.241	0.165	0.000	0.000	0.188	0.000
26	0.172	0.115	0.000	0.000	0.000	0.000
27	0.105	0.066	0.000	0.000	0.000	0.000
28	0.084	0.071	0.000	0.000	0.000	0.000
29	0.047	0.049	0.000	0.000	0.000	0.000
30	0.000	0.000	0.000	0.000	0.000	0.000

Table B.3 - Laboratory Experiment Data (cont'd).

` Number	Control Discharge (cfs)	One-orange (cfs)	Mod. One-orange (cfs)	Isco Doppler (cfs)	Starflow Doppler (cfs)	Control Depth (ft)	Pressure Transducer (ft)
1	0.111	0.092	0.109	0.087	0.000	0.980	0.983
2	0.201	0.122	0.134	0.146	0.159	1.053	1.051
3	0.233	0.150	0.143	0.167	0.203	1.073	1.078
4	0.292	0.149	0.165	0.216	0.285	1.099	1.099
5	0.314	0.092	0.131	0.225	0.332	1.109	1.097
6	0.375	0.162	0.194	0.292	0.362	1.135	1.134
7	0.408	0.100	0.131	0.283	0.366	1.152	1.140
8	0.449	0.156	0.195	0.318	0.319	1.168	1.151
9	0.471	0.171	0.172	0.313	0.345	1.178	1.166
10	0.504	0.215	0.271	0.327	0.365	1.187	1.180
11	0.549	0.186	0.232	0.332	0.479	1.201	1.195
12	0.572	0.088	0.266	0.388	0.501	1.210	1.205
13	0.601	0.103	0.316	0.430	0.618	1.224	1.201
14	0.012	0.000	0.000	0.000	0.000	0.856	0.858
15	0.052	0.053	0.039	0.076	0.000	0.978	0.972
16	0.591	0.140	0.280	0.412	0.573	1.214	1.212
17	0.574	0.220	0.320	0.391	0.553	1.211	1.212
18	0.538	0.081	0.303	0.347	0.480	1.207	1.182
19	0.466	0.168	0.166	0.295	0.362	1.168	1.173
20	0.403	0.141	0.132	0.288	0.290	1.148	1.148
21	0.352	0.164	0.154	0.248	0.261	1.129	1.121
22	0.316	0.142	0.127	0.230	0.281	1.115	1.103
23	0.303	0.154	0.170	0.217	0.224	1.107	1.095
24	0.286	0.127	0.121	0.197	0.228	1.097	1.090
25	0.241	0.062	0.133	0.165	0.213	1.076	1.062
26	0.172	0.071	0.066	0.125	0.176	1.037	1.022
27	0.105	0.049	0.064	0.079	0.144	0.984	0.970
28	0.084	0.036	0.035	0.058	0.127	0.964	0.954
29	0.047	0.000	0.000	0.015	0.097	0.918	0.919
30	0.000	0.000	0.000	0.000	0.101	0.774	0.765

Table B.3 - Laboratory Experiment Data (cont’d).

