December 2003
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Environmental Technology Verification Report

Wet Weather Flow Monitoring Equipment

ADS Environmental Model 3600 Open Channel Flow Monitor

Part I – Laboratory Test Results

Prepared by

NSF International

Under a Cooperative Agreement with
U.S. Environmental Protection Agency

THE ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM

U.S. Environmental Protection Agency

NSF International

ETV Joint Verification Statement

TECHNOLOGY TYPE:	**AREA/VELOCITY FLOW METERS**
APPLICATION:	**FLOW METERING IN SMALL- AND MEDIUM-SIZED (10- to 42-inch) SEWERS**
TECHNOLOGY NAME:	**ADS ENVIRONMENTAL SERVICES MODEL 3600 OPEN CHANNEL FLOW METER**
TEST LOCATION:	**QUEBEC CITY, QUEBEC, CANADA, AND LOGAN, UTAH**
COMPANY:	**ADS ENVIRONMENTAL SERVICES**
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NSF International (NSF) manages the Water Quality Protection Center (WQPC) under the U.S. Environmental Protection Agency's (EPA) Environmental Technology Verification (ETV) Program. NSF evaluated the performance of the Model 3600 Open Channel Flow Meter manufactured by ADS Environmental Services. Utah Water Research Laboratory (UWRL) in Logan, Utah, and BPR of Quebec City, Canada, both NSF-qualified testing organizations, performed the laboratory and field verification testing, respectively.

EPA created the ETV Program to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV program is to further environmental protection by accelerating the acceptance and use of improved and cost-effective technologies. ETV seeks to achieve this goal by providing high-quality, peer-reviewed data on technology performance to those involved in the design, distribution, permitting, purchase, and use of environmental technologies.

ETV works in partnership with recognized standards and testing organizations; stakeholder groups consisting of buyers, vendor organizations, and permitters; and with the full participation of individual technology developers. The program evaluates the performance of innovative technologies by developing test plans that are responsive to the needs of stakeholders, conducting field or laboratory tests (as appropriate), collecting and analyzing data, and preparing peer reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance protocols to ensure that data of known and adequate quality are generated, and that the results are defensible.

TECHNOLOGY DESCRIPTION

The following technology description is provided by the vendor and does not represent verified information.

Area/velocity flow meters are commonly used in wastewater collection, storm sewer, and combined sewer systems. The ADS 3600 flow meter utilizes a quad-redundant ultrasonic sensor that measures the time required for an ultrasonic pulse to travel from the sensor face to the surface of the water and back to the sensor. The meter converts the travel time to distance by calculating the speed of sound through air and adjusting for temperature, which is measured by two sensors inside the ultrasonic sensor head. The depth of the flow is then calculated using the pipe diameter and the range measured by the ultrasonic sensor. A pressure-depth sensor is also installed at the bottom of the pipe to measure surcharge levels and to provide a redundant depth reading when used with the ultrasonic level sensor. Doppler velocity measurements are made by transmitting an ultrasonic signal upstream using a submerged velocity sensor and measuring the frequency shift in the sound waves reflected by the moving particles in the water. The depth and velocity sensor readings are stored in the flow meter's memory until the data can be downloaded to a computer through either a voice-grade telephone line or a cellular network. The computer software calculates flow rates using the depth and velocity readings.

The ADS 3600 flow meter system includes the flow meter unit, sensors, and installation hardware. The flow meter unit is housed in a waterproof, marine-grade aluminum housing. The submersible pressure sensor, ultrasonic level sensor, and velocity sensor are attached to a circular stainless steel band installed around the inner circumference of the sewer pipe. Waterproof cables with sealed connectors convey power and signals between the flow meter unit and the sensors. The system is battery-powered, and can power the unit for about one year at a standard 15-minute measurement interval. The unit is intrinsically safe. According to vendor claims, after the unit is installed, minimal operation and maintenance (O&M) or unit calibration is required; the most common O&M procedure is cleaning the sensors.

VERIFICATION TESTING DESCRIPTION

Laboratory Test Site

The laboratory testing was completed at the Utah Water Research Laboratory (UWRL), at Utah State University in Logan, Utah. The flow meter was installed in three nominal pipe sizes: 10-inch, 20-inch, and 42-inch. The straight lengths were sized so they were at least 40 times the pipe diameter for the 10- and 20-inch pipes and at least 22 times for the 42-inch pipes. Pipe slopes were adjustable to allow the flow meter to be evaluated under different slope conditions. Sluice gates at both ends of the pipes were used to regulate appropriate flow, head, and obstruction during testing. Reference devices were directly traceable to the National Institute of Standards and Technology (NIST), and were regularly calibrated. Uncertainty for the reference devices was less than 0.25 percent.

Field Test Site

Field verification testing was conducted in a section of the Quebec Urban Community's sewer network, located in the City of Sainte-Foy, Quebec, Canada. The ADS flow meter and reference meters were installed in a 41.7-inch diameter interceptor pipe, near the downstream end of a straight run of pipe that had a mean slope of 0.169 percent. The reference devices, which consisted of a bubbler for reference level measurement, a reference flow monitor, and an Accusonic 4-path flow monitor, were installed downstream of the ADS flow meter. Upstream and downstream sluice gates were used to create the required flow conditions.

Validation of the reference flow monitor and bubbler were performed by lithium tracer dye tests. Flow rates under the upstream and downstream gates were calculated using standard hydraulic equations for a redundant check of flow data.

Methods and Procedures

Laboratory evaluation of the flow meters consisted of collecting depth, velocity, and flow data from the ADS meter and comparing it to the depth, velocity, and flow data from the reference devices. These tests were performed under normal operating conditions of uniform flow, backwater flow, full pipe (manhole surcharged), and simulated silt. Water transmission through the pipes, as a ratio of flow depth versus the pipe diameter (d/D), ranged from 10 to 250 percent (surcharged conditions). Tests were also performed under the abnormal operating conditions of reverse flow and grease accumulation.

Field evaluation of the ADS flow meter at the Quebec site consisted of a general evaluation of the flow meter (Test A) and the performance of the meter under varying flow conditions. Testing consisted of collecting depth, velocity, and flow data at regular time intervals and comparing the data to the corresponding depth, velocity, and flow data from the reference devices. Four test scenarios were used:

1. Test B—accuracy under low weather flow (approximately 1.71 million gallons per day [MGD]), with back-flow conditions;
2. Test C—accuracy under wet weather flow (1.71–29.7 MGD), without back-flow conditions;
3. Test D—accuracy under wet weather flow (1.71–29.7 MGD), with back flow-conditions; and,
4. Test E—accuracy under short-term (26-day) continuous operation, with various flow rates.

Three conditions were identified during testing that created an unintended challenge to the ADS flow meter:

1. The water used in the testing at UWRL did not contain the particulate concentrations of normal sewage, so small quantities of coffee creamer were added to the water on some test runs. The operating principle utilized by the ADS flow meter requires particles in the water to serve as reflectors for sound waves. The vendor maintained that the coffee creamer additive provided a level of reflectivity, but the particulate concentration in the test water did not approach that of sewage and could be a source of measurement error.

2. During each field test, a portion of the ADS flow meter data collected at one-minute intervals was not recorded. ADS personnel indicated that this happened because the flow meter was configured for maximum error checking and sensor refiring. They further indicate that the ADS 3600 flow meter can be reconfigured to collect data at one-minute intervals by reducing the level of real-time error checking.

3. The field testing results include data in which it appears that standing waves and troughs were present beneath the ADS 3600 flow meter's ultrasonic depth sensor. During portions of the testing, the depth sensor was likely affected by standing waves and troughs up to $\pm$5 inches. The ADS flow meter measures depth with a downward-looking, narrow-beam ultrasonic sensor mounted on the top of the pipe, so depth measurements would be susceptible to influence by waves. Based on a review of the field data, it appears that waves were most prevalent at higher depths and flow rates.

No editing was allowed on the metered data during field or laboratory testing. In actual applications, the flow monitoring service provider may implement post-monitoring quality control measures to attempt to improve the accuracy of final data. According to ADS, the company typically bundles flow meter sales with post-monitoring quality control and reporting services.

VERIFICATION OF PERFORMANCE

System Operation

The testing organizations found the equipment durable and easy to use, and that it required minimal maintenance. The flow meter operation and data retrieval software programs were easy to learn. The ultrasonic sensors and stainless steel band did not promote accumulation of debris during testing.

Laboratory Testing Results

The mean deviations and the 95-percent confidence intervals under normal operating conditions (i.e., all test conditions except grease tests and reverse flow) are presented in Table 1. The width of the 95-percent confidence interval is a function of the variation in instrument deviation, and the number of test runs in each reported category. Categories with a fewer number of runs show wider confidence intervals. The calculations exclude "abnormal condition" tests, where grease was applied to the sensors or where reverse-flow conditions were created. The mean deviation for the abnormal operating conditions was 1.9 percent for the 0.5-mm grease tests, -100.0 percent for the 2.0-mm grease tests, and –72.7 percent for the reverse-flow tests.

Table 1. Deviation and 95-Percent Confidence Interval by Test Configuration for Lab Testing

Pipe size (inches)	Deviation (percent)	95-percent confidence interval
10	2.8	0.2 – 5.4
20	7.2	2.4 – 12.0
42	1.6	-1.8 – 5.0
Pipe slope (percent)		
0.1	4.9	-1.4 – 11.2
0.2	1.6	-1.8 – 5.0
0.5	5.6	1.6 – 9.6
1.25	4.2	-1.6 – 9.9
2.0	6.1	-3.8 – 16.1
Percent full (d/D, percent)		
10	3.6	-9.4 – 16.6
30	11.1	6.5 – 15.7
50	3.4	0.2 – 6.7
80	1.3	-3.1 – 5.6
150	0.9	0.9 – 2.8
250	4.8	-5.0 – 14.6
Condition		
Free-flow	2.6	-1.4 – 6.7
Back-flow	5.8	2.9 – 8.7
All conditions	4.5	2.1 – 6.9

The overall accuracy of the ADS flow meter under normal operating conditions is shown in Figure 1. The meter deviation is segregated into two components—bias and precision. Overall bias was 1.6 percent, as calculated by the slope of the best-fit line. Precision, as calculated with the correlation coefficient (r^2), was 0.45 percent.

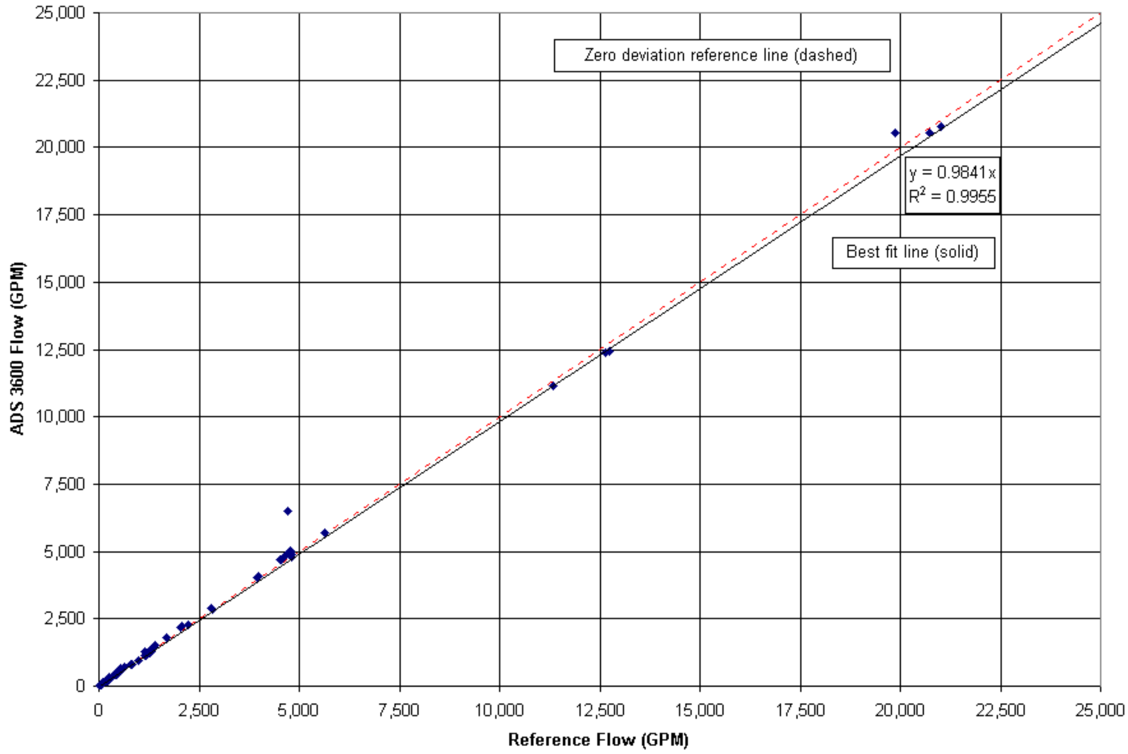

Figure 1. Laboratory metered flow rate versus reference.

Field Testing Results

Table 2 summarizes the field testing results in two categories: mean deviation and trimmed mean deviation. The mean deviation is the arithmetic mean of all of the one-minute–interval data. The trimmed mean deviation is calculated by eliminating values greater than ±99 percent, making it less susceptible to skewing from large outliers, such as those produced when the ADS flow meter recorded zero velocity.

Table 2. Deviation from Reference Flow: Tests B, C, and D

Flow regime	Mean deviation (percent)	Trimmed mean deviation (percent)
Test B	-29.7	2.4
Test C	5.0	5.0
Test D	-1.0	4.7
Test B-D combined	**-5.7**	**2.1**
Simulated low flow	-7.6	12.2
Simulated high flow	-4.3	-4.1
Combined flows	**-5.7**	**2.1**

Analysis of the data collected during Test B (low flow) revealed that the deviation was –100 percent in nearly one-third of the samples. This occurred most frequently during back-flow conditions when the ADS 3600 recorded zero velocity and calculated zero flow. The data collected during Tests C and D showed a much lower occurrence of data with deviations exceeding ±99 percent.

Test E (not included in Table 2) evaluated the performance of the flow meter over an extended (26-day) time period. Generally, the data collected during Test E closely correlated with the reference flow monitor data. Spikes were noted in water level measurements collected toward the end of the test, which may have been the result of accumulated condensation on the ultrasonic depth probe. No debris accumulation was observed on the equipment, and, aside from a thin film of grease on the probes, the equipment was in good condition and did not require maintenance.

QUALITY ASSURANCE/QUALITY CONTROL

A complete description of the quality assurance/quality control procedures and findings are included in the verification reports. Calibration records were maintained by the testing organizations and validation of the reference flow devices fell within control limits. NSF completed a data quality audit of at least 10 percent of the test data to ensure that the reported data represented the data generated during testing. Audits of the field and laboratory testing were conducted by NSF with no significant issues noted.

Original Signed by
Lee A. Mulkey *March 31, 2004*

Lee A. Mulkey Date
Acting Director
National Risk Management Laboratory
Office of Research and Development
United States Environmental Protection Agency

Original Signed by
Gordon Bellen *April 26, 2004*

Gordon Bellen Date
Vice President
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NOTICE: Verifications are based on an evaluation of technology performance under specific, predetermined criteria and the appropriate quality assurance procedures. EPA and NSF make no expressed or implied warranties as to the performance of the technology, and do not certify that a technology will always operate as verified. The end user is solely responsible for complying with any and all applicable federal, state, and local requirements. Mention of corporate names, trade names, or commercial products does not constitute endorsement or recommendation for use of specific products. This report is not an NSF Certification of the specific product mentioned herein.

Availability of Supporting Documents

Copies of the *Draft 4.0 – Generic Verification Protocol, Flow Monitors for Wet Weather Flows Applications in Small- and Medium-Sized Sewers, September, 2000,* the verification statement, and the verification report (NSF Report #03/12/WQPC-WWF) are available from:

ETV Water Quality Protection Center Program Manager (order hard copy)
NSF International
P.O. Box 130140
Ann Arbor, Michigan 48113-0140
NSF web site: http://www.nsf.org/etv (electronic copy)
EPA web site: http://www.epa.gov/etv (electronic copy)

(NOTE: Appendices are not included in the verification report. Appendices are available upon request from NSF.)

Environmental Technology Verification Report

WET WEATHER FLOW MONITORING EQUIPMENT VERIFICATION

ADS ENVIRONMENTAL MODEL 3600
OPEN CHANNEL FLOW MONITOR

PART I - LABORATORY TEST RESULTS
UTAH WATER RESEARCH LABORATORY TEST SITE

Prepared for:

NSF International
Ann Arbor, Michigan

Prepared by:

Utah Water Research Laboratory
Logan, Utah

December 2003

Under a cooperative agreement with the U.S. Environmental Protection Agency

Raymond Frederick, Project Officer
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Notice

The U.S. Environmental Protection Agency (EPA) through its Office of Research and Development has financially supported and collaborated with NSF International (NSF) under a cooperative agreement. This verification effort was supported by the Water Quality Protection Center operating under the Environmental Technology Verification (ETV) Program. This document has been peer reviewed and reviewed by NSF and EPA and recommended for public release.

Foreword

The following is the final report on an Environmental Technology Verification (ETV) test performed for NSF International (NSF) and the United States Environmental Protection Agency (EPA) by Utah Water Research Laboratory, in cooperation with ADS Environmental Services for the Model 3600 Open Channel Flow Monitor. The test protocol for flow monitors requires both laboratory and field testing. The final report for this verification is divided into two parts to address both portions of testing.

This part of the report (Part I) describes the testing and summarizes the data from the laboratory testing. Part II: Field Test Results, describes the testing and summarizes the data of the field testing. Both parts of the report are available on the NSF and EPA websites.

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

Contents

Tables

Figures

Acronyms and Abbreviations

ADS	ADS Environmental Services, a division of ADS Corporation
BPR	BPR, Quebec, Canada
cfs	Cubic feet per second
ENS	Event Notification System
EPA	United States Environmental Protection Agency
ETV	Environmental Testing Verification
ft	Foot or feet
FTO	Field testing organization
gpm	Gallons per minute
in.	Inch or inches
lb	Pound
LTO	Laboratory testing organization
mg/L	Milligrams per liter
min	Minimum
NIST	National Institute of Standards and Technology
NSF	NSF International (formerly National Sanitation Foundation)
NTU	Nephelometric turbidity units
QA	Quality assurance
QUC	Quebec Urban Community
SAG	Stakeholders Advisory Group
SCADA	Supervisory control and data acquisition
UWRL	Utah Water Research Laboratory
VTP	Verification test plan
WWF	Wet weather flow

Acknowledgments

The Laboratory Testing Organization, Utah Water Research Laboratory, and the Field Testing Organization, BPR, Quebec, Canada, were responsible for all elements in the testing sequence, including test set-up, calibration and verification of instruments, data collection and analysis, data management, data interpretation, and the preparation of this report.

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The manufacturer of the equipment:

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Contact Person: Eugene C. Cullie

The Utah Water Research Laboratory wishes to thank the UWRL shop for the many hours spent preparing the piping for these tests. Also, special thanks to Utah State University Engineering students Randy Geldmacher, Tyler Smith, John Nunley, and Garrett McMullen for their assistance in establishing proper test conditions and collecting test data. It is also necessary to thank ADS personnel for their support throughout the test program. ADS support was provided by George Kurz, Pat Stevens, Keith Waites, Christy Kennamer, Heather Hackett, Jeffrey White, Erica Blanken, Mark MacPherson, and Gillian Woodward.