Number	Control Ave. Vel (ft/s)	MMB Ave. Vel (ft/s)	Price AA Ave. Vel (ft/s)	Pygmy Ave. Vel (ft/s)	Valeport Ave. Vel (ft/s)	Global Ave. Vel (ft/s)	Isco Ave. Vel (ft/s)	Starflow Ave. Vel (ft/s)
1	0.112	0.113	0.000	0.000	0.000	0.000	0.000	0.000
2	0.189	0.147	0.000	0.000	0.141	0.000	0.154	0.154
3	0.216	0.140	0.000	0.000	0.157	0.000	0.190	0.190
4	0.263	0.187	0.000	0.111	0.167	0.000	0.266	0.266
5	0.281	0.187	0.130	0.152	0.226	0.000	0.202	0.299
6	0.328	0.253	0.235	0.228	0.266	0.000	0.255	0.317
7	0.353	0.237	0.000	0.201	0.240	0.000	0.245	0.316
8	0.383	0.243	0.190	0.160	0.266	0.180	0.274	0.275
9	0.399	0.267	0.190	0.197	0.266	0.000	0.266	0.293
10	0.422	0.337	0.235	0.210	0.299	0.110	0.275	0.306
11	0.454	0.287	0.280	0.241	0.331	0.183	0.274	0.396
12	0.470	0.310	0.280	0.274	0.331	0.043	0.318	0.410
13	0.490	0.397	0.404	0.395	0.436	0.137	0.351	0.504
14	0.014	0.013	0.000	0.000	0.000	0.000	0.000	0.000
15	0.055	0.067	0.000	0.000	0.000	0.000	0.077	0.000
16	0.483	0.373	0.456	0.340	0.403	0.250	0.341	0.475
17	0.471	0.347	0.354	0.331	0.394	0.180	0.324	0.458
18	0.446	0.310	0.280	0.284	0.331	0.000	0.289	0.399
19	0.394	0.310	0.280	0.140	0.253	0.000	0.247	0.304
20	0.349	0.240	0.250	0.205	0.253	0.000	0.248	0.250
21	0.311	0.230	0.220	0.153	0.207	0.000	0.218	0.230
22	0.282	0.207	0.200	0.140	0.223	0.000	0.206	0.251
23	0.272	0.197	0.190	0.153	0.184	0.103	0.195	0.201
24	0.259	0.183	0.160	0.084	0.200	0.000	0.177	0.205
25	0.223	0.153	0.000	0.000	0.174	0.000	0.153	0.197
26	0.166	0.110	0.000	0.000	0.000	0.000	0.119	0.168
27	0.106	0.067	0.000	0.000	0.000	0.000	0.080	0.145
28	0.086	0.073	0.000	0.000	0.000	0.000	0.060	0.131
29	0.051	0.053	0.000	0.000	0.000	0.000	0.017	0.105
30	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.128

APPENDIX C

Statistics –
Field Data Descriptive Statistics
Duncan’s Multiple Range Test Results
Laboratory Data Descriptive Statistics
Covariance Results

Table C.3 - FIELD DATA % RELATIVE ERROR DESCRIPTIVE STATISTICS.

	TSB-1	CC-1	TSB-3	CC-3	TSB-5	CC-5
Mean	-36.441	60.060	-27.945	46.921	138.251	137.035
Standard Error	7.313	5.600	5.159	2.470	3.080	5.179
Median	-42.964	60.940	-26.241	46.294	141.393	143.018
Mode	#N/A	82.210	-73.647	#N/A	149.863	161.712
Standard Deviation	40.054	30.670	28.259	13.527	17.149	28.367
Sample Variance	1604.352	940.676	798.569	182.987	294.095	804.691
Kurtosis	-0.242	-0.092	-0.560	0.411	0.453	-1.096
Skewness	0.732	-0.298	-0.452	-0.061	-0.294	-0.239
Range	151.393	115.047	105.184	57.087	76.230	105.168
Minimum	-100.000	1.881	-87.751	20.267	99.044	77.125
Maximum	51.393	116.929	17.432	77.354	175.273	182.293
Sum	-1093.217	1801.804	-838.346	1407.645	4285.792	4111.064
Count	30.000	30.000	30.000	30.000	31.000	30.000
Largest(1)	51.393	116.929	17.432	77.354	175.273	182.293
Smallest(1)	-100.000	1.881	-87.751	20.267	99.044	77.125
Confidence Level(95.0%)	14.957	11.453	10.552	5.051	6.290	10.592

	TSB-2	CC-2	TSB-4	CC-4	TSB-6	CC-6
Mean	-70.730	21.044	-19.829	23.716	35.603	36.459
Standard Error	4.418	3.082	5.282	3.466	3.229	2.413
Median	-84.363	25.865	-24.010	24.039	32.004	35.084
Mode	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
Standard Deviation	24.198	16.882	30.344	20.508	17.683	13.217
Sample Variance	585.539	284.995	920.764	420.569	312.705	174.700
Kurtosis	-0.958	1.328	1.723	0.584	-0.896	0.450
Skewness	0.862	-1.030	1.224	0.383	0.423	0.556
Range	74.297	74.310	126.480	91.959	59.680	60.809
Minimum	-96.228	-29.268	-61.512	-17.719	9.557	12.185
Maximum	-21.931	45.042	64.968	74.240	69.237	72.994
Sum	-2121.888	631.323	-654.364	830.048	1068.084	1093.767
Count	30.000	30.000	33.000	35.000	30.000	30.000
Largest(1)	-21.931	45.042	64.968	74.240	69.237	72.994
Smallest(1)	-96.228	-29.268	-61.512	-17.719	9.557	12.185
Confidence Level(95.0%)	9.036	6.304	10.760	7.045	6.603	4.935

Site/Device Code:

1 = Price AA	2 = Pygmy	3 = Valeport	4 = Marsh McBirney
5 = Global	6 = One-orange	7 = Isco	8 = Starflow
9 = Dilution	10 = Pressure Trans.	11 = Pressure Trans. 2	
CC = Crab Creek	TSB = Thorne Springs Branch		

(e.g. CC-3 means the Valeport current meter used at Crab Creek)

Table C.3 - FIELD DATA % RELATIVE ERROR DESCRIPTIVE STATISTICS (CONT'D):

	TSB-7	CC-7	TSB-9	CC-9	CC-11
Mean	117.229	109.292	64.990	52.583	-3.945
Standard Error	4.517	7.900	19.388	20.774	0.221
Median	122.224	116.707	77.591	39.770	-4.211
Mode	89.356	109.423	#N/A	#N/A	-4.211
Standard Deviation	26.721	43.270	43.353	46.453	1.231
Sample Variance	714.008	1872.297	1879.479	2157.860	1.516
Kurtosis	-1.413	11.838	0.253	2.097	-0.131
Skewness	0.246	-3.167	-1.063	1.044	1.036
Range	74.266	223.236	103.392	126.678	4.116
Minimum	89.048	-76.393	-1.753	-0.229	-5.729
Maximum	163.313	146.844	101.639	126.449	-1.613
Sum	4103.023	3278.751	324.952	262.916	-122.303
Count	35.000	30.000	5.000	5.000	31.000
Largest(1)	163.313	146.844	101.639	126.449	-1.613
Smallest(1)	89.048	-76.393	-1.753	-0.229	-5.729
Confidence Level(95.0%)	9.179	16.157	53.830	57.679	0.452

	TSB-8	CC-8	TSB-10	CC-10
Column1				
Mean	64.202	59.900	10.060	3.508
Standard Error	3.518	3.650	2.831	0.943
Median	64.473	57.717	3.333	0.000
Mode	79.802	84.028	3.333	0.000
Standard Deviation	19.268	19.990	15.505	5.253
Sample Variance	371.254	399.604	240.399	27.593
Kurtosis	1.140	-0.524	-0.223	-1.565
Skewness	-0.914	0.527	1.290	0.404
Range	85.127	74.929	43.125	14.432
Minimum	14.344	32.172	-3.125	-2.604
Maximum	99.470	107.100	40.000	11.828
Sum	1926.054	1796.991	301.815	108.760
Count	30.000	30.000	30.000	31.000
Largest(1)	99.470	107.100	40.000	11.828
Smallest(1)	14.344	32.172	-3.125	-2.604
Confidence Level(95.0%)	7.195	7.464	5.790	1.927

DUNCAN'S MULTIPLE RANGE TEST OUTPUT:

The SAS System 51

General Linear Models Procedure
Class Level Information

Class	Levels	Values
TREAT	9	1 2 3 4 5 6 7 8 9

Number of observations in data set = 250

The SAS System 52

General Linear Models Procedure

Dependent Variable: DIFF

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	20.549084	2.568636	245.09	0.0001
Error	241	2.525812	0.010481		
Corrected Total	249	23.074896			