Chapter 1
Introduction

1.1 ETV Purpose and Program Operation

The U.S. Environmental Protection Agency (EPA) created the Environmental Technology Verification (ETV) Program to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV program is to further environmental protection by substantially accelerating the acceptance and use of improved and more cost-effective technologies. ETV achieves this goal by providing high quality, peer-reviewed data on technology performance to those involved in the design, distribution, permitting, purchase, and use of environmental technologies.

ETV works in partnership with recognized standards and testing organizations; stakeholder groups, which consist of buyers, vendor organizations, and permitters; and with the full participation of individual technology developers. The program evaluates the performance of innovative technologies by developing test plans that are responsive to the needs of stakeholders, conducting field or laboratory testing (as appropriate), collecting and analyzing data, and preparing peer-reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance protocols to ensure that data of known and adequate quality are generated, and that the results are defensible.

NSF International (NSF) operates the Wet Weather Flow (WWF) Technologies Area in cooperation with the EPA under the Water Quality Protection Center. The WQPC evaluated the performance of the ADS Model 3600 open channel flow monitor, which is an area/velocity flow meter used to measure flows in municipal sewers. The performance claim evaluated during laboratory testing of the ADS Model 3600 was that the instrument is capable of measuring depths and velocities in a wide range of pipe sizes and flow conditions. This document provides the laboratory verification test results for the ADS Model 3600 open channel flow monitor.

1.2 Testing Participants and Responsibilities

The ETV testing of the ADS 3600 Open Channel Flow Monitor was a cooperative effort of the following participants:

- U.S. Environmental Protection Agency
- NSF International
- Utah Water Research Laboratory
- BPR
- ADS Environmental

The following is a brief description of the ETV participants and their roles and responsibilities.

1.2.1 U.S. Environmental Protection Agency

The EPA Office of Research and Development, through the Urban Watershed Branch, Water Supply and Water Resources Division, National Risk Management Research Laboratory (NRMRL), provides administrative, technical, and quality assurance guidance and oversight on all ETV Water Quality Protection Center activities.

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1.2.2 NSF International

NSF is a not-for-profit testing and certification organization dedicated to public health, safety, and protection of the environment. Founded in 1946 and located in Ann Arbor, Michigan, NSF has been instrumental in the development of consensus standards for the protection of public health and the environment. NSF also provides testing and certification services to ensure that products bearing the NSF Name, Logo and/or Mark meet the organization's standards.

NSF had several different roles in completing this verification. NSF reviewed the verification of the verification test plan (VTP) and provided technical oversight of the verification testing, including auditing of the laboratory's analytical, data gathering, and data recording procedures. NSF also provided review of this verification report.

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1.2.3 Laboratory Testing Organization

The Utah Water Research Laboratory (UWRL), a Utah State University hydraulic research facility, is an NSF-qualified testing organization (TO) for the WQPC and conducted the verification testing of the ADS 3600 flowmeter. UWRL provided all needed logistical support, established a communications network, and scheduled and coordinated the activities of all participants. It was responsible for ensuring that the testing location and feed water conditions could meet the stated objectives of the verification testing. UWRL prepared the VTP; oversaw the pilot testing; managed, evaluated, interpreted and reported on the data generated by the testing; and evaluated and reported on the performance of the technology.

UWRL employees manufactured and prepared the test piping, set test conditions, and measured and recorded data during the testing. The UWRL's Project Manager provided testing oversight.

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1.2.4 Field Testing Organization

BPR is an NSF-qualified TO for the WQPC and was responsible for conducting the field verification testing of the ADS 3600 flowmeter. The testing was conducted on a section of the Quebec Urban Community's (QUC) western sewer network located in the City of Sainte-Foy, along the east side of Boulevard Chaundière, approximately between Bombardier and Mendel Streets.

BPR provided all needed logistical support, established a communications network, and scheduled and coordinated the activities of all participants. It was responsible for ensuring that the testing location and feed water conditions could meet the stated objectives of the verification testing. It prepared the VTP, oversaw the pilot testing; managed, evaluated, interpreted, and reported on the data generated by the testing; and evaluated and reported on the performance of the technology.

BPR employees prepared the test site, set test conditions, and measured and recorded data during the testing. BPR's Project Manager provided oversight of the daily tests.

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1.2.5 Vendor

The flow monitoring equipment is manufactured by ADS Corporation. ADS was responsible for supplying a field-ready open channel flow meter equipped with all necessary components, including an installation and operation manual. The manufacturer was also responsible for providing technical support personnel. This individual was responsible for installing and precalibrating the flow monitoring equipment in the simulated sewer for each test series, and was available during all tests to provide technical assistance as needed.

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1.3 Laboratory Verification Testing Site

The Utah Water Research Laboratory, constructed in 1965, is one of the largest water research laboratories of its kind in the country. The laboratory, which occupies more than 50,000 square feet of floor space, contains a variety of flumes, channels, pumps, pipelines, equipment, and instrumentation for conducting hydraulic research, model studies, hydraulic valve testing, and flow meter calibrations. It is capable of performing an array of hydraulic tests and research programs. A network of steel piping (18-, 24-, 36-, and 48-inch diameter), located under the floor of the lab, provides maximum flexibility in constructing test lines from 1/2-inch to 60-inches. Under-the-floor channels conduct water from the experiments back to the river, to recirculating pumps, or to the precise flow measurement facilities.

The primary water supply for the laboratory is an 85-acre-foot reservoir approximately 500 feet from the facility. The water supply, which is conveyed to the laboratory through a 48-inch pipe, provides a constant 25 feet of head to the main level of the laboratory and 35 feet of head to the lower level at shutoff. Flow can also be supplied from either high-pressure pumps or a constant level tank within the laboratory.

For direct National Institute of Standards (NIST) traceability, flow rates are measured using the laboratory's weigh and volumetric tanks. These tanks are calibrated regularly and are NIST-traceable by weight. The UWRL primary flow measurement system consists of one 1,000 lb weigh tank, two 30,000 lb weigh tanks, and a 222,144 lb (3,560 ft^3) volumetric tank. Flow rates up to 40 cubic feet per second (cfs) can be accurately measured with the primary flow measurement system.

A number of venturi meters—6-, 12-, 20-, 24-, and 48-inch—are installed in various test lines throughout the laboratory. These master meters are calibrated in place using the UWRL primary flow measurement system. As a secondary standard with NIST-traceability, these meters allow accurate flow measurements to be made for flow rates up to approximately 200 cfs.

Chapter 2
ADS Equipment Description and Operating Processes

The information contained in this chapter is provided by the vendor and does not represent verified information. The information is intended to provide the reader with a description of the ADS 3600 flow monitor and to explain how the technology operates. The verified performance characteristics of the ADS 3600 are described in subsequent chapters.

2.1 Equipment Description

The ADS 3600 flow monitor is specially designed to meet the demands of measuring flow over long-term periods in open channel applications, such as wastewater collection systems, storm sewer systems, and combined sewer systems. The battery-powered system acquires highly accurate depth and velocity data, and transmits the data through telemetry to a remote computer. The ADS 3600 is certified as Intrinsically Safe (IS) by Factory Mutual (United States), and by SIRA Certification Services (International). IS certification confirms that it meets both U.S. and international standards for electrical apparatus installed in potentially explosive environments.

The ADS 3600 is used for many project applications, including:

- Infiltration/inflow analysis and reduction;
- Master plan studies;
- Interagency billing networks;
- Combined sewer overflow characterization;
- Storm sewer monitoring;
- Sewer capacity analysis; and
- Sewer system performance studies/trending.

Precise pipe dimensions (height and width) are measured during installation because they are critical to both depth and cross-sectional area. ADS depth sensors measure the distance from the down-looking sensor to the water surface (range) and depth of flow is obtained by subtracting the range from the diameter. This is an important step since the inside diameter of most sewer pipe is not equal to its nominal diameter. Velocity sensor confirmation is another critical-to-quality activity. While the ADS 3600 velocity sensor will perform in most sites using factory default settings, it can be adjusted by a trained technician to improve performance in unique hydraulic conditions.

The ADS 3600 features:

- Quad-redundant Ultrasonic Level Sensor. This nonintrusive, zero-drift sensing method results in a stable, accurate, and reliable flow depth calculation.
- Peak Velocity Sensor. Readings from this sensor are used to calculate average velocity. Its miniature size minimizes fouling and flow disruption.
- Pressure Depth Sensor. This sensor is used to measure surcharge levels or to provide a redundant depth reading when used in conjunction with the ultrasonic level sensor.

- Water Quality Sampler Interface. A variety of industry standard water quality samplers are compatible and easily interfaced with the Model 3600. Sampling is initiated automatically based on a fixed-time or flow proportional basis. The sampler must be certified to maintain IS certification.
- Tipping Bucket Interface. Where installation criteria allow, the flow monitor can be interfaced to a tipping bucket unit to record rainfall amounts.
- Supervisory Control and Data Acquisition (SCADA) System Interface. An external modem unit can communicate both with a SCADA system remote computer and via telemetry with QuadraScan™ Software.
- QuadraScan™ Software. This enables a SCADA system to retrieve various data entities, including depth of flow, average velocity, flow rate, daily flow totals, etc.
- Accurate Flow Measurement. This technology has been shown to be highly accurate in both laboratory and in-field tests. It measures flow under open channel, free flow conditions, and non-free flow conditions, including surcharge and backwater.
- QuadraScan™ Software Interface. This complete hydraulics and analysis package provides telemetered data collection, trending, reporting, and file management.
- Automated Data Collection. Data can be collected at user-defined times, including group collections of multiple monitoring units, increasing the efficiency and flexibility of flow data analysis.
- Event Notification System (ENS) Capability. Consisting of the ADS 3600 Monitor, QuadraScan™ Software, and event reporting software, this versatile system can initiate an alarm to a remote location and/or activate other instrumentation activity such as water quality sampling based on preset conditions.
- Low Cost Telemetry. The standard telemetry interface allows remote communications and diagnostics, resulting in a significant reduction in field labor.
- Manufacturing Quality Control. Each unit undergoes factory testing and certification by qualified technicians.
- Ultra-low Power Consumption. Batteries can last more than one year under most operating and environmental conditions.
- Fully Water-Resistant Housing. The housing reliably withstands harsh sewer environments, even under surcharge conditions.
- Low Battery Warning. Each unit monitors battery voltages to warn the operator in advance of battery failure.
- Optional Non-IS Configuration. This unit is suitable for installations where protection from explosive environments is not required.

Figure 2-1 is a view of the ADS 3600 meter's canister. Figure 2-2 shows the stainless steel ring and sensing devices installed inside a pipe.

The ADS meter installation is similar to nearly all depth velocity meters, but the ADS meter differs in that only its velocity sensor is mounted in the flow. The velocity sensor offers a cross-sectional area of around one-half square inch, and measures velocity in depths of less than one inch. Both the depth and velocity sensors are mounted on a stainless-steel ring that is expanded into place with a hand crank and spreader bars. The meter is either attached to rungs in the manhole or to an attachment hook drilled into place on the manhole wall. The meter is activated by downloading BASIC code with monitor and sensor configuration. The monitor clock is synchronized with the central computer each time data are collected.

Figure 2-1. ADS Model 3600 Open Channel Flow Monitor.

It is important that the actual pipe dimensions be measured for two reasons: (1) the correct diameter will be used to calculate cross-sectional area of the pipe; and (2) the depth of flow equals the actual diameter minus the range measured by the depth sensor. An incorrect diameter translates directly to an incorrect depth. The inside diameter of most sewer pipe is not equal to its nominal diameter. For example, a 15-inch PVC sewer line with SDR 35 wall thickness has a maximum manufactured diameter of 14.4 inches.

The monitor and software manuals offer approximately 600 pages of instruction, including graphics, on installing the meter, activating the meter, collecting data, and processing data.

ADS provides hardware as well as flow monitoring services throughout the United States. Technical support is provided by its headquarters office as well as by 16 regional and local offices. Most offices are staffed with data analysts and operations people who will readily assist with any hardware, software, or operational problem. Parts can be ordered through any office.

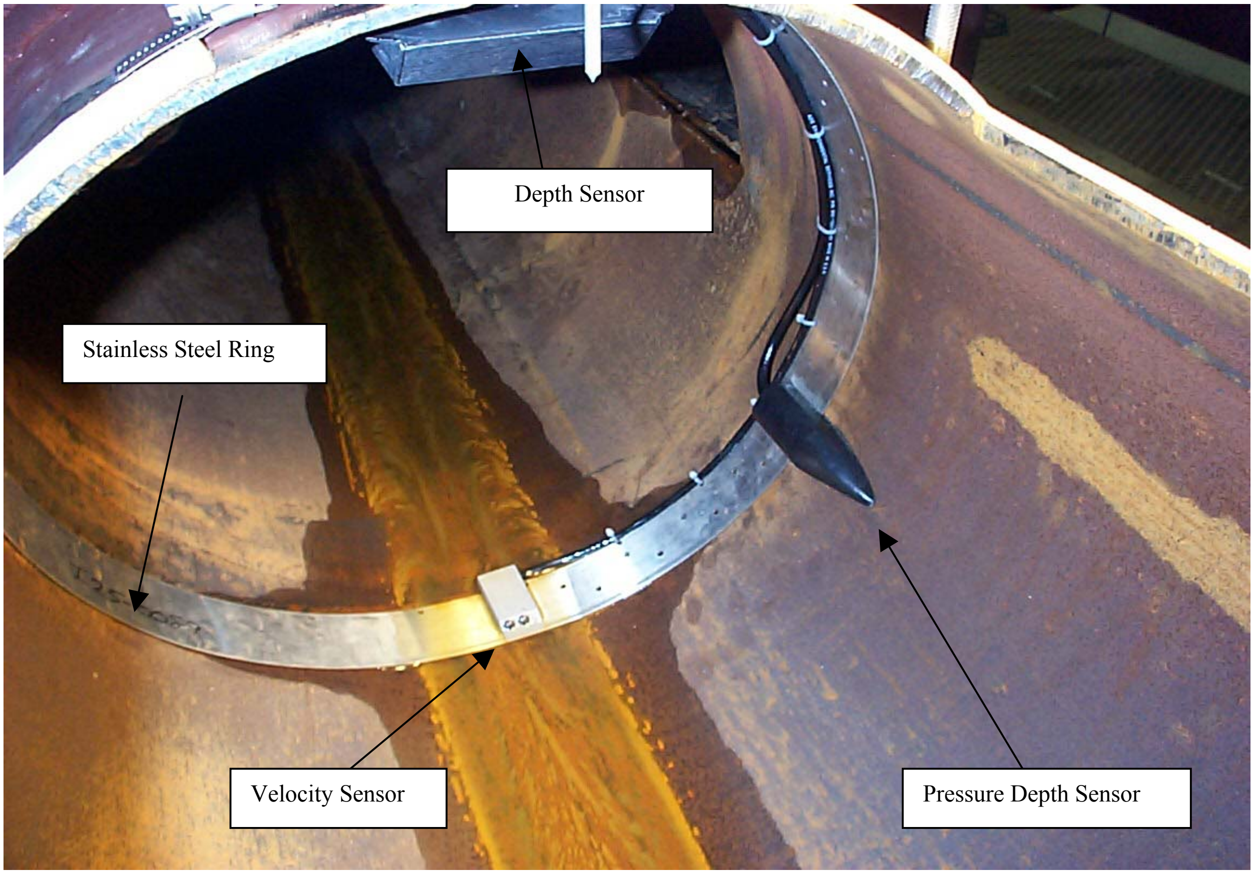


Figure 2-2. ADS flow monitoring sensors (laboratory 20-inch installation).

No special tools are required for installation. Most installations are accomplished with standard wrenches, screwdrivers, wire ties, and a drill and bits.

Once placed in service, continued calibrations are not required to obtain valid data, but periodic site visits are recommended to spot hydraulic changes. The ultrasonic sensor has zero drift, but it is recommended that the sites with silt be visited regularly to verify silt depth. Silt reduces the cross-sectional area of flow and creates inaccuracy in the continuity equation. Hydraulic changes can also affect the average-to-peak ratio, which should be confirmed periodically through velocity profiles.

The unit operates with little routine maintenance. The most common maintenance needed is cleaning the ultrasonic depth sensor should it become coated with grease during a surcharge event in a greasy sewer. In most sewers the ultrasonic sensors are not affected by surcharging, and they immediately begin reporting depth the moment surcharging subsides. The velocity sensor is not affected by grease, but can be impaired by heavy silt or debris covering the sensor. In such cases, the sensor can be rotated off the bottom of the sewer to avoid silt and debris. Ultrasonic depth sensor crystals that deteriorate with age can be diagnosed and taken out of service remotely. A visit to the site can be avoided by switching to an inactive sensor pair. There are 12 possible sensor pairs, and the meter will operate with only one pair in service.

2.2 Operating Process

2.2.1 Depth

Depth is measured by a quad-redundant ultrasonic sensor installed at the top of the pipe facing down toward the water surface. The meter measures the time of travel of an ultrasonic pulse from the sensor to the water and back to the sensor. The meter converts the time of travel to distance by calculating the speed of sound through air and adjusting for temperature, which is measured by two temperature sensors inside the ultrasonic sensor head.

Each of the four transducers can operate in either transmit or receive mode, allowing for 12 possible transmit–listen pairs, as illustrated in Figure 2-3. A crystal cannot transmit and listen for its own signal. The paired sensors essentially eliminate the dead zone inherent to a single ultrasonic crystal that transmits and then listens. The dead zone is usually less than one inch.

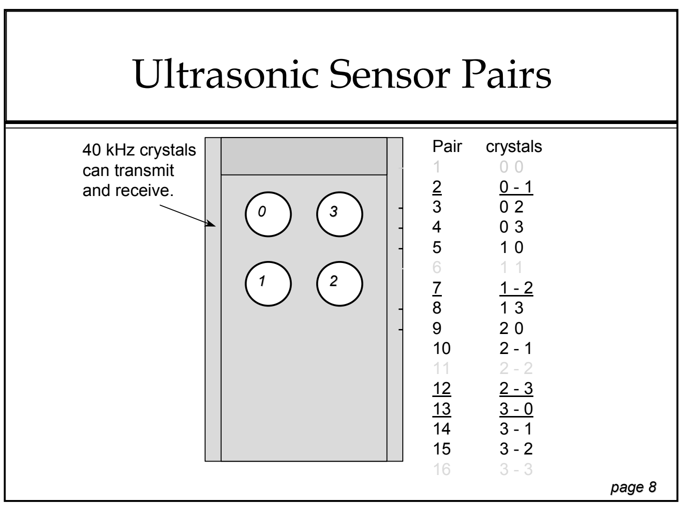


Figure 2-3. Ultrasonic sensor illustration.

Up to four of the 12 sensor pairs are in operation at any moment, and the operator can remotely diagnose the operating pairs for strength and quality of signal. The operator can remotely add and remove sensor pairs from operation. When activated for a reading, each pair in turn measures distance 32 successive times for a total of 128 readings. Errant readings from each sensor pair are discarded and four depth readings are recorded. The sensors are designed to have zero drift, where only extremely noisy or wavy sites affect performance.