R-Square	C.V.	Root MSE	DIFF Mean
0.890539	35.88437	0.1024	0.2853

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	8	20.549084	2.568636	245.09	0.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TREAT	8	20.549084	2.568636	245.09	0.0001

The SAS System 53

General Linear Models Procedure

Duncan's Multiple Range Test for variable: DIFF

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 241 MSE= 0.010481
WARNING: Cell sizes are not equal.
Harmonic Mean of cell sizes= 19.48454

Number of Means	2	3	4	5	6	7	8	9
Critical Range	.06461	.06802	.07029	.07196	.07327	.07433	.07522	.07597

Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	TREAT
	A	0.93413	30	7
	B	0.52515	30	5
	C	0.38891	30	8
	D	0.27800	5	9
	E	0.13581	30	3
	E			
	E	0.13199	30	1
	E			
F	E	0.07568	35	4
F	E			
F	E	0.07133	30	6
F				
F		0.05547	30	2

The SAS System 54

General Linear Models Procedure
Class Level Information

Class	Levels	Values
TREAT	9	1 2 3 4 5 6 7 8 9

Number of observations in data set = 253

The SAS System 55

General Linear Models Procedure

Dependent Variable: DIFF

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	4.7053998	0.5881750	100.34	0.0001
Error	244	1.4303127	0.0058619		
Corrected Total	252	6.1357125			

R-Square	C.V.	Root MSE	DIFF Mean
0.766887	30.69206	0.0766	0.2495

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	8	4.7053998	0.5881750	100.34	0.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TREAT	8	4.7053998	0.5881750	100.34	0.0001

The SAS System 56

General Linear Models Procedure

Duncan's Multiple Range Test for variable: DIFF

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 244 MSE= 0.005862
WARNING: Cell sizes are not equal.
Harmonic Mean of cell sizes= 17.72354

Number of Means	2	3	4	5	6	7	8	9
Critical Range	.05066	.05333	.05511	.05642	.05745	.05828	.05898	.05957

Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	TREAT
	A	0.50600	31	5
	B	0.41237	35	7
	C	0.31725	4	9
	C			
D	C	0.27017	30	2
D				
D		0.23749	30	8
	E	0.17184	30	1
	E			
F	E	0.13198	30	6
F	E			
F	E	0.12377	33	4
F				
F		0.10985	30	3

The SAS System 57

General Linear Models Procedure
Class Level Information

Class	Levels	Values
TREAT	2	10 11

Number of observations in data set = 62

The SAS System 58

General Linear Models Procedure

Dependent Variable: DIFF

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0.0000209	0.0000209	0.59	0.4466
Error	60	0.0021365	0.0000356		
Corrected Total	61	0.0021574			

R-Square	C.V.	Root MSE	DIFF Mean
0.009689	73.69965	0.0060	0.0081

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	1	0.0000209	0.0000209	0.59	0.4466

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TREAT	1	0.0000209	0.0000209	0.59	0.4466

The SAS System 59

General Linear Models Procedure

Duncan's Multiple Range Test for variable: DIFF

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 60 MSE= 0.000036

Number of Means	2
Critical Range	.003032

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	TREAT
A	0.008677	31	10
A			
A	0.007516	31	11

The SAS System 60

General Linear Models Procedure
Class Level Information

Class	Levels	Values
TREAT	2	10 11
SITE	2	0 1

Number of observations in data set = 92

The SAS System 61

General Linear Models Procedure

Dependent Variable: DIFF

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.0005057	0.0002528	8.15	0.0006
Error	89	0.0027613	0.0000310		
Corrected Total	91	0.0032670			

R-Square	C.V.	Root MSE	DIFF Mean
0.154785	85.69386	0.0056	0.0065

Source	DF	Type I SS	Mean Square	F Value	Pr > F

TREAT	1	0.0000483	0.0000483	1.56	0.2155
SITE	1	0.0004574	0.0004574	14.74	0.0002

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TREAT	1	0.0000209	0.0000209	0.67	0.4139
SITE	1	0.0004574	0.0004574	14.74	0.0002

The SAS System 62

General Linear Models Procedure

Duncan's Multiple Range Test for variable: DIFF

NOTE: This test controls the type I comparisonwise error rate,
not the experimentwise error rate

Alpha= 0.05 df= 89 MSE= 0.000031
WARNING: Cell sizes are not equal.
Harmonic Mean of cell sizes= 41.1087

Number of Means	2
Critical Range	.002441

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	TREAT
A	0.007516	31	11
A			
A	0.005984	61	10

LABORATORY DATA % ERROR DESCRIPTIVE STATISTICS:

	Global	*Marsh McBirney*	*Price AA*	*Pygmy*	*Pres. Trans.*
Mean	-87.43	-23.18424	-59.3665	-62.06383	-0.63504202
Standard Error	4.304	2.6903378	6.486536	5.5024846	0.130029629
Median	-100	-27.53538	-47.60201	-50.86996	-0.63810392
Mode	-100	#N/A	-100	-100	#N/A
Standard Deviation	23.57	14.735587	35.528221	30.138349	0.700230983
Sample Variance	555.6	217.13753	1262.2545	908.3201	0.49032343
Kurtosis	5.47	3.4877397	-1.652126	-1.120465	-0.77328079
Skewness	2.214	1.8144647	-0.105909	-0.098542	-0.21605795
Range	100	63.86946	100	100	2.613866044
Minimum	-100	-37.29192	-100	-100	-2.10439105
Maximum	0	26.577535	0	0	0.509474992
Sum	-2623	-695.5272	-1780.995	-1861.915	-18.4162185
Count	30	30	30	30	29
Confidence Level(95.0%)	8.802	5.5023617	13.266463	11.253851	0.26635392

	Bray	*One-Orange*	*Mod. One-orange*	*Isco*	*Starflow*
Mean	-42.67	-58.99284	-51.16735	-29.89514	-13.9323444
Standard Error	6.033	4.3789954	3.8293421	3.9461259	7.261253855
Median	-29.66	-60.20249	-53.06018	-29.4854	-11.8969533
Mode	-100	-100	-100	#N/A	-100
Standard Deviation	33.04	23.984746	20.97417	21.613822	39.77152532
Sample Variance	1092	575.26803	439.91582	467.15728	1581.774226
Kurtosis	-0.407	1.4943087	2.1123277	8.6913049	3.182738441
Skewness	-1.122	0.9081256	0.1328459	0.3060247	0.089606451
Range	100	103.32655	100	146.98607	204.1533744
Minimum	-100	-100	-100	-100	-100
Maximum	0	3.3265547	0	46.986066	104.1533744
Sum	-1280	-1769.785	-1535.021	-896.8543	-417.970332
Count	30	30	30	30	30
Confidence Level(95.0%)	12.34	8.9560562	7.8318882	8.070738	14.85093973

ANALYSIS OF COVARIANCE RESULTS:

Non-Linear Least Squares Summary Statistics   Dependent Variable MEAS

Source	DF	Sum of Squares	Mean Square
Regression	20	17.774214821	0.888710741
Residual	200	0.462605179	0.002313026
Uncorrected Total	220	18.236820000	
(Corrected Total)	219	4.588630836	