2.2.2 Velocity

Doppler velocity measurements are made by transmitting an ultrasonic signal upstream and measuring particle velocity, similar to police radar. The sensor receives echoes from the particles and records the frequency shift (velocity) and strength of each echo. The ADS 3600 uses Peak Velocity Doppler, which is ADS's third generation velocity technology (V3). V3 technology takes advantage of the fact that the fastest particle in sewage remains constant from moment to moment, regardless of its size. V3 technology measures the velocity of the fastest particle (particle C in Figure 2-4) in sewage and converts it to average velocity. The ratio of average to peak velocity is around 0.9 in most sewers, and velocity profiles are used to determine the ratio in unusual flow.

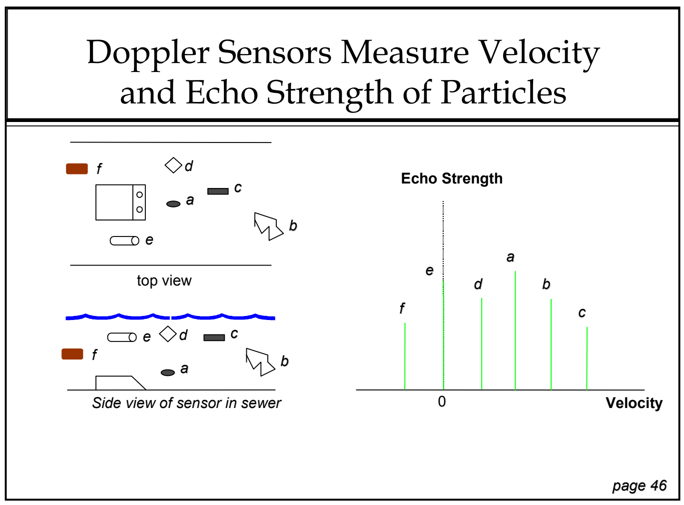


Figure 2-4. Doppler velocity sensor illustration.

Chapter 3
Laboratory Report

This chapter presents the procedures used in generating the laboratory performance data for the ADS 3600, along with the test data generated from the verification testing. This chapter addresses only the laboratory portion of the verification. Chapter 4, contained in Part II of the report, addresses the field testing portion of the verification testing.

3.1 Test Set-Up, Test Equipment, and Procedures

3.1.1 Test Description

The laboratory flow meter verification was performed in three different nominal pipe sizes: 10-inch, 20-inch, and 42-inch. Figures 3-1 through 3-3 show the piping prepared for the tests in the three respective sizes. Although the schematic drawings are not to scale, the dimensions and the relative locations of flow meters, risers, valves, and manholes are accurate. Each set-up was constructed using steel pipe.

An opening was cut in the top of the pipe near where the vendor test sensors were installed. The opening provided access to the sensor location so that a precision point gauge could be used to accurately measure flow depths and to allow test participants to view the installation from above and to observe flow conditions around the flow meter. The access opening had a watertight cover that was closed during pressurized (full-pipe) tests. Figure 3-4 shows the 20-inch pipe with the access hole open and closed. The other pipe sizes were similarly constructed.

A manhole was also constructed in each test set-up near the location of the test flow meter. The size and location of the manhole was sufficient to provide access for the installation of the test flow meter, and to provide a suitable location for monitoring surcharge flow conditions. The manhole consisted of a cylindrical steel tank with a watertight bottom. Each manhole was constructed to the dimensions indicated in the figures. The section of pipe passing through the manhole had its top removed (down to the spring-line). A sloping steel floor was installed in the bottom of the manhole, so that all water drained to the pipe spring-line. Figure 3-5 is a photograph of the outside and inside of the manhole in the 20-inch pipe set-up. The other pipe size set-ups were similarly constructed.

The test flow meter sensors were installed in the upstream pipe adjacent to the manhole. The precise location of the meter in the test pipe depended on ADS's specifications for the meter and its installation requirements. The crown of the pipe was removable near the installation location for access to the installed flow meter, but this access location was not used to install the flow meter. The access hole was covered and sealed for tests requiring surcharged flow conditions. All cables and wires connected to the sensor were directed into the test pipe through the manhole.

In the 10- and 20-inch test pipes, the length of straight pipe installed upstream of the manhole/flow meter test location was at least 40 times the pipe diameter. This length of straight pipe was necessary to provide near-uniform flow to the flow monitoring equipment during tests with no backwater effects. In the 42-inch test pipe, the length of straight pipe upstream of the manhole/flow meter test location was at least 22 times the pipe diameter. This shorter length was sufficient to provide near-uniform flow at the single pipe slope (0.2 percent).

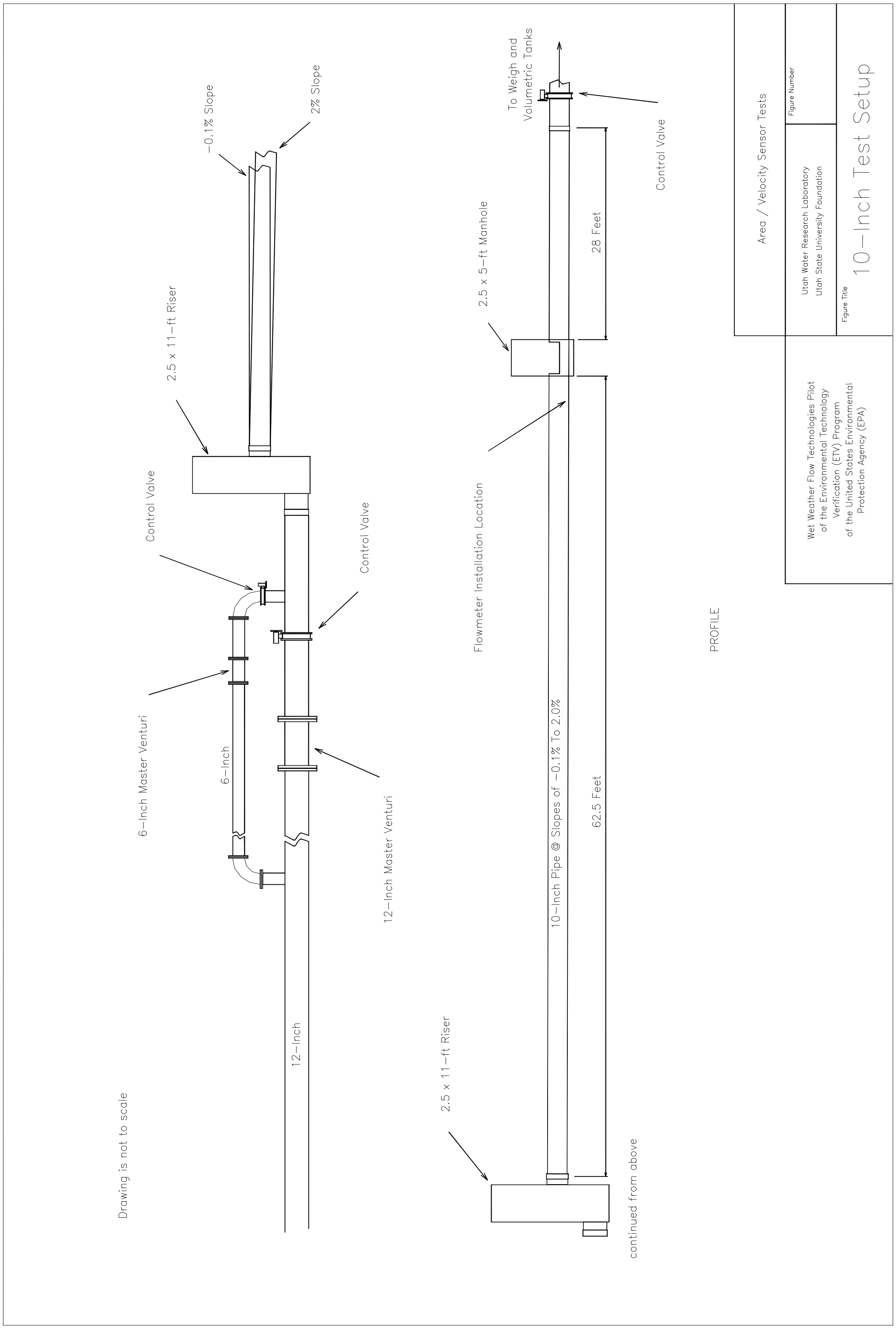


Figure 3-1. The 10-inch pipe test set-up.

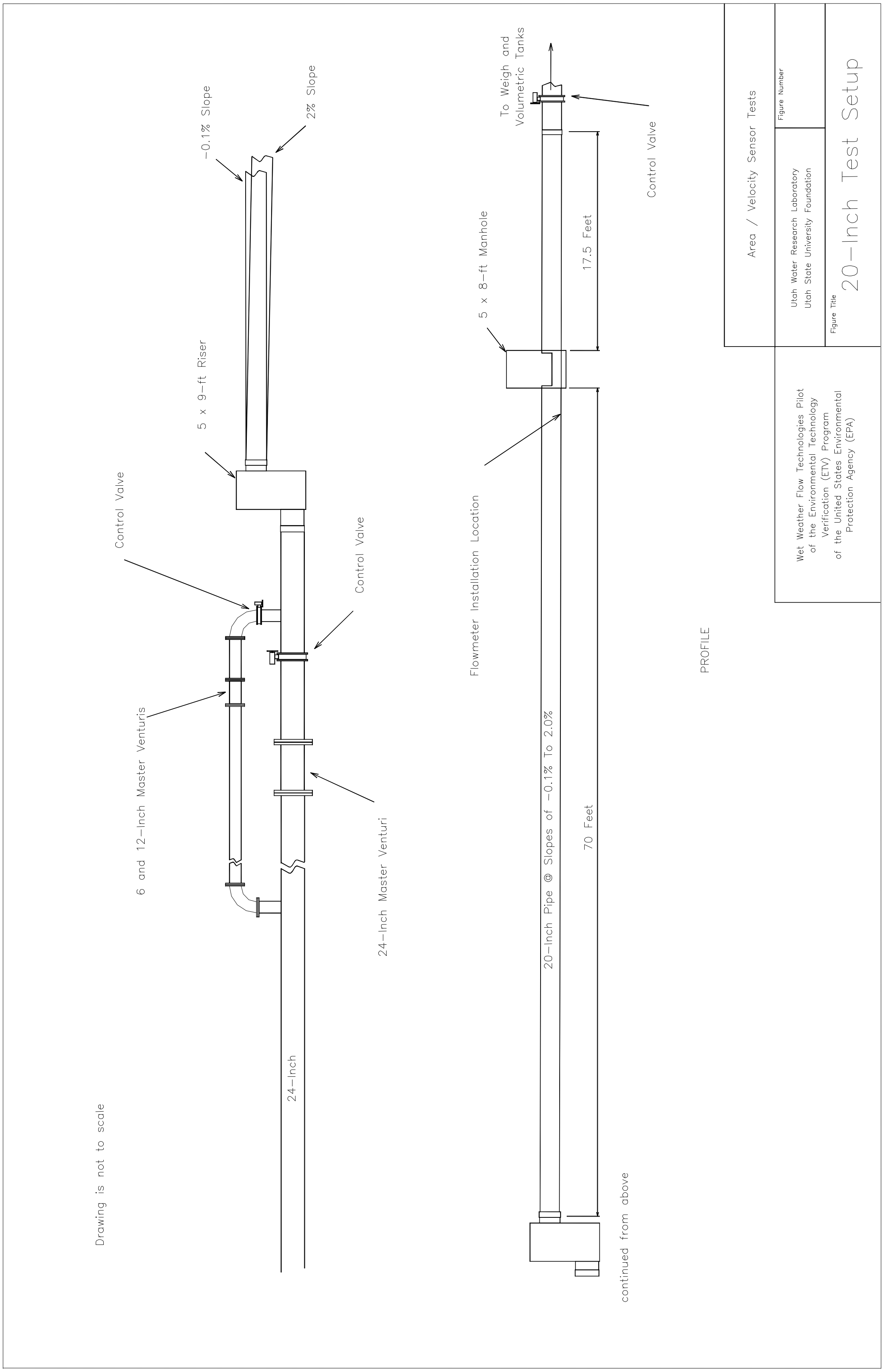


Figure 3-2. The 20-inch pipe test set-up.

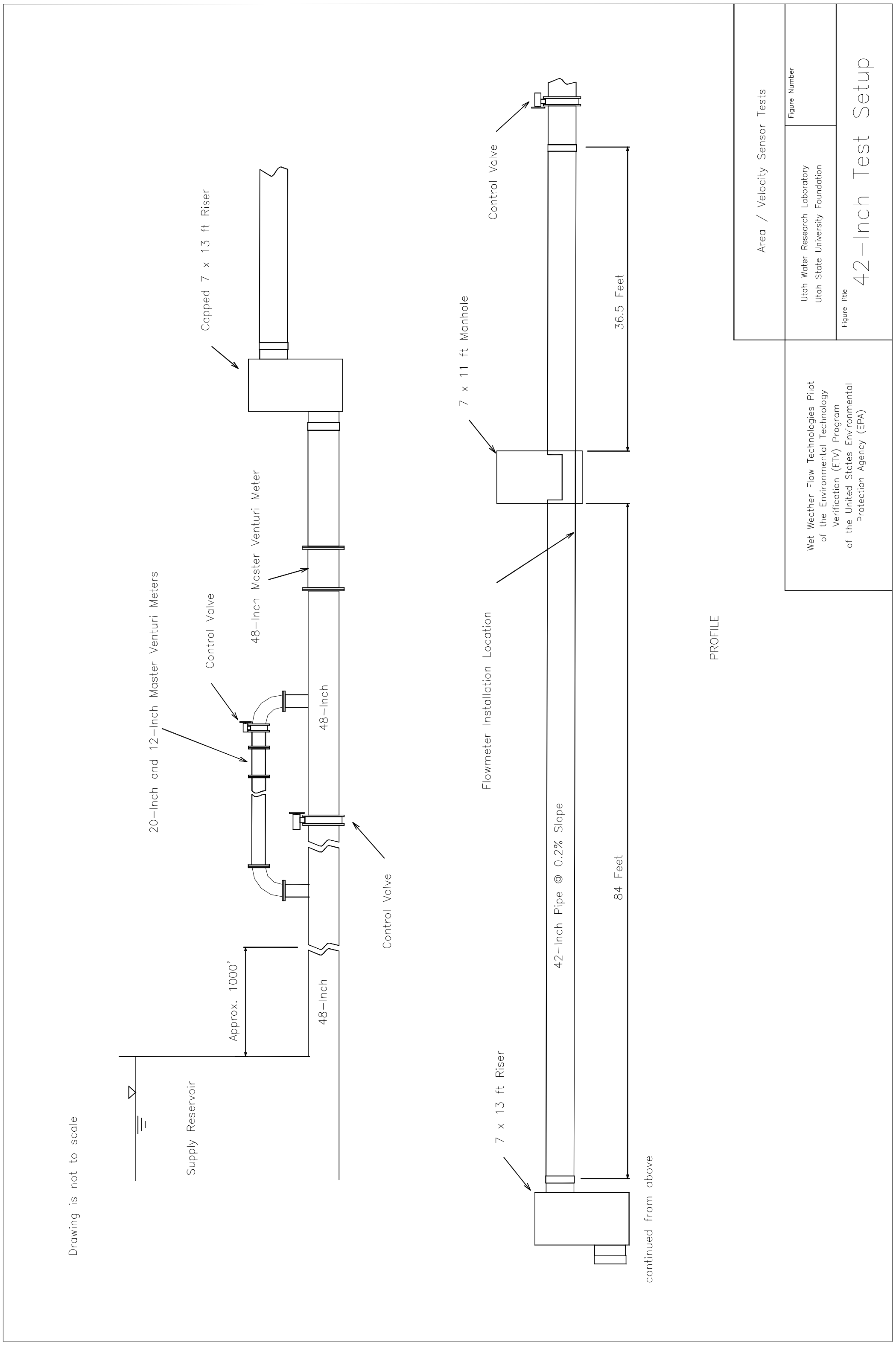


Figure 3-3. The 42-inch pipe test set-up.

(a) Closed pipe.

(b) Open pipe.

Figure 3-4. The access hole opening for testing.

(a) Outside view.

(b) Inside view.

Figure 3-5. View of manhole for 20-inch pipe.

A minimum of 10 diameters of straight pipe was installed downstream of each manhole to simulate the flow conditions exiting the manhole. Figure 3-6 shows the 20-inch set-up. The other pipe size set-ups were similarly constructed.

Figure 3-6. Simulated 20-inch sewer (riser-pipe-manhole shown from right to left).

Each test line was laid at a constant slope along the full length of the pipe. The test set-up allowed for the adjustment of pipe slope in the 10- and 20-inch sizes. The supports for these two test lines were capable of supporting pipe from a slightly negative slope condition to a maximum slope of 2.0 percent. The 42-inch pipe set-up was set at a constant slope (0.2 percent) for all tests. The vertical pipe supports prevented the pipe from sagging under the weight of the water. The spacing between vertical pipe supports for the three steel pipe set-ups was no greater than ten pipe diameters. No horizontal supports were needed.

A control valve was placed both upstream and downstream of the model piping. The valves were used to control the rate of flow through the simulated sewer. The upstream valve was used to control the rate of flow entering the riser supplying the test line. The downstream valve was used to impose a downstream control to the test line, providing backwater during surcharge test conditions.

A vertical riser was installed upstream of each test pipe to help dissipate the energy of the incoming flow, to provide a smooth pour-over into the model pipe for open channel tests, and to provide a surcharge stand-pipe during full-pipe tests. The dimensions of each riser are shown in Figures 3-1 through 3-3.

The test pipe was connected to the vertical supply riser with a flexible coupling that allowed for the required adjustment of pipe slope. The point of connection was high enough on the riser to allow the test pipe to be set at a maximum slope of 2.0 percent along its entire length. (The coupling can be seen on the right side of the photograph in Figure 3-6. In the photograph, flow is from right to left.) The elevation of the pipe at the coupling was always the same. The adjustable stands were raised or lowered to set the appropriate slopes for each test so that the entire test line rotated about the upstream coupling.

Water was supplied by a reservoir near the laboratory. This constant head source was capable of maintaining constant and steady water depths in the test pipe for the duration of each test run. A turbidity test was performed in the Environmental Quality Laboratory at UWRL and found to be at a level of 0.58 nephelometric turbidity units (NTU). One NTU is the limit for public drinking water supplies. The lower limit on the laboratory meter that made the measurement is approximately 0.1 NTUs. A turbidity measurement of 0.58 NTU indicates water with high clarity.

3.1.2 Reflectors

The Doppler shift principle requires particles in the water to serve as reflectors for sound waves. The clear water used in the UWRL contains considerably fewer particles than sewage. Since it was not practical to replicate the particulate concentrations of normal sewage, coffee creamer was added to the water in small quantities on some test runs. The vendor maintains that although the coffee creamer additive did provide a level of reflectivity, the particulate concentration in the test water did not replicate that of sewage, and thus could be a source of measurement error. It was not necessary to add creamer while the laboratory was making reference measurements.

For test configurations where particulate levels were especially low, ADS technicians made compensations during confirmations by changing adjustable parameters on the ADS 3600 velocity subsystem. This sensitivity adjustment was made using the Fieldscan standard field configuration software. It allowed the meter to register the faint echoes from the few particles that were in the fastest portion of the flow, and adequately compensated for the clarity issue. In typical sewer installations, this type of adjustment is not necessary.

3.1.3 Laboratory Test Instrumentation

The laboratory instruments used during the verification tests are described in this section. Calibration records for the instruments are shown in Appendix A.

3.1.3.1 Flow Measurement Tanks and Calibrated Flow Meters

Laboratory weigh tanks and master venturi meters were used to determine the reference flow rate for each test run. The measurement tanks are directly traceable to the National Institute of Standards and Technology (NIST) by weight. The master venturi flow meters are regularly calibrated and are NIST-traceable. Uncertainty for the tanks and flow meters is less than 0.25 percent.

3.1.3.2 Precision Point Gauge

A precision point gauge was used as the reference depth measurement in determining the depth of flow near the test flow meter focal point (Figure 3-7). The precision point gauge is readable to the nearest one-thousandth (0.001) of a foot. The point gauge was mounted as close as possible to the downstream edge of the access hole. Likewise, the ADS depth sensor was also mounted as close as possible to the downstream edge of the access hole. The reference depth measurement was compared to the indicated depth measurement from the meter.

3.1.3.3 Thermometer

A calibrated thermometer was used to measure the temperature of the water flowing through the test pipe. The temperature measurement was used for spreadsheet calculations requiring temperature. The thermometer was calibrated for accuracy before the verification tests.

Figure 3-7. Reference depth point gauge.

3.1.3.4 Timer

A calibrated stopwatch/timer was used to measure the collection time of the water entering the weigh tanks. The time measurement was used with the weight reading to calculate the actual flow rate for each test in which the master venturi meters were not used. The timer was calibrated before the verification tests.

3.1.3.5 Precision Calipers

Precision calipers were used to measure the inside diameter of the model piping and to verify the roundness of the pipe. An accurate measurement of each pipe diameter was necessary for correct area calculations.

3.1.4 Pretest Procedures

The VTP included a detailed set of test procedures that was followed during the verification tests. The procedures were consistent with the requirements established in the protocol. Laboratory personnel performed the following tasks before beginning the verification test on a specific pipe set-up:

- The geometry of the test pipe and location of the vendor instrument within the pipe was measured and documented.
- A digital photograph was taken of the installed flow meter sensors in each pipe size (Figures 2-2, 3-7, 3-8, and 3-9).
- The time required for flow meter installation and set-up by the vendor was recorded.

3.1.5 General Test Procedures

Flow, depth, and velocity data from the test flow meter was logged electronically as recorded by the vendor-supplied electronics. Average recorded values were entered into a computer spreadsheet.

Tables 3-1, 3-2, and 3-3 define each run that was tested in 10-, 20-, and 42-inch pipe, respectively.

The procedures described in this section were conducted for each set of test conditions established in Tables 3-1 through 3-3. The procedures were repeated each time the flow conditions were changed. The following procedural steps were taken for each run.

3.1.5.1 Set Flow Condition

Both the upstream and downstream control valves were used to set the flow. Uniform flow (free flow) tests had no downstream control. Conversely, the downstream control valve was throttled for submerged and backwater tests. Tables 3-1 through 3-3 list the target flow conditions for each run.

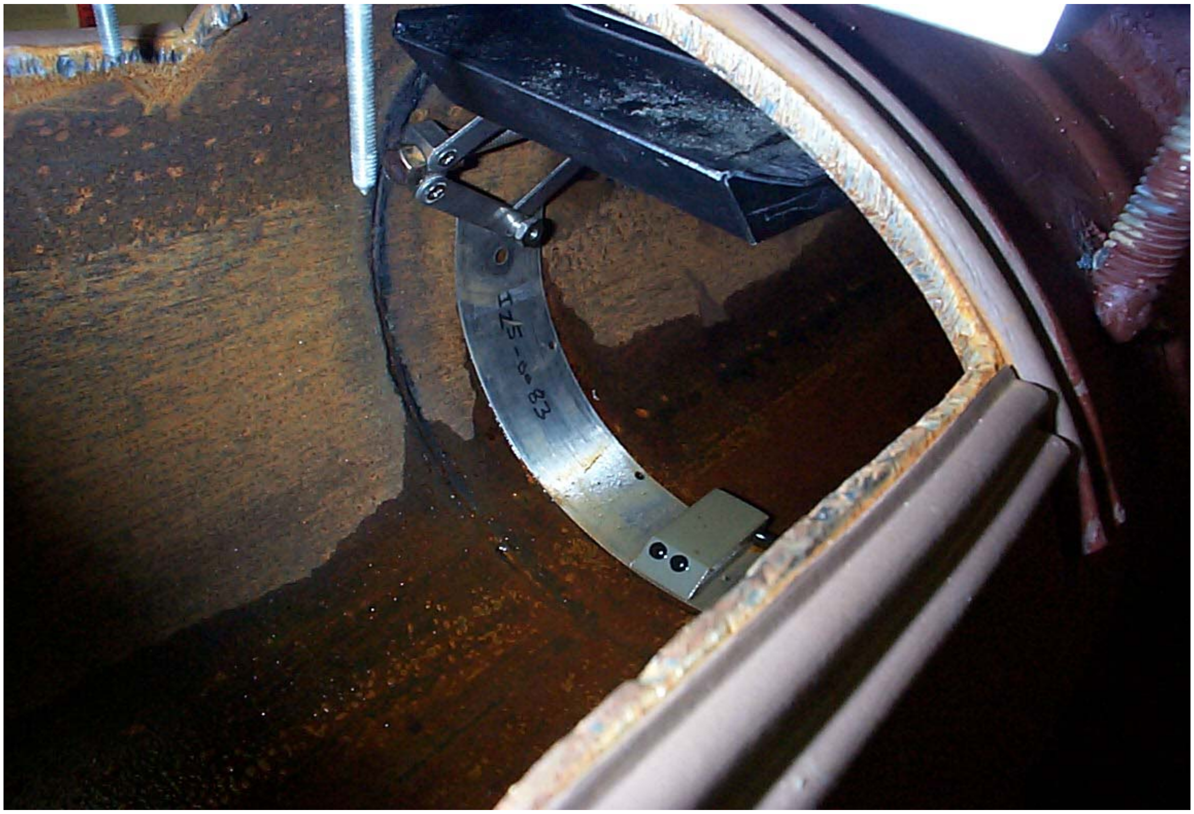


Figure 3-8. ADS flow monitoring sensors (laboratory 10-inch pipe installation).

3.1.5.2 Allow Flow To Stabilize

Test measurements were not made until the water had stabilized in the pipe. The flow was stabilized when the depth in the pipe did not change over time. The precision point gauge mounted on the centerline of the flow path acted as a gauge for setting and stabilizing the flow. The flow depth was set within .02 D (D = diameter of the pipe) of the flow depths specified in Tables 3-1 through 3-3.

3.1.5.3 Measure Water Temperature

The temperature of the water in the test pipe was measured using a calibrated mercury thermometer. This manual reading was recorded after the mercury in the thermometer had stabilized.

3.1.5.4 Measure Reference Flow

The reference flow rate was measured and recorded utilizing the laboratory instrumentation before and after each logging period. Laboratory personnel measured the actual flow rate using the laboratory master flow meters. The master venturi flow meters are used often and are regularly calibrated at the laboratory. Flows too small to be accurately measured by the master venturi meters were measured using the laboratory weigh tanks.

Figure 3-9. ADS flow monitoring sensors (laboratory 42-inch pipe installation).

3.1.5.5 Measure Reference Depth

The actual depth was measured and recorded before and after the logging period of each run. Laboratory personnel measured the actual flow depth at the centerline of the pipe. This measurement was made very near the focal point for the sensor depth measurement. The depth was determined by taking the difference between the water surface measurement and the reference pipe invert measurement made by the centerline point gauge.

If the water surface was mounded slightly at the measurement location, a measurement of the complete cross-sectional water surface profile was necessary to generate the correct flow area for mean velocity calculations. An evaluation of each water surface profile was performed to decide the necessity of conducting either a single centerline depth or a complete cross-sectional water surface profile. This check was made by comparing the depths at the centerline and near the wall of the pipe.

If the peak-to-peak difference in depth across the water surface profile was greater than 0.02 D inches, a complete cross-sectional water surface profile was necessary. A special adjustable point gauge was used to measure water surface depths at five equally spaced locations across the water surface. Since the water surface width changes with increased depth, the spacing and position for the five equally spaced point gauges also varied.

3.1.5.6 Log Meter Data

Average flow, depth, and velocity measurements were electronically logged and recorded from the ADS output device. ADS provided a laptop computer to retrieve the logged data. The logged data was manually entered into a desktop computer spreadsheet at the end of each day of testing.

Once the flow stabilized, and after recording the first reference depth and flow measurements, laboratory personnel logged data from the flow monitoring equipment. Data was recorded in accordance with the operational procedures provided by the vendor, except that average flow rate, depth, and velocity readings were logged and recorded at one-minute intervals over a five-minute period. Data was reported for each one-minute interval. ADS prepared the instrument so that each one-minute sample was independent and was not averaged with prior samples. The operational procedure and data-logging method devised and utilized by ADS is given in Appendix C.

3.1.5.7 Measure Reference Flow and Depth (Second Time)

After the ADS flow meter completed its logging cycle (during the five-minute period), the reference flow and reference depth measurements were repeated. This was done to ensure that the flow conditions had remained constant during the five-minute logging period.

3.1.5.8 Calculate Reference Velocity

Using the measured cross-sectional water surface profile, the flow area was calculated using a computer spreadsheet. The mean velocity for the test was calculated by dividing the flow area into the reference flow measurement. The mean velocity was based on the average reference depth and flow measurements for the run.

3.1.5.9 Record Observations

The flow conditions for each run were recorded. Appendix B contains the raw data and notes documented by laboratory personnel during the verification tests.

3.1.5.10 Review Reference Data

Once all pertinent reference data for a single run had been entered into the computer, the results were reviewed before the flow conditions were changed for the next run. If flow conditions changed during a logging period, the test run was repeated. A run was repeated if the difference between the flow measurements taken at the start and end of the logging period were greater than one percent of the lesser value. Before repeating any given run, the vendor technician and laboratory personnel came to agreement that flow conditions had changed.

After all measurements for the run had been made, the flow conditions were changed and a new run was started. Each step listed above was repeated for each run.

3.1.5.11 Download Meter Data

The data was retrieved from the meter at the end of each test day. The five flow rate, depth, and velocity readings for each run were manually entered into a computer spreadsheet. The average of all five one-minute samples was calculated and reported.

3.1.6 Test Conditions

3.1.6.1 Free Flow and Backwater Tests

Free flow conditions were established by setting the desired depth in the pipe with no downstream control. Partial backwater conditions were simulated by closing the downstream control valve in the pipe. Each backwater test (nonuniform flow condition) had a corresponding uncontrolled flow test (uniform or free flow condition). The flow velocities for the backwater tests were set to approximately one-half the flow velocities for the uncontrolled tests by using the supply master venturi device. No backwater tests were performed for slopes greater than 0.5 percent.

3.1.6.2 Full Pipe Tests (Manhole Surcharged)

For tests in which there was downstream control and the pipe was full and pressurized, the opening on the top of the pipe through which the sensor is accessed and point gauge readings taken was closed. The access opening was covered with a watertight lid (see Figure 3-7). During these tests, the depth of water (hydraulic grade line) was not measured. For runs where the pipe was full during surcharged conditions, this report indicates the pipe diameter as the flow depth.

The reference flow measurement was divided by the pipe area to determine mean velocity. Flow and velocity were compared, but no comparisons of surcharged pressures were made. The ADS output indicated that the depth of flow in the pipe was equal to the diameter of the pipe. A piezometric measurement of the submergence was made and reported as an indication of the magnitude of submergence only, and not as a reference pressure measurement.

3.1.6.3 Silt Simulation Tests

A simulated deposit of silt or sediment in the bottom of the pipe was conducted during the 42-inch pipe tests. A rigid flat bed was installed in the bottom of the 42-inch pipe at a depth of three inches. The simulated fixed sediment bed was constructed of wood, and extended five pipe diameters at a depth of three inches. A 5:1 smooth sloped transition was installed at the leading edge of the fixed bed to reduce turbulence.

ADS personnel adjusted installation of the flow measurement device so that it sat above the simulated silt bed. Runs were made as indicated in Table 3-3. Figure 3-10 shows the fixed bed in the bottom of the 42-inch pipe.

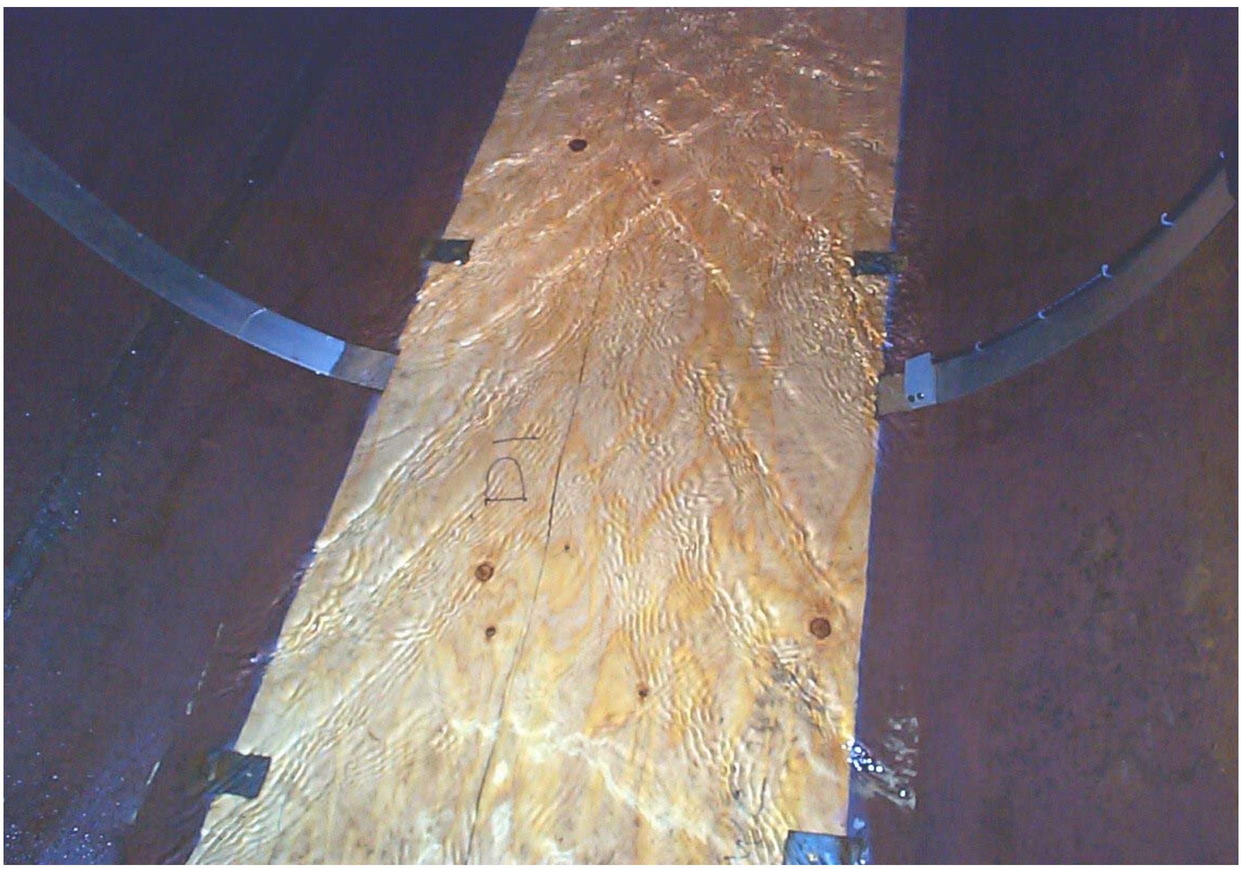


Figure 3-10. Silt simulation using a fixed bed (looking downstream).

3.1.6.4 Grease Build-up Tests

Tests were performed with thin layers of grease (Crisco) placed on all submerged components of the flow monitoring equipment. These tests evaluated the ability of the meter to continue functioning accurately when grease built up on the wetted components, and also allowed technicians to observe and record whether the grease remained on the components. Both a

0.5-mm and 2.0-mm layer of grease was tested under three different flow conditions (six runs). Runs were made as indicated in Table 3-3. Figure 3-11 shows the depth sensor with a thin layer of grease applied. The grease thickness in the photograph is 0.5 mm thick. The 2.0-mm tests had four times the thickness of grease, which was applied manually. Figure 3-11 shows the flow sensor after grease was applied.

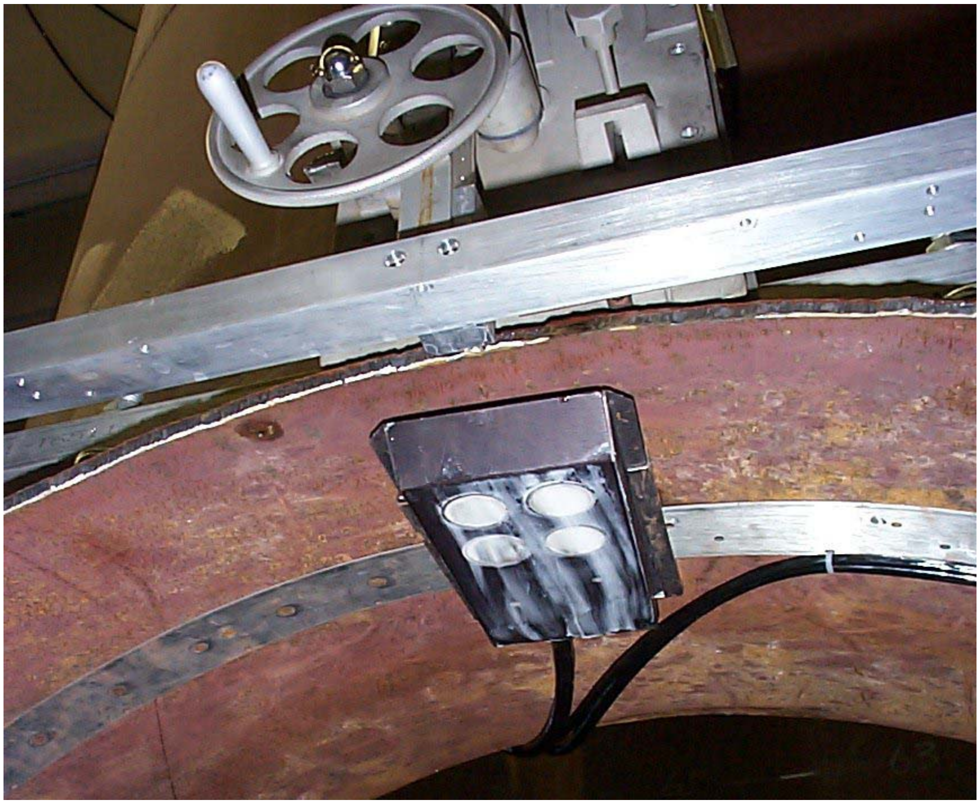


Figure 3-11. ADS depth sensor shown during the 0.5 mm grease test.

3.1.6.5 Reverse Flow Tests

A reversed pressure flow condition was also tested. This was accomplished by elevating the test pipe to a slightly negative slope, installing the flow meter in the test line backwards, submerging the manhole, and forcing water uphill. The sensor was installed on the downstream side of the manhole (uphill side) and runs were made as indicated in Tables 3-1 and 3-2. Reverse flow tests were performed on the 10- and 20-inch pipes, but not the 42-inch pipe.