Parameter	Estimate	Asymptotic Std. Error	Asymptotic 95 % Confidence Interval Lower	Upper
B0	0.000000000	0.03529639983	-0.0696016445	0.0696016445
B1	1.000000000	0.08220300460	0.8379023262	1.1620976738
Z01	-0.012431261	0.04991664735	-0.1108628510	0.0860003284
Z02	-0.209161177	0.04991664735	-0.3075927669	-0.1107295875
Z03	-0.176065195	0.04991664735	-0.2744967851	-0.0776336058
Z04	-0.029629056	0.04991664735	-0.1280606456	0.0688025338
Z05	-0.138143428	0.04991664735	-0.2365750177	-0.0397118384
Z06	0.111603751	0.04991664735	0.0131721611	0.2100353405
Z07	0.005064614	0.04991664735	-0.0933669754	0.1034962039
Z08	0.023632389	0.04991664735	-0.0747992008	0.1220639785
Z09	-0.033287612	0.04991664735	-0.1317192013	0.0651439781
Z11	-0.256279705	0.11625260397	-0.4855204335	-0.0270389761
Z12	0.074183637	0.11625260397	-0.1550570913	0.3034243661
Z13	-0.050621274	0.11625260397	-0.2798620031	0.1786194543
Z14	-0.186764108	0.11625260397	-0.4160048364	0.0424766210
Z15	-0.506897288	0.11625260397	-0.7361380163	-0.2776565589
Z16	-0.929448226	0.11625260397	-1.1586889550	-0.7002074976
Z17	-0.541478207	0.11625260397	-0.7707189357	-0.3122374783
Z18	-0.368615174	0.11625260397	-0.5978559024	-0.1393744450
Z19	-0.056164680	0.11625260397	-0.2854054089	0.1730760484

The MIXED Procedure

Class Level Information

Class	Levels	Values
TRT	10	0 1 2 3 4 5 6 7 8 9

Covariance Parameter Estimates (REML)

Cov Parm	Estimate
Residual	0.00231303

Model Fitting Information for MEAS

Description	Value
Observations	220.0000
Res Log Likelihood	313.0373
Akaike's Information Criterion	312.0373
Schwarz's Bayesian Criterion	310.3882
-2 Res Log Likelihood	-626.075

Solution for Fixed Effects

Effect	TRT	Estimate	Std Error	DF	t	Pr > |t|
TRT	0	0.00000000	0.03529640	200	0.00	1.0000
TRT	1	-0.01243126	0.03529640	200	-0.35	0.7251
TRT	2	-0.20916118	0.03529640	200	-5.93	0.0001
TRT	3	-0.17606520	0.03529640	200	-4.99	0.0001
TRT	4	-0.02962906	0.03529640	200	-0.84	0.4022
TRT	5	-0.13814343	0.03529640	200	-3.91	0.0001
TRT	6	0.11160375	0.03529640	200	3.16	0.0018
TRT	7	0.00506461	0.03529640	200	0.14	0.8860
TRT	8	0.02363239	0.03529640	200	0.67	0.5039
TRT	9	-0.03328761	0.03529640	200	-0.94	0.3468
CONTROL*TRT	0	1.00000000	0.08220300	200	12.17	0.0001
CONTROL*TRT	1	0.74372030	0.08220300	200	9.05	0.0001
CONTROL*TRT	2	1.07418364	0.08220300	200	13.07	0.0001
CONTROL*TRT	3	0.94937873	0.08220300	200	11.55	0.0001
CONTROL*TRT	4	0.81323589	0.08220300	200	9.89	0.0001
CONTROL*TRT	5	0.49310271	0.08220300	200	6.00	0.0001

CONTROL*TRT	6	0.07055177	0.08220300	200	0.86	0.3918
CONTROL*TRT	7	0.45852179	0.08220300	200	5.58	0.0001
CONTROL*TRT	8	0.63138483	0.08220300	200	7.68	0.0001
CONTROL*TRT	9	0.94383532	0.08220300	200	11.48	0.0001

Tests of Fixed Effects

Source	NDF	DDF	Type III F	Pr > F
TRT	10	200	8.75	0.0001
CONTROL*TRT	10	200	89.05	0.0001