Table 3-1. Test Conditions and Sequence: 10-inch Test Pipe

Run number	Pipe slope (percent)	Water depth	Uniform flow (downstream-uncontrolled)	Nonuniform flow (downstream-controlled)
1	0.1	0.1 D	Yes	
2	0.1	0.3 D	Yes	
3	0.1	0.5 D	Yes	
4	0.1	0.8 D	Yes	
5	0.1	0.1 D		Yes
6	0.1	0.3 D		Yes
7	0.1	0.5D		Yes
8	0.1	0.8 D		Yes
9[a]	0.1	~1.5 D		Yes
10[a]	0.1	~2.5 D		Yes
11	0.5	0.1 D	Yes	
12	0.5	0.3 D	Yes	
13	0.5	0.5D	Yes	
14	0.5	0.8 D	Yes	
15	0.5	0.1 D		Yes
16	0.5	0.3 D		Yes
17	0.5	0.5D		Yes
18	0.5	0.8 D		Yes
19[a]	0.5	~1.5 D		Yes
20[a]	0.5	~2.5 D		Yes
21	1.25	0.1 D	Yes	
22	1.25	0.3 D	Yes	
23	1.25	0.5D	Yes	
24	1.25	0.8 D	Yes	
25[a]	1.25	~1.5 D		Yes
26[a]	1.25	~2.5 D		Yes
27	2.0	0.1 D	Yes	
28	2.0	0.3 D	Yes	
29	2.0	0.5D	Yes	
30	2.0	0.8 D	Yes	
31[a]	2.0	~1.5 D		Yes
32[a]	2.0	~2.5 D		Yes
33[b]	-0.1	~1.5 D		Yes
34[b]	-0.1	~2.5 D		Yes

[a] Manhole is surcharged.

[b] Flow meter installed backwards, pipe slope set negative, surcharged conditions.

Table 3-2. Test Conditions and Sequence: 20-inch Test Pipe

Run number	Pipe slope (percent)	Water depth	Uniform flow (downstream-uncontrolled)	Nonuniform flow (downstream-controlled)
1	0.1	0.1 D	Yes	
2	0.1	0.3 D	Yes	
3	0.1	0.5 D	Yes	
4	0.1	0.8 D	Yes	
5	0.1	0.1 D		Yes
6	0.1	0.3 D		Yes
7	0.1	0.5D		Yes
8	0.1	0.8 D		Yes
9[a]	0.1	~1.5 D		Yes
10[a]	0.1	~2.5 D		Yes
11	0.5	0.1 D	Yes	
12	0.5	0.3 D	Yes	
13	0.5	0.5D	Yes	
14	0.5	0.8 D	Yes	
15	0.5	0.1 D		Yes
16	0.5	0.3 D		Yes
17	0.5	0.5D		Yes
18	0.5	0.8 D		Yes
19[a]	0.5	~1.5 D		Yes
20[a]	0.5	~2.5 D		Yes
21	1.25	0.1 D	Yes	
22	1.25	0.3 D	Yes	
23	1.25	0.5D	Yes	
24	1.25	0.8 D	Yes	
25[a]	1.25	~1.5 D		Yes
26[a]	1.25	~2.5 D		Yes
27	2.0	0.1 D	Yes	
28	2.0	0.3 D	Yes	
29	2.0	0.5D	Yes	
30	2.0	0.8 D	Yes	
31[a]	2.0	~1.5 D		Yes
32[a]	2.0	~2.5 D		Yes
33[b]	-0.1	~1.5 D		Yes
34[b]	-0.1	~2.5 D		Yes

[a] Manhole is surcharged.

[b] Flow meter installed backwards, pipe slope set negative, surcharged conditions.

Table 3-3. Test Conditions and Sequence: 42-inch Test Pipe

Run number	Pipe slope (percent)	Water depth	Uniform flow (downstream-uncontrolled)	Nonuniform flow (downstream-controlled)
1	0.2	0.1 D	Yes	
2	0.2	0.3 D	Yes	
3	0.2	0.5 D	Yes	
4	0.2	0.8 D	Yes	
5	0.2	0.1 D		Yes
6	0.2	0.3 D		Yes
7	0.2	0.5D		Yes
8	0.2	0.8 D		Yes
9[a]	0.2	~1.5 D		Yes
10[a]	0.2	~2.5 D		Yes
11[b]	0.2	0.1 D		Yes
12[b]	0.2	0.7 D		Yes
13[b]	0.2	~1.5 D		Yes
14[c]	0.2	0.1D	Yes	
15[c]	0.2	0.3D	Yes	
16[c]	0.2	0.8D	Yes	
17[d]	0.2	0.1D	Yes	
18[d]	0.2	0.3D	Yes	
19[d]	0.2	0.8D	Yes	

[a] Manhole is surcharged.
[b] Silt simulation test.
[c] Grease build-up test with 0.5-mm grease layer.
[d] Grease build-up test with 2.0-mm grease layer.

3.1.7 Data Management and Analysis

All raw data, notes, observations, and test descriptions were recorded using Microsoft Excel. Reference values for flow, depth, and velocity were calculated for each test run. These reference values provided the basis for determining the accuracy of the values from the flow meter output.

The reference flow value for each run was the arithmetic average of the flow at the beginning and at the end of logging period, as determined using the calibrated master venturi meter or weigh tank.

The reference depth value for each run was the arithmetic average of the depth at the beginning and at the end of the logging period, as determined using precision point gauges.

The reference velocity value for each run was the arithmetic average of the velocity values calculated from the depth and flow measurements taken at the beginning and end of the logging period.

Meter output of flow, depth, and velocity was recorded in the Microsoft Excel spreadsheet for each of the five one-minute samples. When no data was available, the one-minute sample field was left blank. An average of the five one-minute samples was made to indicate the five-minute average for the meter.

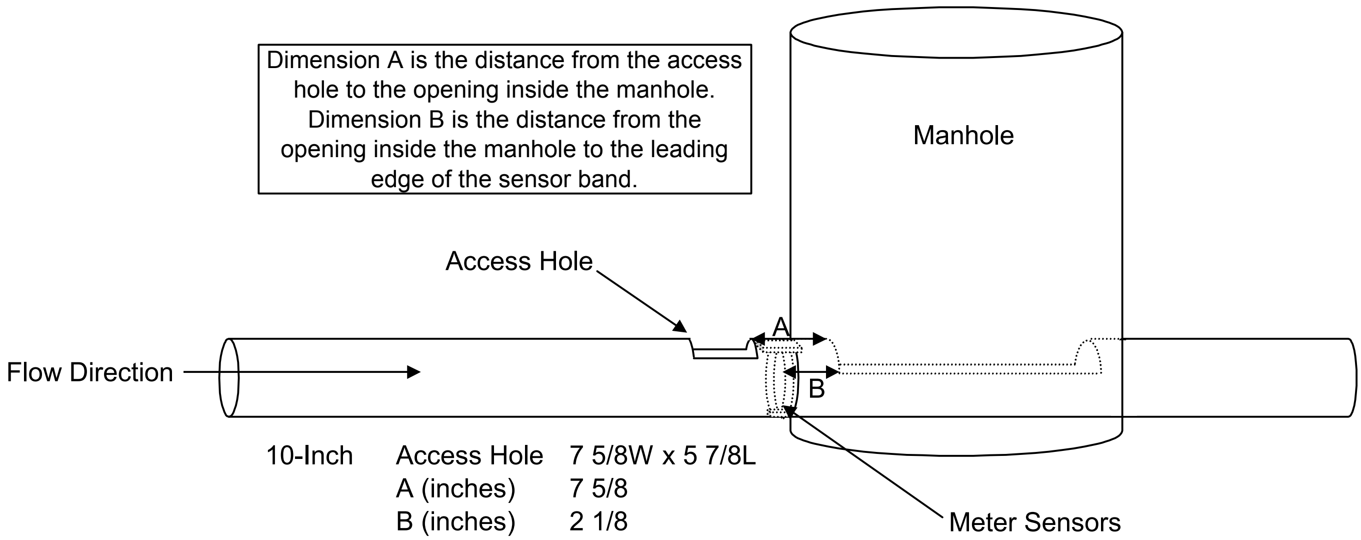
3.1.8 Quality Assurance

The Utah State University Research Foundation has an active quality control program at UWRL. Flow meter manufacturers and nuclear power plants regularly audit the laboratory for quality assurance. Under the laboratory quality assurance program, equipment is calibrated for accuracy on a scheduled cycle or occasionally as-needed. Instrumentation calibrations are normally subcontracted to outside organizations, although some are performed using the calibration facilities at the laboratory itself. Where applicable, calibrations indicate traceability to NIST. All laboratory instrumentation that was used during this testing program was calibrated prior to performing verification tests. Calibration sheets for all applicable instrumentation are provided in Appendix A. The laboratory master venturi flow meters were used during most of the test program as the reference flow measurement. These venturi meters have uncertainties less than 0.25 percent, which falls within the desired accuracy for the measurement.

3.2 Test Results

3.2.1 Preliminary Test Measurements

Prior to each test series the geometry of the test pipe and location of the vendor instrument within the pipe were measured and documented. Figure 3-12 shows the size and location of the access hole in each of the three test set-ups and establishes the location of the ADS stainless steel mounting ring for each test set-up. Tables 3-4 through 3-6 summarize the preliminary information recorded for each pipe size. The reference inside-pipe-diameter measurements were made using precision calipers at the location in the pipe where the flow meter sensors were installed. Measurements were made in four directions and averaged (every 45 degrees). Only three measurements were made in the 10-inch pipe because it was quite round. The time required to install and set up the flow meter was also recorded.



10-Inch	Access Hole	7 5/8W x 5 7/8L
	A (inches)	7 5/8
	B (inches)	2 1/8
20-Inch	Access Hole	13 13/16W x 11 7/8L
	A (inches)	13
	B (inches)	8 1/4
42-Inch	Access Hole	29 3/4W x 23 7/8L
	A (inches)	16 1/2
	B (inches)	11 1/2

(Note: All dimensions are in inches)

Figure 3-12. Sensor installation locations.

Table 3-4. Preliminary ADS 3600 10-inch Pipe Test Measurements

Meter (monitor) serial number:	02527
Ultrasonic serial number:	16405
Velocity sensor serial number:	11652
Pressure transducer serial number:	8710
Test size:	10-inch
Test dates:	5/2/01 to 5/11/01
Sensor location U.S. of manhole opening:	2.125 in.
Straight pipe U.S. of manhole:	63.9 ft
Straight pipe D.S. of manhole:	28.7 ft
Three pipe inside diameter measurement:	10.285 in., 10.29 in., 10.27 in.
Average pipe inside diameter:	10.282 in.
ADS pipe diameter measurement:	10.250 in.
Pipe invert point gauge reference:	1.731 ft
Time required to install the sensor:	15 min
Time required to set up the sensor:	90 min
Calibration performed by:	Steven Barfuss, Randy Geldmacher, Tyler Smith
Vendor technicians:	Keith Waites, Christy Kennamer

Table 3-5. Preliminary ADS 3600 20-inch Pipe Test Measurements

Meter (monitor) serial number:	02527
Ultrasonic serial number:	16405
Velocity sensor serial number:	11652
Pressure transducer serial number:	8710
Test size:	20-inch
Test dates:	5/30/01 to 6/4/01
Sensor location U.S. of manhole opening:	8.25 in.
Straight pipe U.S. of manhole:	74.0 ft
Straight pipe D.S. of manhole:	17.6 ft
Four pipe inside diameter measurement:	19.435 in., 19.555 in., 19.615 in., 19.553 in.
Average pipe inside diameter:	19.535 in.
ADS pipe diameter measurement:	19.500 in.
Pipe invert point gauge reference:	0.907 ft
Time required to install the sensor:	30 min
Time required to set up the sensor:	120 min
Calibration performed by:	Steven Barfuss, Randy Geldmacher, Tyler Smith
Vendor technicians:	Jeffrey White, Heather Hackett

Table 3-6. Preliminary Model 3600 42-inch Pipe Test Measurements

Meter (Monitor) Serial Number:	02527
Ultrasonic Serial Number:	16405
Velocity Sensor Serial Number:	11652
Pressure Transducer Serial Number:	8710
Test Size:	42-nch
Test Dates:	5/30/01 to 6/4/01
Sensor Location U.S. of manhole opening:	11.5 in.
Straight Pipe U.S. of manhole:	84.0 ft
Straight Pipe D.S. of manhole:	36.6 ft
Four Pipe Inside Diameter Measurement:	3.424 ft, 3.455 ft, 3.437 ft, 3.448 ft
Average Pipe Inside Diameter:	3.441 ft
Average Pipe Inside Diameter:	41.292 in.
ADS Pipe Diameter Measurement:	41.250 in.
Pipe Invert Point Gauge Reference:	-0.100 ft
Time required to install the sensor:	60 min
Time required to set up the sensor:	150 min
Calibration Performed by:	Steven L. Barfuss, Randy Geldmacher, Tyler Smith
Vendor Technicians:	Erica Blanken, Gillian Woodward

3.2.2 Test Data

The data obtained during testing was compiled in both graphical and statistical formats. The graphs are presented in the following sections, while the statistical tables are included in Appendix D. The time listed for each run in the statistical tables represents the start time for the five-minute logging period. This recorded time was critical to the success of the tests since the logged data was retrieved some time after the run was finished. It was necessary to find the recorded start time in the logged data to retrieve the corresponding set of five flow, depth, and velocity readings. For this reason, the times for the UWRL computer and the laptop computer used to log the data from the ADS flow meter were synchronized each day.

For each run, the data include the pipe slope, desired flow condition, and the date and time when the five-minute logging period occurred. Up to five depth measurements were made for each logging period. It was usually not required to make all five depth measurements since the transverse water surface profiles were normally quite flat. During submerged tests, the depth readings in the tables in Appendix D show "FP," indicating that the pipe was running full.

Select runs were either not practical or not possible, and are indicated by "NA" in the data tables in Appendix D. In some cases, the meter did not record data during a particular one-minute interval or a reference depth reading was not made, and hyphens (-) were placed in the table when no data was collected. ADS was allowed to re-test certain runs due to changes in the test protocol subsequent to the original tests. An "R" following the run number indicates these runs in the data tables.

3.2.2.1 Statistical Data Evaluation

Deviation is summarized by the various test configurations in Table 3-7. Deviation is calculated as the mean of the percentage deviation for each given category. Depth, velocity, and flow data for each test run is outlined in Appendix D.

The tables also contain the 95-percent confidence interval for the deviation data. The equation used to establish the confidence bounds is:

$$\text{Confidence} = \bar{x} \pm \left(t \times \left[\frac{s}{\sqrt{n}} \right] \right)$$

Where:

$\bar{x} =$ sample mean
$s =$ standard deviation
$n =$ sample size
$t =$ Student's t-distribution with $(n-1)$ degrees of freedom

Therefore, the width of the interval is a function of not only the variation in instrument deviation, but also the number of test runs in each reported category. In general, the categories with the greatest number of runs will show the narrowest confidence intervals.

Table 3-7. Deviation by Test Configuration: Normal Operating Conditions

Pipe size (inches)	Deviation (percent)	95-percent confidence interval
10	2.8	0.2 – 5.4
20	7.2	2.4 – 12.0
42	1.6	-1.8 – 5.0
Pipe slope (percent)		
0.1	4.9	-1.4 – 11.2
0.2	1.6	-1.8 – 5.0
0.5	5.6	1.6 – 9.6
1.25	4.2	-1.6 – 9.9
2.0	6.1	-3.8 – 16.1
Percent full (d/D)		
10	3.6	-9.4 – 16.6
30	11.1	6.5 – 15.7
50	3.4	0.2 – 6.7
80	1.3	-3.1 – 5.6
150	0.9	0.9 – 2.8
250	4.8	-5.0 – 14.6
Condition		
Free flow	2.6	-1.4 – 6.7
Backwater	5.8	2.9 – 8.7
All normal conditions	4.5	2.1 – 6.9

The ADS 3600 was also tested under "abnormal conditions," defined previously as tests where grease was applied to the depth sensor and reverse flow conditions existed. During the tests where 0.5 mm of grease was applied to the ultrasonic depth sensors, the mean deviation was 1.9 percent. When 2.0 mm of grease was applied to the ultrasonic depth sensors, the meter was unable to read depth, resulting in zero flow. The mean deviation for reverse flow tests was –72.7 percent. The grease was not removed significantly by the flow during the grease tests.

3.2.2.2 Graphical Evaluation of All Flow Data

The overall accuracy of the ADS flow meter under normal operating conditions is shown in Figure 3-13, the plot of measured flow rates versus the laboratory reference. This plot excludes tests where grease was applied to the sensors and tests with reverse flow.

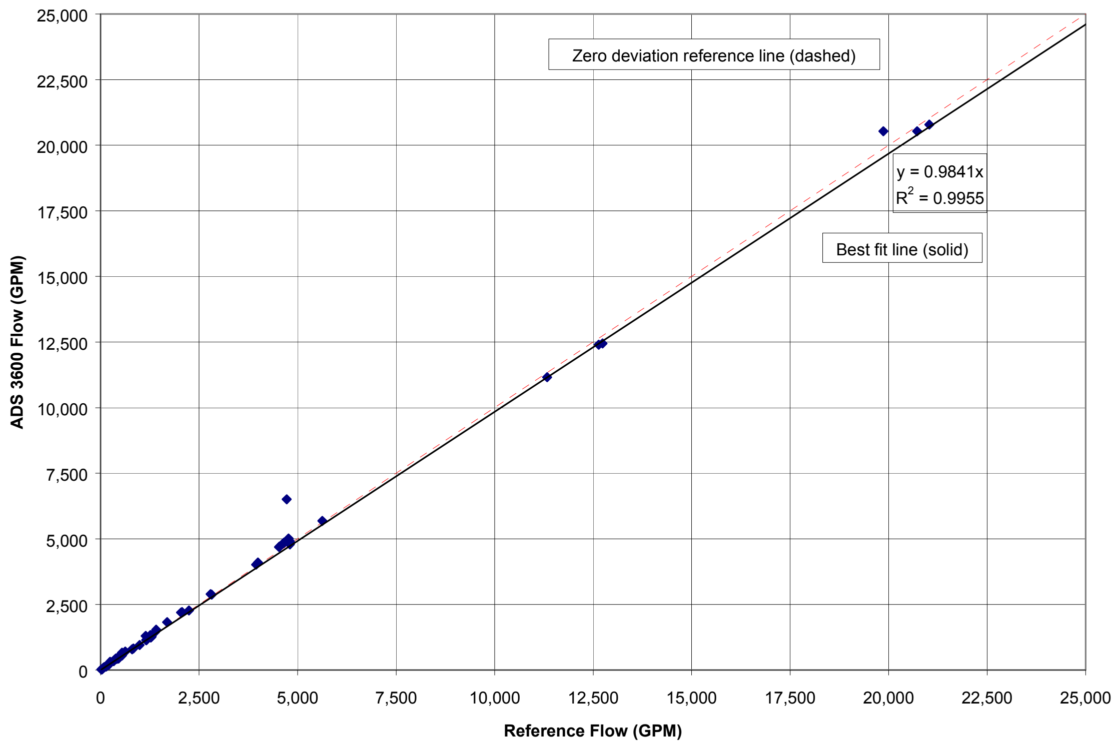


Figure 3-13. Metered flow rate versus reference flow rate.

Figure 3-13 was generated using formulas available in Microsoft Excel for characterizing a linear trend line. The line is fitted through the origin (y-intercept of zero). The slope of the regression line is computed as:

$$\text{slope} = \frac{\sum xy}{\sum x^2}$$

Where:

x = reference flow rates
y = ADS flow rates

The correlation coefficient, r^2, is defined as:

$$r^2 = 1 - \frac{\text{SSE}}{\text{SST}}$$

Where:

SSE is the sum of squares for the error component
SST is the sum of squares total

With the slope and correlation coefficient, bias and precision can be calculated. Bias and precision are expressed as functions of the slope and correlation coefficient, respectively, using the following equations:

$$\text{Bias} = \left(1 - \frac{\text{slope of zero deviation reference line}}{\text{slope of best fit line}}\right) \times 100\%$$

$$\text{Precision} = \left(1 - \frac{r^2 \text{ of zero deviation reference line}}{r^2 \text{ of best fit line}}\right) \times 100\%$$

Values of 1.0 for both slope and correlation coefficient would yield results of zero percent for both bias and precision, and would indicate a one-to-one relationship between the metered flow and the reference flow, with changes in the reference flow accounting for all of the variation in the metered flow.

Evaluation of the ADS 3600 data for the three pipe sizes (10-inch, 20-inch, and 42-inch) under normal operating conditions yields a bias of 1.6 percent and precision of 0.45 percent.

3.2.2.3 Graphical Evaluation of Flow Data by Test Condition

The flow, depth, and velocity readings, in addition to the average of the readings, are compared to the average reference flow, depth, and velocity for each run. The average reference flow, depth, and velocity are equal to the mathematical average of the initial and final reference measurements made for each run.

The graphical evaluation of the flow data by test condition is provided in Tables 3-15 through 3-32. The free flow and backwater data have been differentiated in each figure. The scatter-graph figures for slopes of 0.1 percent and 0.5 percent have both free flow and backwater data shown on the same figure. Scatter-graph figures for pipe slopes of 1.25 percent and 2.0 percent do not have backwater data shown because no backwater data was collected for these slopes. It should be noted that the free flow curves are not always smooth. Laboratory personnel attempted to eliminate all backwater effects during free flow tests, but in some cases were not able to completely eliminate the effect of the valve at the downstream end of the test pipe. As an example, Figure 3-16 shows the free flow curve dropping off on the upper end. This shows that the velocity was lower than the desired free flow condition, indicating some backwater effect. Even though this occurred periodically, it did not affect the test results, since the verification is a direct comparison between the reference measurements and the meter data regardless of the flow condition.

Two sets of plots are presented for each pipe size illustrating the deviation from reference flow. One series of plots (Figures 3-19, 3-25, and 3-31) show deviation as percent of reference across the full range of reference flows. Another series of plots (Figures 3-20, 3-26, and 3-32) show flow meter quantities compared to reference quantities. The reference line is the point of equality between the ADS flow meter and the reference measurements, where the deviations between the two would be zero. The slope and correlation coefficient of the best-fit line are measures of bias and precision, respectively, where 1.0 is the ideal value.

For the tests performed in the 10-inch pipe, Figures 3-15 through 3-18 are scatter-graph plots of the free flow and backwater tests, Figure 3-19 shows the deviation from the reference flow, and Figure 3-20 is a plot of reference flow versus meter flow.

For the tests performed in the 20-inch pipe, Figures 3-21 through 3-24 are scatter-graph plots of the free flow and backwater tests, Figure 3-25 shows the deviation from the reference flow, and Figure 3-26 is a plot of reference flow versus meter flow for all tests.

For the tests performed in the 42-inch pipe, Figures 3-27 through 3-30 are scatter-graph plots of the free flow and backwater tests, Figure 3-31 shows the deviation from the reference flow for all tests, and Figure 3-32 is a plot of reference flow versus meter flow.

3.2.2.4 Data Analysis Discussion

The protocol outlines the procedure for characterizing flow meter accuracy by calculating deviation using the following formula:

$$\text{percent deviation (\%D)} = (X_M - X_R) / X_R \times 100\%$$

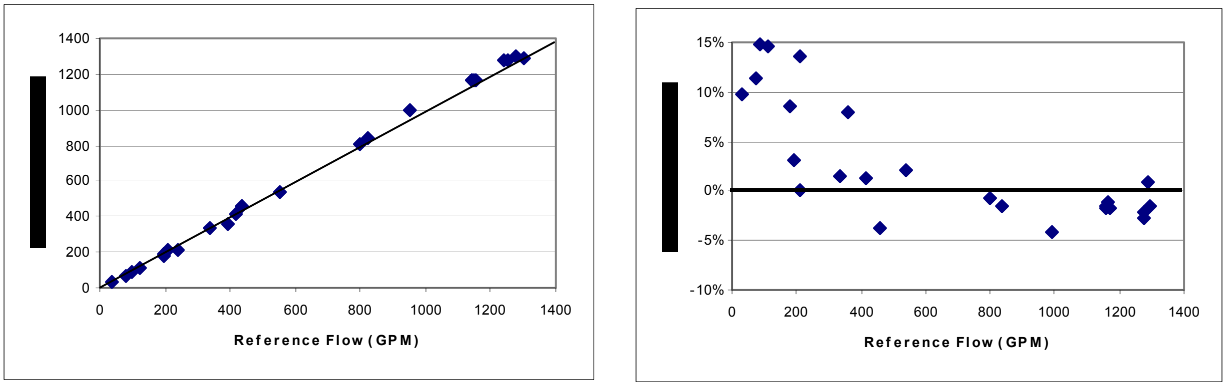
Where:

X_M = mean value recorded by test flow meter
X_R = mean reference value

Calculating deviation as a percent of the reference value can exaggerate the apparent deviation at low flows. During low flow conditions, a low absolute $|X_M - X_R|$ deviation results in a high percent (%D) deviation, creating a disproportionate percent deviation bias at low flow conditions.

For example, during the ADS 3600 tests with the 10-inch pipe, test run number 16 recorded a test flow meter reading of 99.91 gallons per minute (gpm) and a reference reading of 87.01 gpm. This results in an absolute deviation of 12.90 gpm but a percent deviation of 14.83 percent. By contrast, test run number 26, which had the highest reference reading for the 10-inch pipe tests at 1,293.89 gpm, had a corresponding test flow meter reading of 1,274.39 gpm, which computes to a larger absolute deviation (19.50 gpm) when compared to test run 16 but a much lower percent deviation (-1.51 percent).

This phenomenon can also be represented graphically. Evaluating the ADS 3600 10-inch pipe test runs with an arbitrary “low flow” range of 0–600 gpm, the same data can be expressed on two separate plots: absolute deviation and percent deviation. When this is done, the absolute deviation data shows a strong correlation in absolute terms despite the relatively high percent deviation, as shown in Figure 3-14.



(a) Absolute deviation **(b) Percent deviation**

Figure 3-14. ADS 3600 data summary, 10-inch pipe, 0–600 gpm reference flow.

The percent deviation data is presented in the ETV verification report because it is a common statistical method of computing the difference between a measured value and a reference value. This statistical anomaly is presented to inform the end-users of flow monitoring equipment that using percent deviation data when evaluating the performance of flow monitoring equipment at low flows may result in misleading information. During low flow conditions, a flow meter can report flow very close to a reference or actual flow but can be off by a disproportionately high percent deviation, especially when compared against high flow condition data. This phenomenon is reflective of a statistical limitation rather than a flow meter limitation.

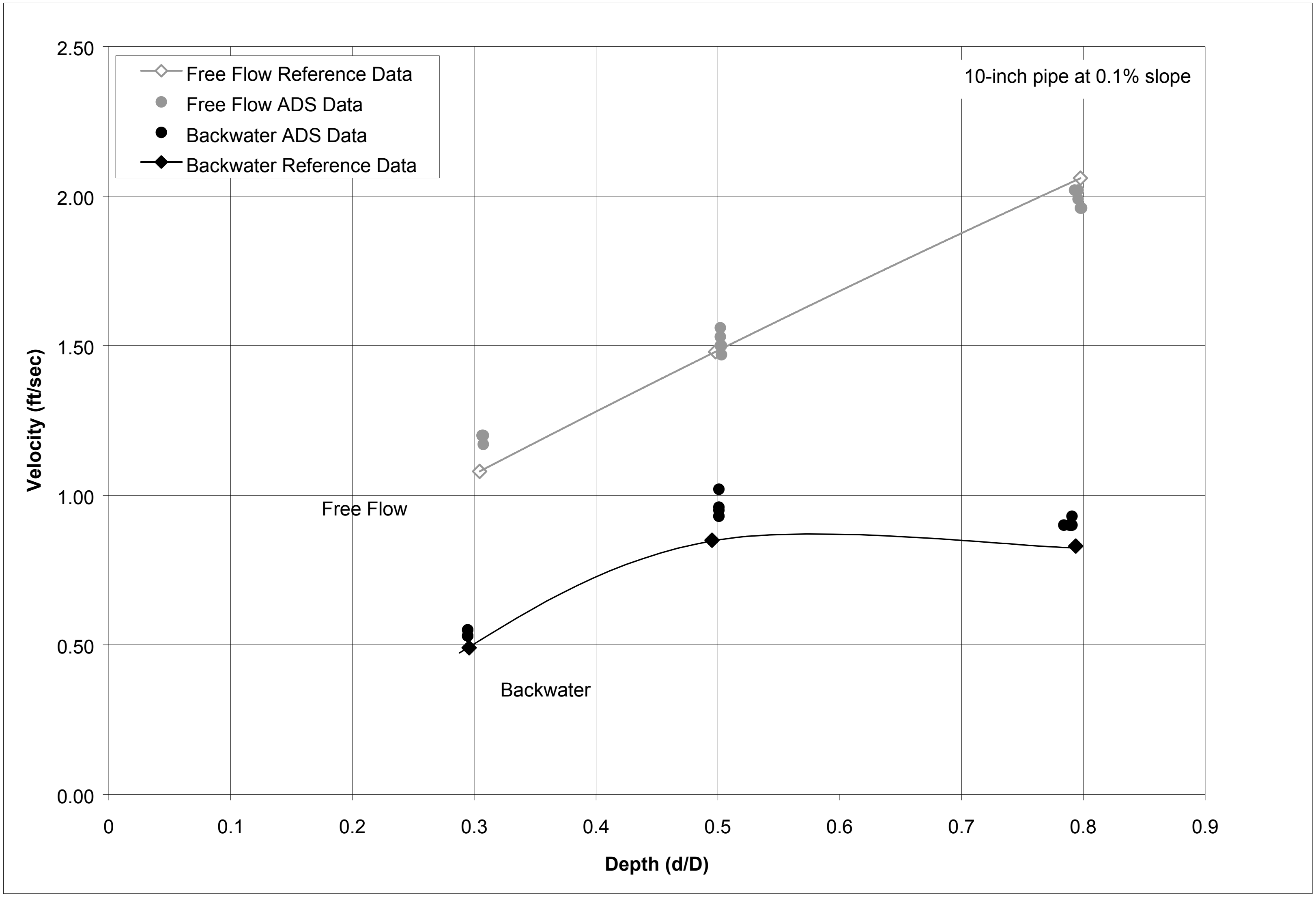


Figure 3-15. Scatter-graph for 10-inch pipe test at 0.1 percent slope.

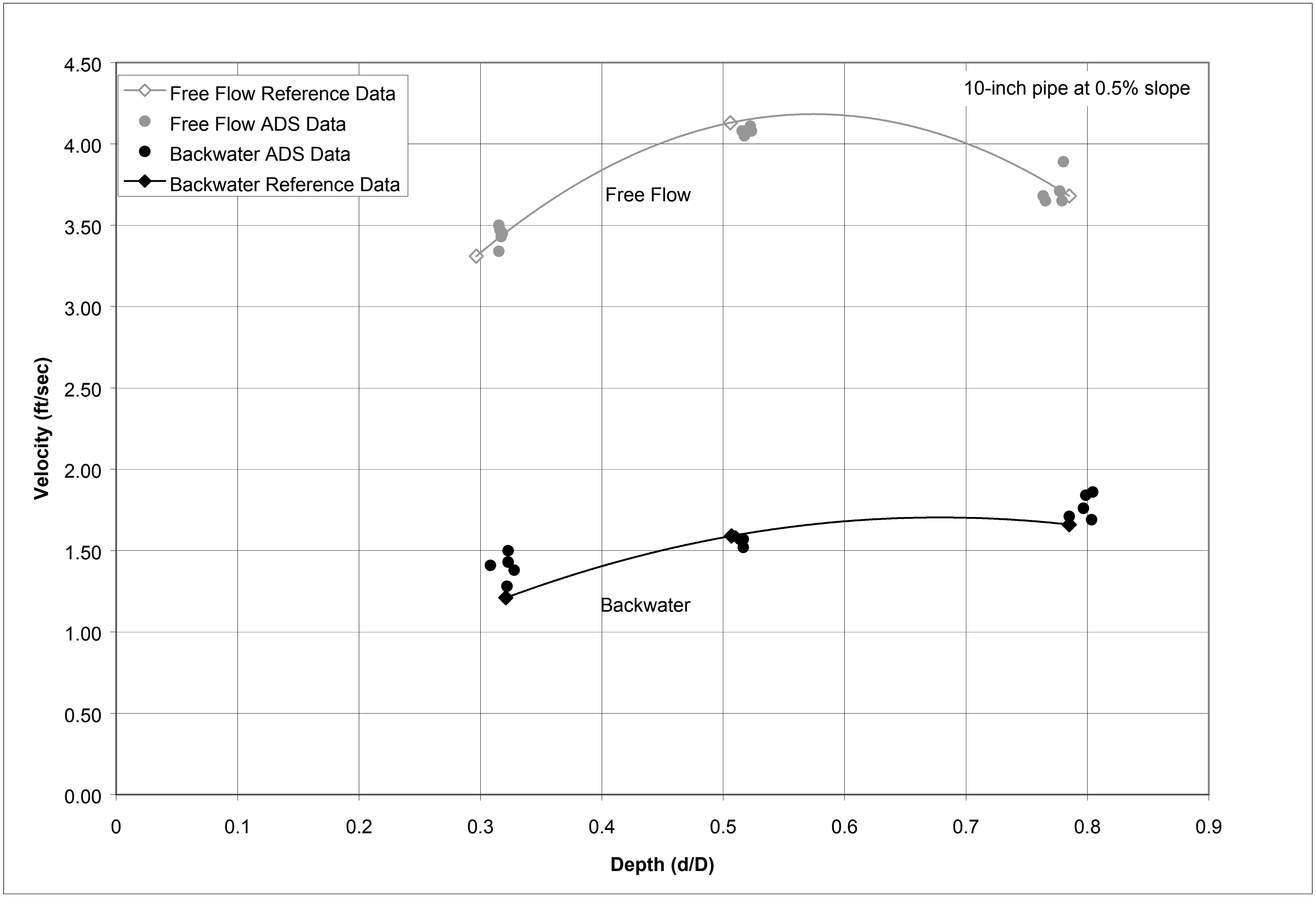


Figure 3-16. Scatter-graph for 10-inch pipe test at 0.5 percent slope.

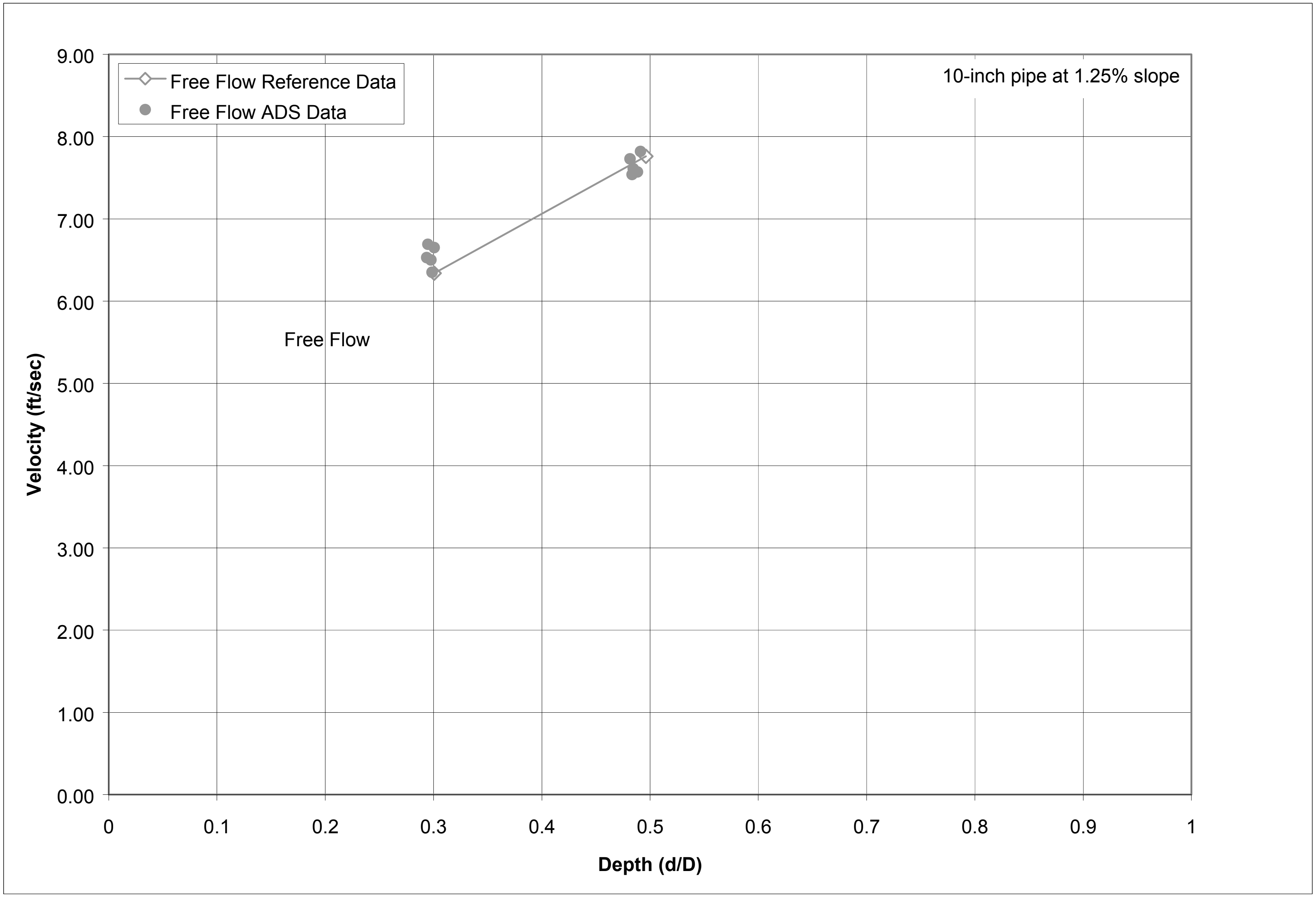


Figure 3-17. Scatter-graph for 10-inch pipe test at 1.25 percent slope.