ESTIMATE Statement Results

Parameter	Estimate	Std Error	DF	t	Pr > |t|
b1-control	-0.25627970	0.11625260	200	-2.20	0.0286
b2-control	0.07418364	0.11625260	200	0.64	0.5241
b3-control	-0.05062127	0.11625260	200	-0.44	0.6637
b4-control	-0.18676411	0.11625260	200	-1.61	0.1097
b5-control	-0.50689729	0.11625260	200	-4.36	0.0001
b6-control	-0.92944823	0.11625260	200	-8.00	0.0001
b7-control	-0.54147821	0.11625260	200	-4.66	0.0001
b8-control	-0.36861517	0.11625260	200	-3.17	0.0018
b9-control	-0.05616468	0.11625260	200	-0.48	0.6295
b3-b2	0.12480491	0.11625260	200	1.07	0.2843
b4-b2	0.26094775	0.11625260	200	2.24	0.0259
b9-b2	0.13034832	0.11625260	200	1.12	0.2635
b4-b3	0.13614283	0.11625260	200	1.17	0.2430
b9-b3	0.00554341	0.11625260	200	0.05	0.9620
b9-b4	-0.13059943	0.11625260	200	-1.12	0.2626

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	0.39497	0.39497	53.589	0.0001
Error	20	0.14741	0.00737		

C Total	21	0.54238

Root MSE	0.08585	R-square	0.7282
Dep Mean	0.23218	Adj R-sq	0.7146
C.V.	36.97566		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > |T|
INTERCEP	1	-0.209161	0.06300634	-3.320	0.0034
C2	1	1.074184	0.14673765	7.320	0.0001

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	0.30852	0.30852	116.856	0.0001
Error	20	0.05280	0.00264		
C Total	21	0.36132			

Root MSE	0.05138	R-square	0.8539
Dep Mean	0.21400	Adj R-sq	0.8466
C.V.	24.01056		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > |T|
INTERCEP	1	-0.176065	0.03770998	-4.669	0.0001
C3	1	0.949379	0.08782407	10.810	0.0001

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	0.22638	0.22638	220.092	0.0001
Error	20	0.02057	0.00103		
C Total	21	0.24695			

Root MSE	0.03207	R-square	0.9167
Dep Mean	0.30450	Adj R-sq	0.9125
C.V.	10.53246		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > |T|
INTERCEP	1	-0.029629	0.02353734	-1.259	0.2226
C4	1	0.813236	0.05481693	14.835	0.0001

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	0.30493	0.30493	138.808	0.0001
Error	20	0.04394	0.00220		
C Total	21	0.34886			

Root MSE	0.04687	R-square	0.8741
Dep Mean	0.35450	Adj R-sq	0.8678
C.V.	13.22135		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > |T|
INTERCEP	1	-0.033288	0.03439791	-0.968	0.3447
C9	1	0.943835	0.08011048	11.782	0.0001

Vita:

Charles E. Mitchem, Jr.

Charles E. Mitchem, Jr. was born on August 8, 1966 in Altus, Oklahoma to Hazel Ann Mitchem. He moved quite a lot until he graduated from Giles High School in 1985. During the next seven years, he worked as an appliance deliveryman, hardwood floor mechanic's helper, and high voltage coil winder. In 1989, he enrolled full-time in the Engineering program at Virginia Western Community College, while working second shift at Virginia Transformer Corp. in Roanoke, Virginia. He was promoted from the manufacturing floor at Virginia Transformer Corp. to Quality Assurance in 1992, the same year he graduated from Virginia Western Community College. He continued to work part-time in his new position as he began attending Virginia Polytechnic Institute and State University in the Fall of 1992. He graduated from the Agricultural Engineering Department at Virginia Tech on December 17, 1994, the day after he was married to Kimberely Ann Mitchem. He began working for Timber Truss Housing Systems in Salem, Virginia in January 1995 as an Engineering Representative. In January 1998, he left Timber Truss to begin graduate study for a Master of Science degree in the Biological Systems Engineering Department. He and Kim spent a month hiking on the Appalachian Trail in June 1999. He began working as an Agricultural Engineer at MapTech, Inc. in October 1999 and completed his graduate study in January 2000.