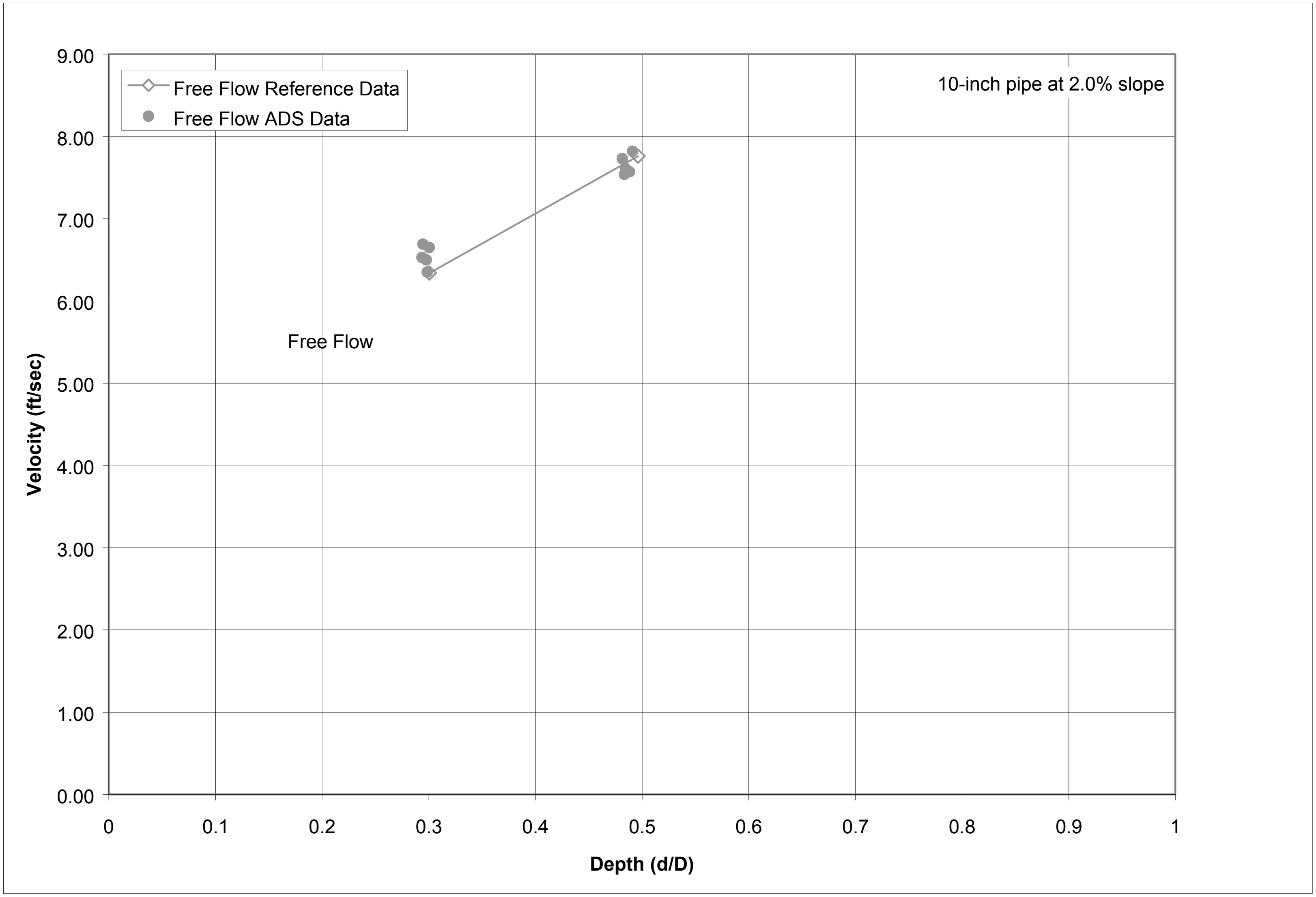


Figure 3-18. Scatter-graph for 10-inch pipe test at 2.0 percent slope.

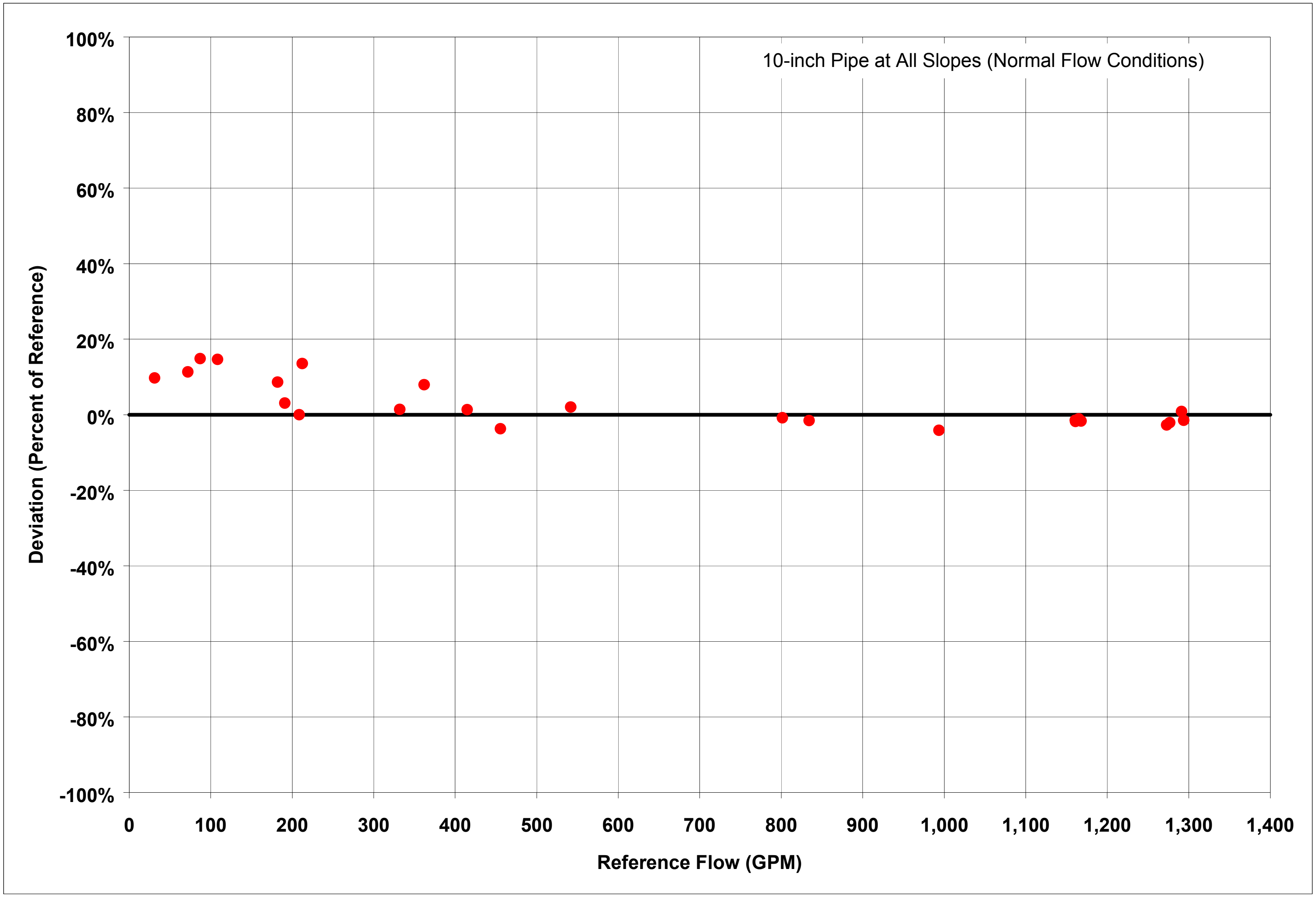


Figure 3-19. Deviation of meter flow to reference flow for 10-inch pipe.

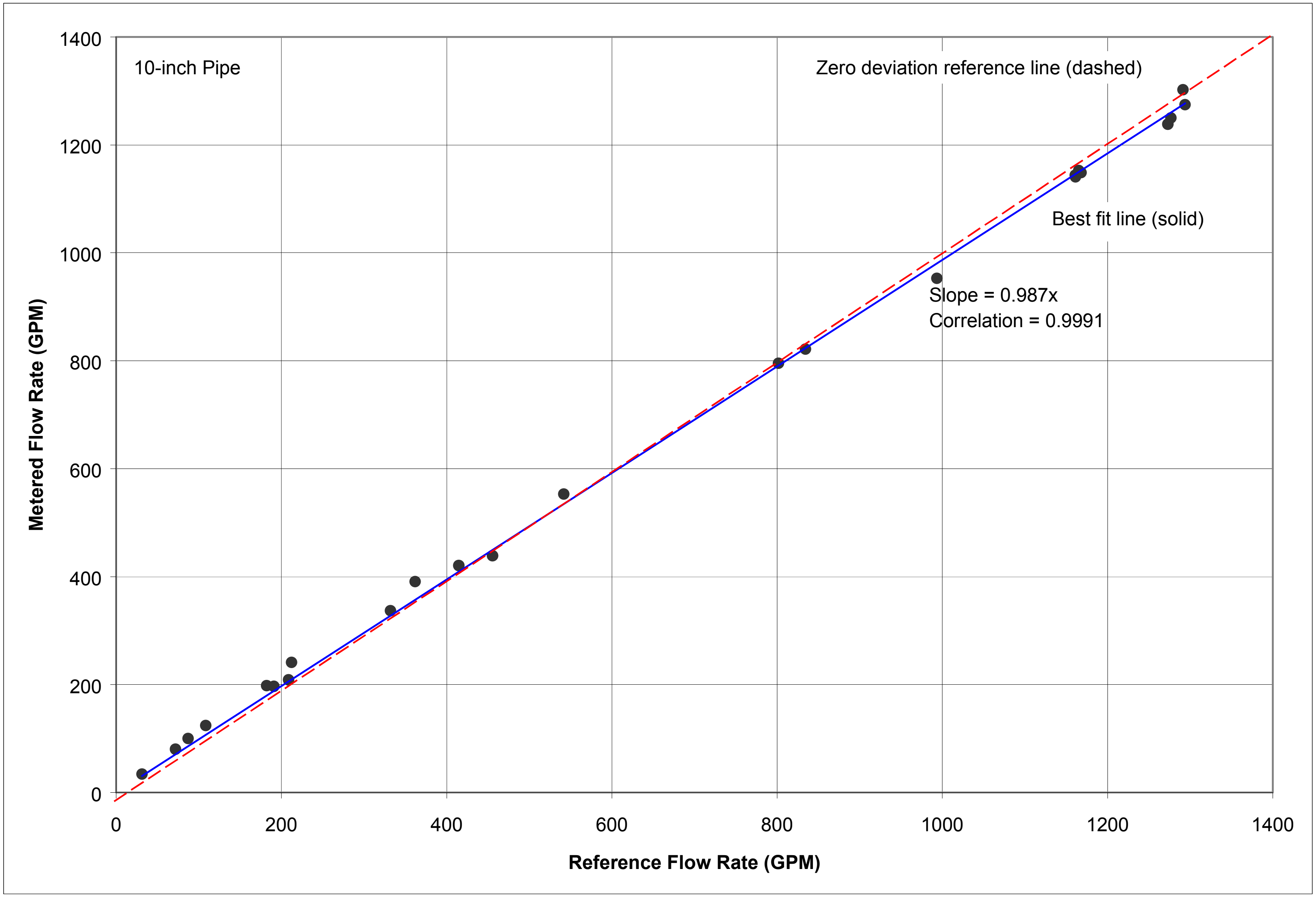


Figure 3-20. Plot of reference flow versus meter flow in 10-inch pipe.

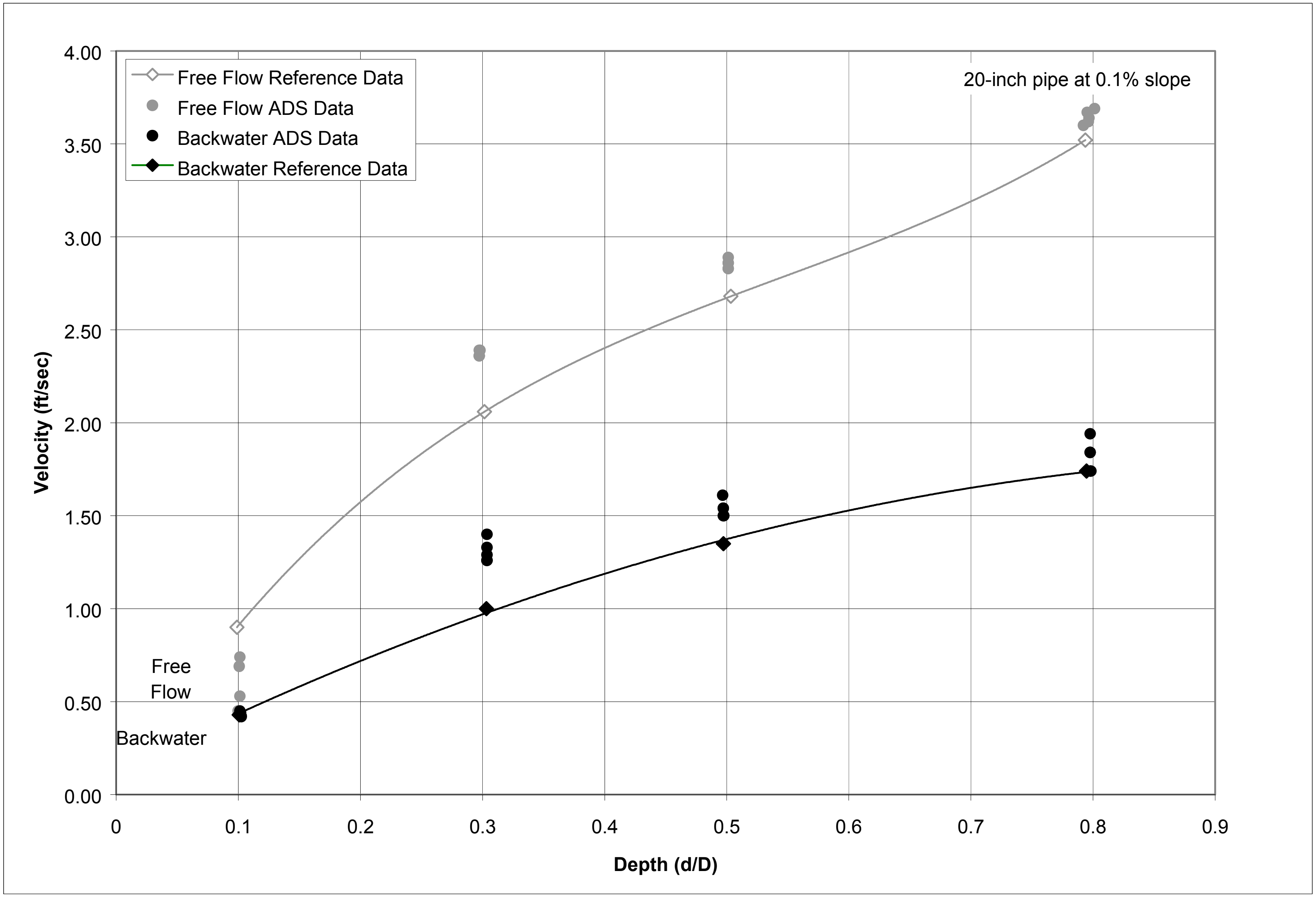


Figure 3-21. Scatter-graph for 20-inch pipe test at 0.1 percent slope.

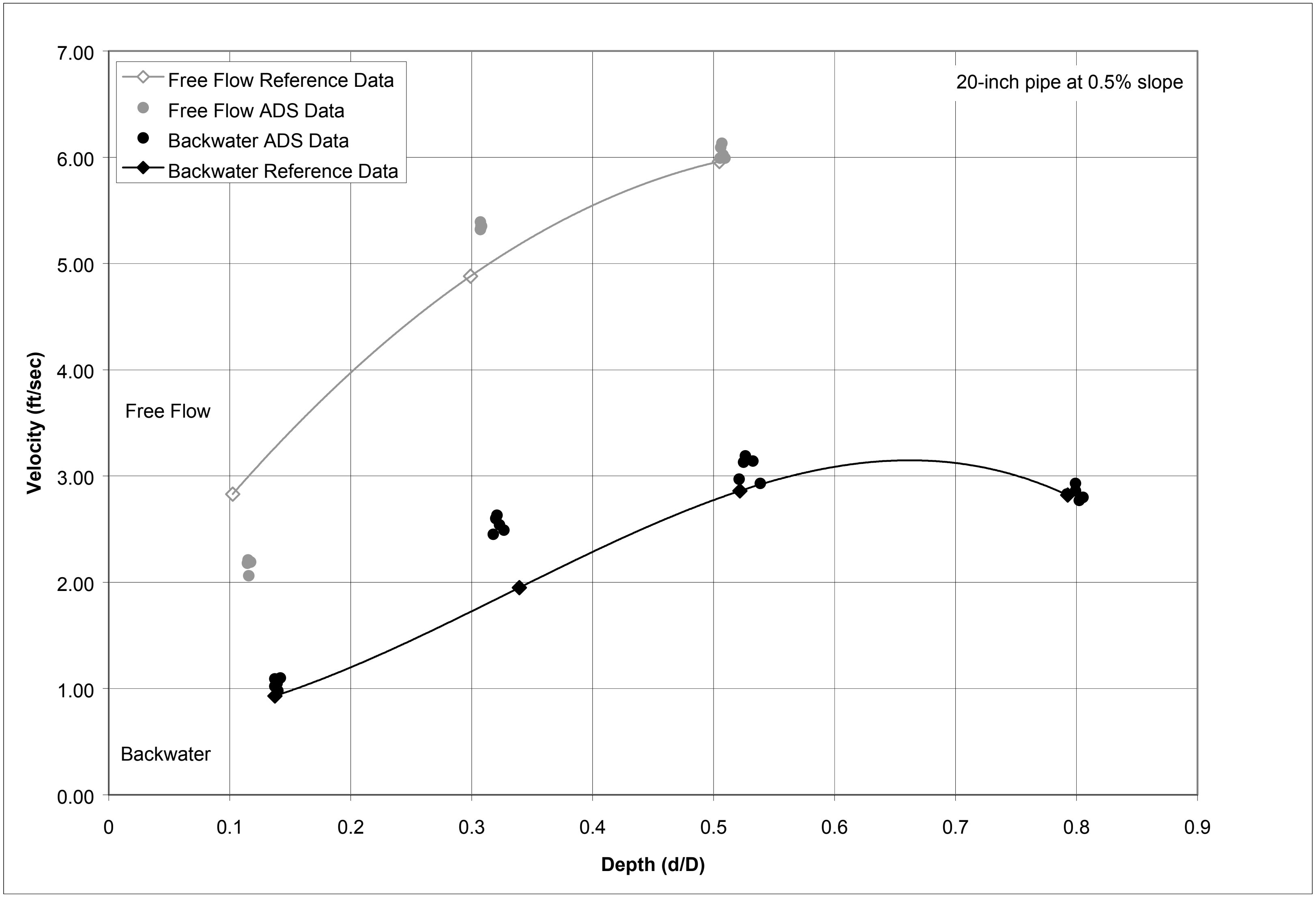


Figure 3-22. Scatter-graph for 20-inch pipe test at 0.5 percent slope.

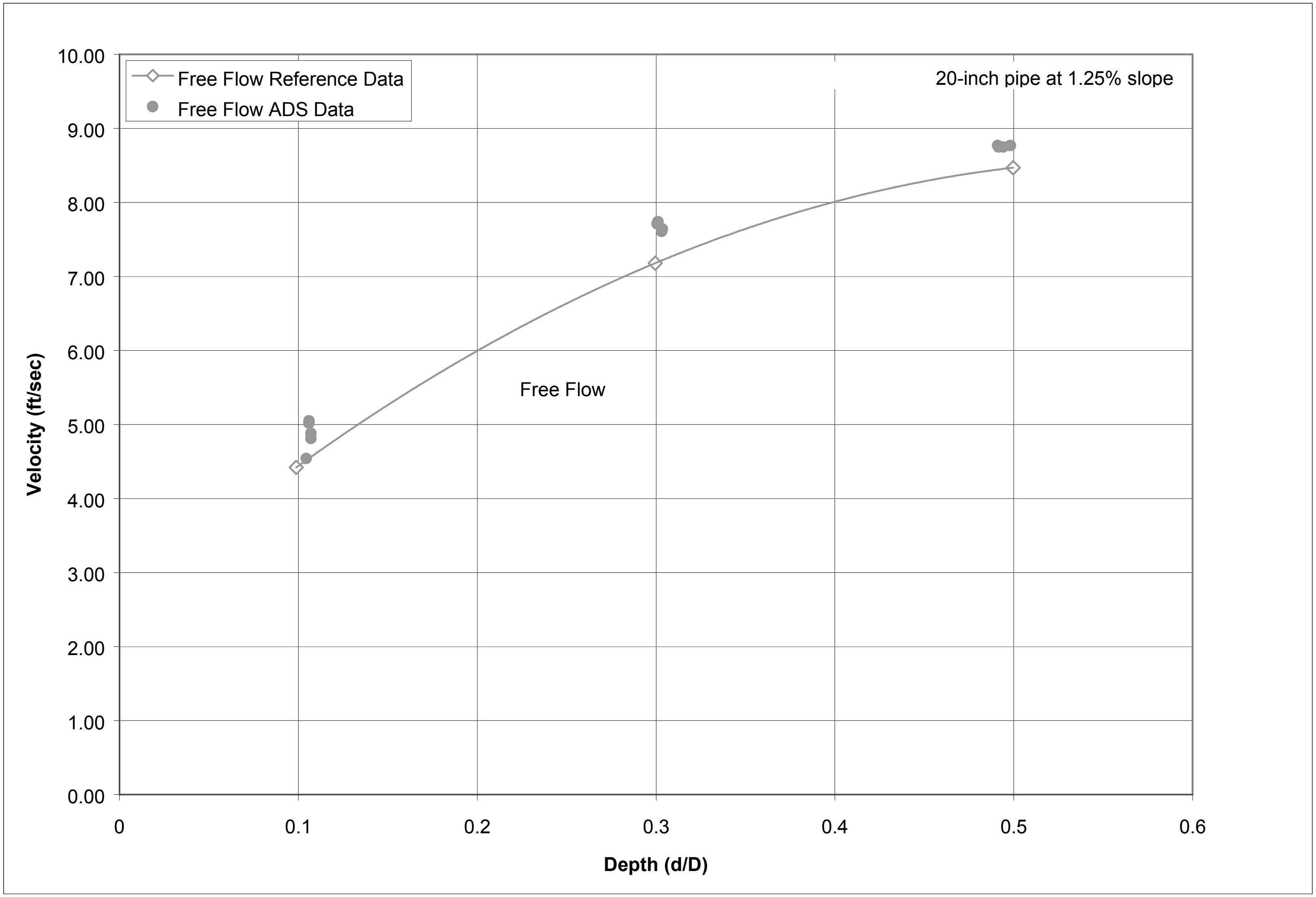


Figure 3-23. Scatter-graph for 20-inch pipe test at 1.25 percent slope.

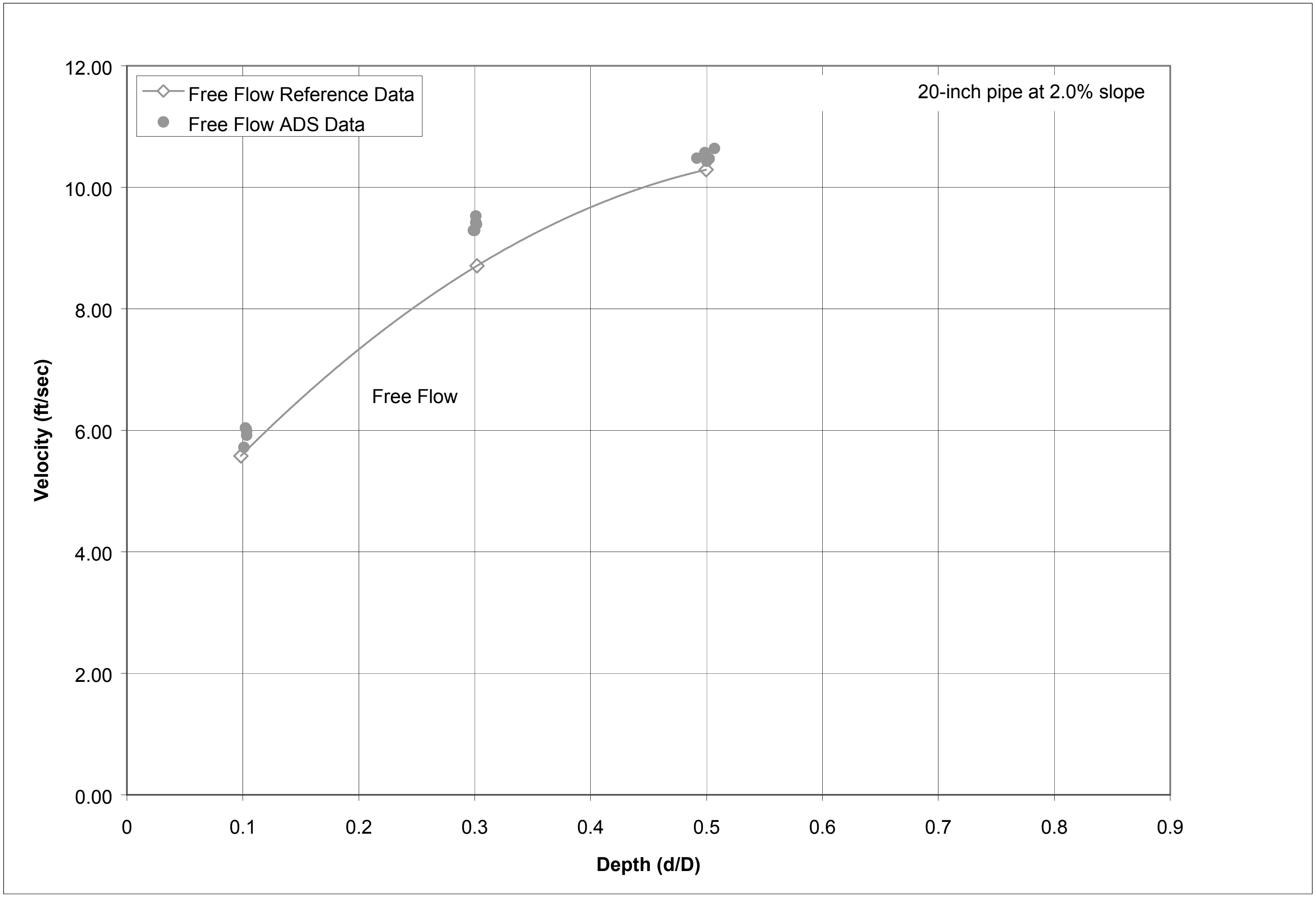


Figure 3-24. Scatter-graph for 20-inch pipe test at 2.0 percent slope.

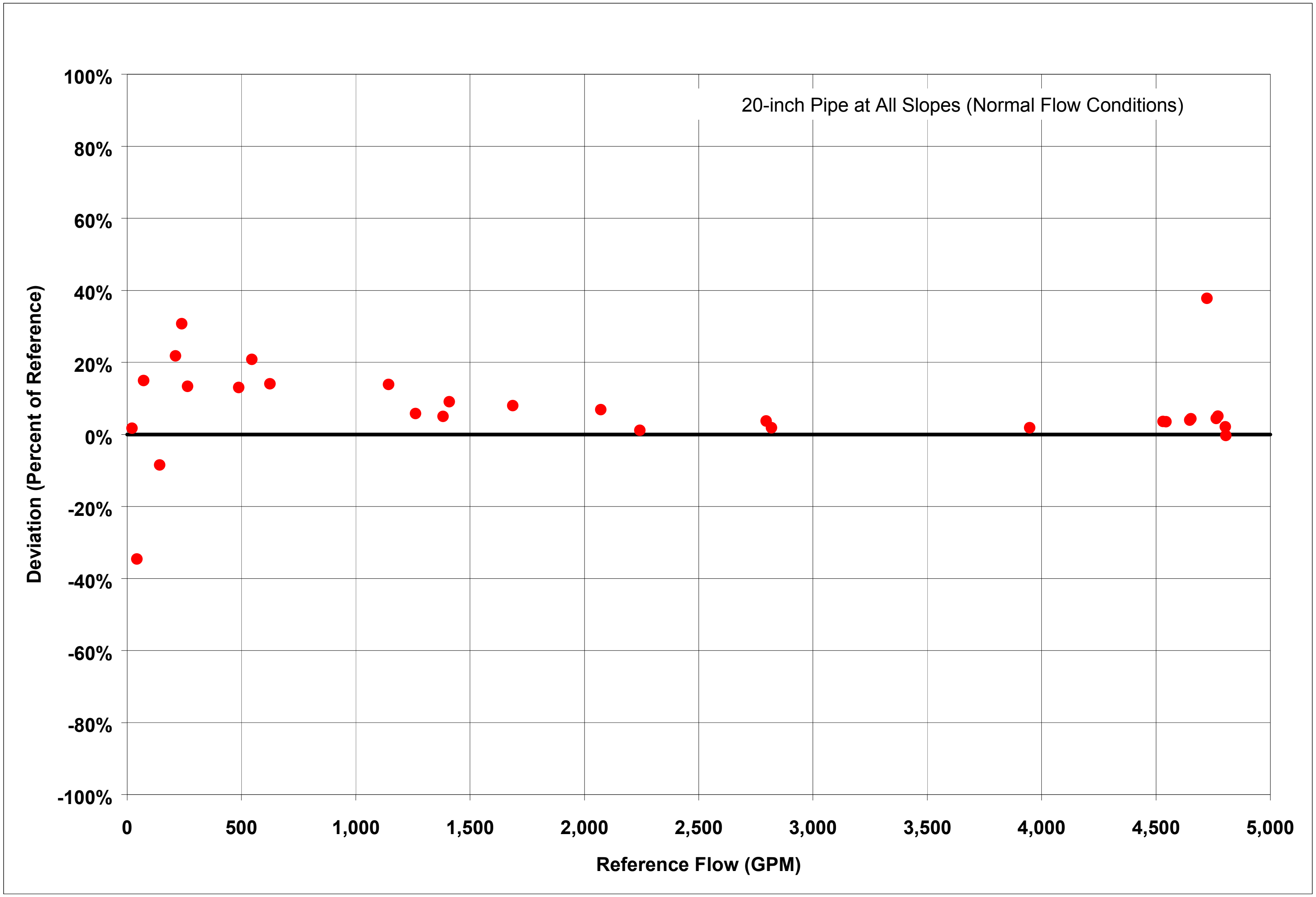


Figure 3-25. Deviation of meter flow to reference flow for 20-inch pipe.

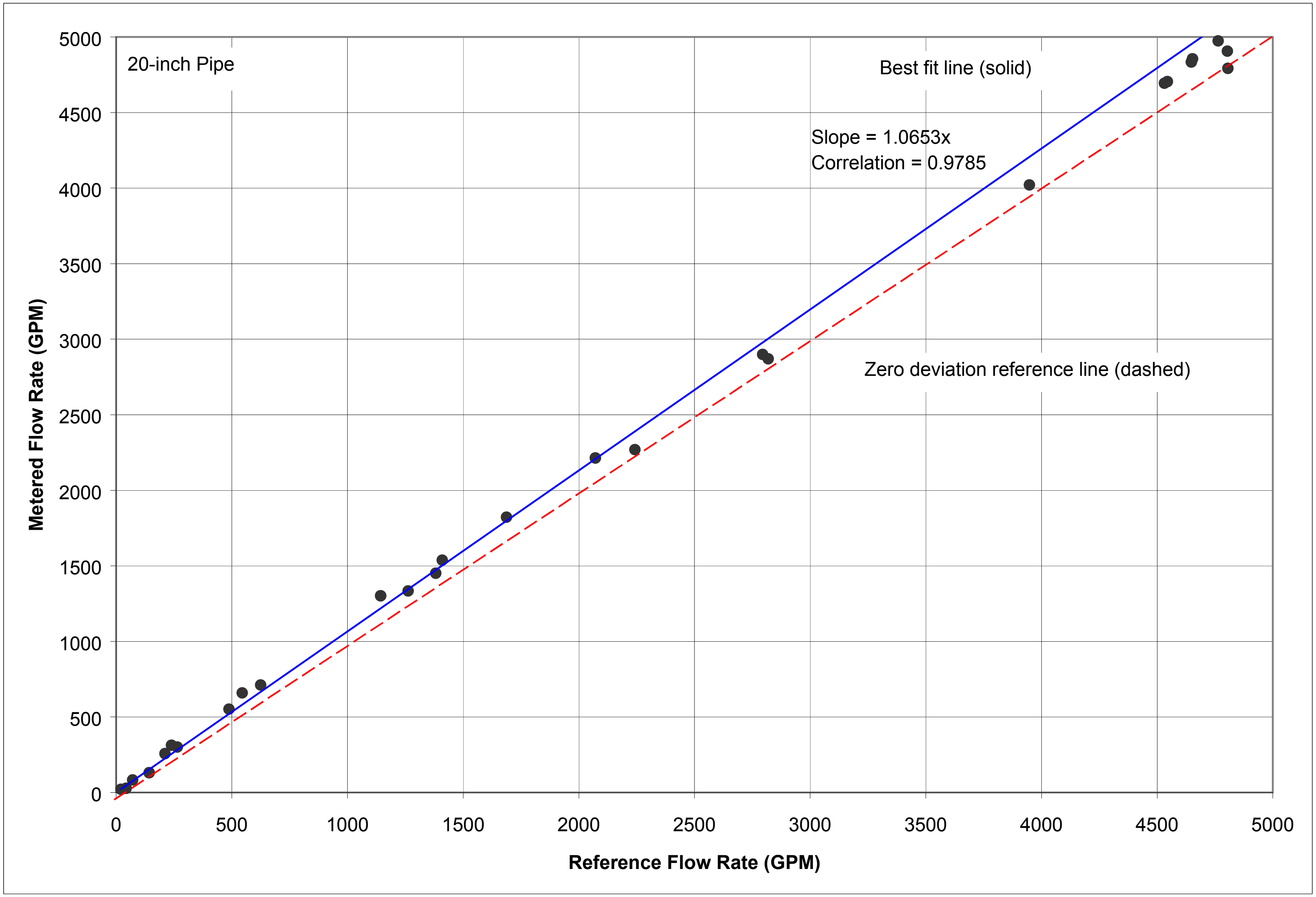


Figure 3-26. Plot of reference flow versus meter flow in 20-inch pipe.

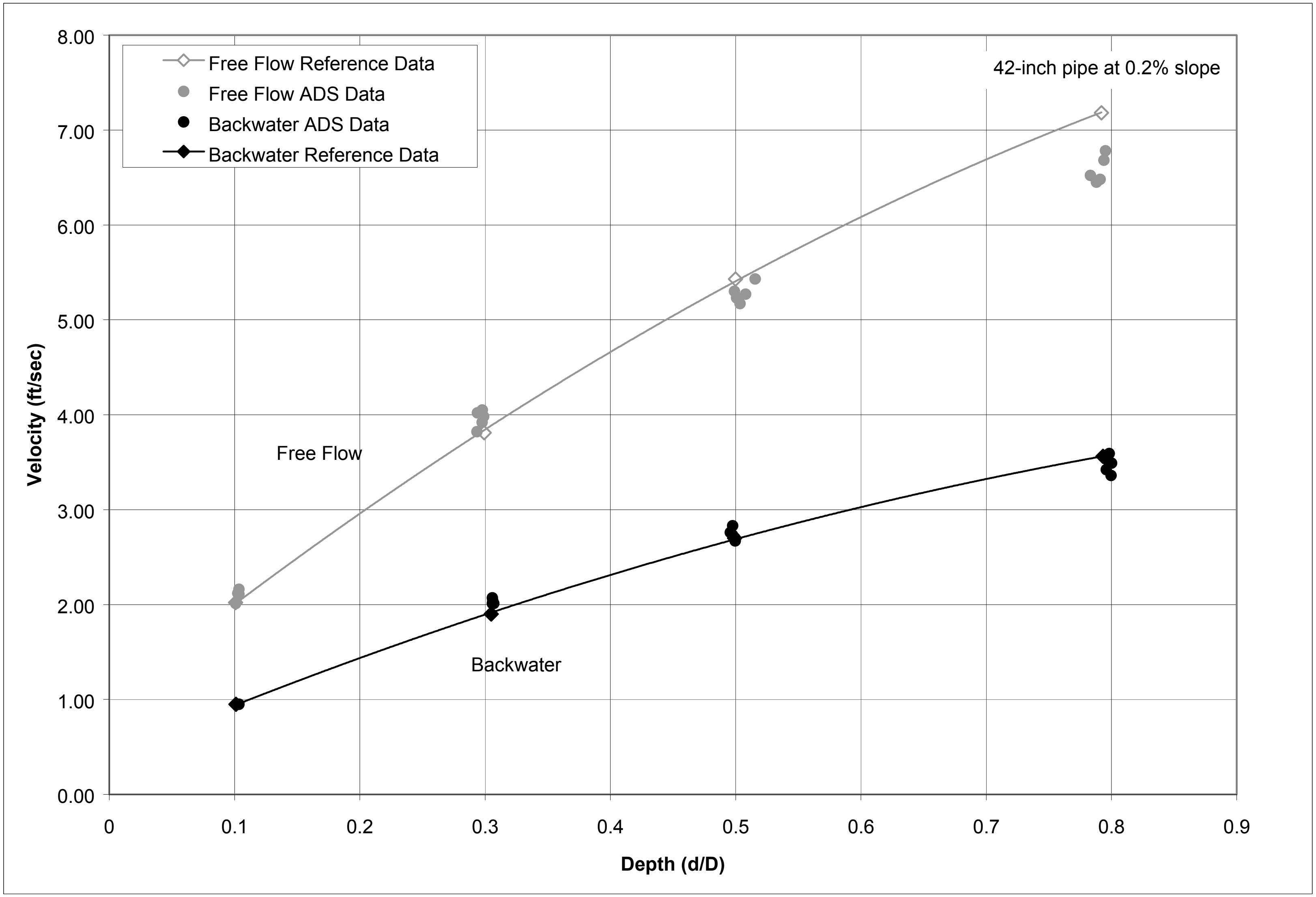


Figure 3-27. Scatter-graph for 42-inch pipe test at 0.2 percent slope.

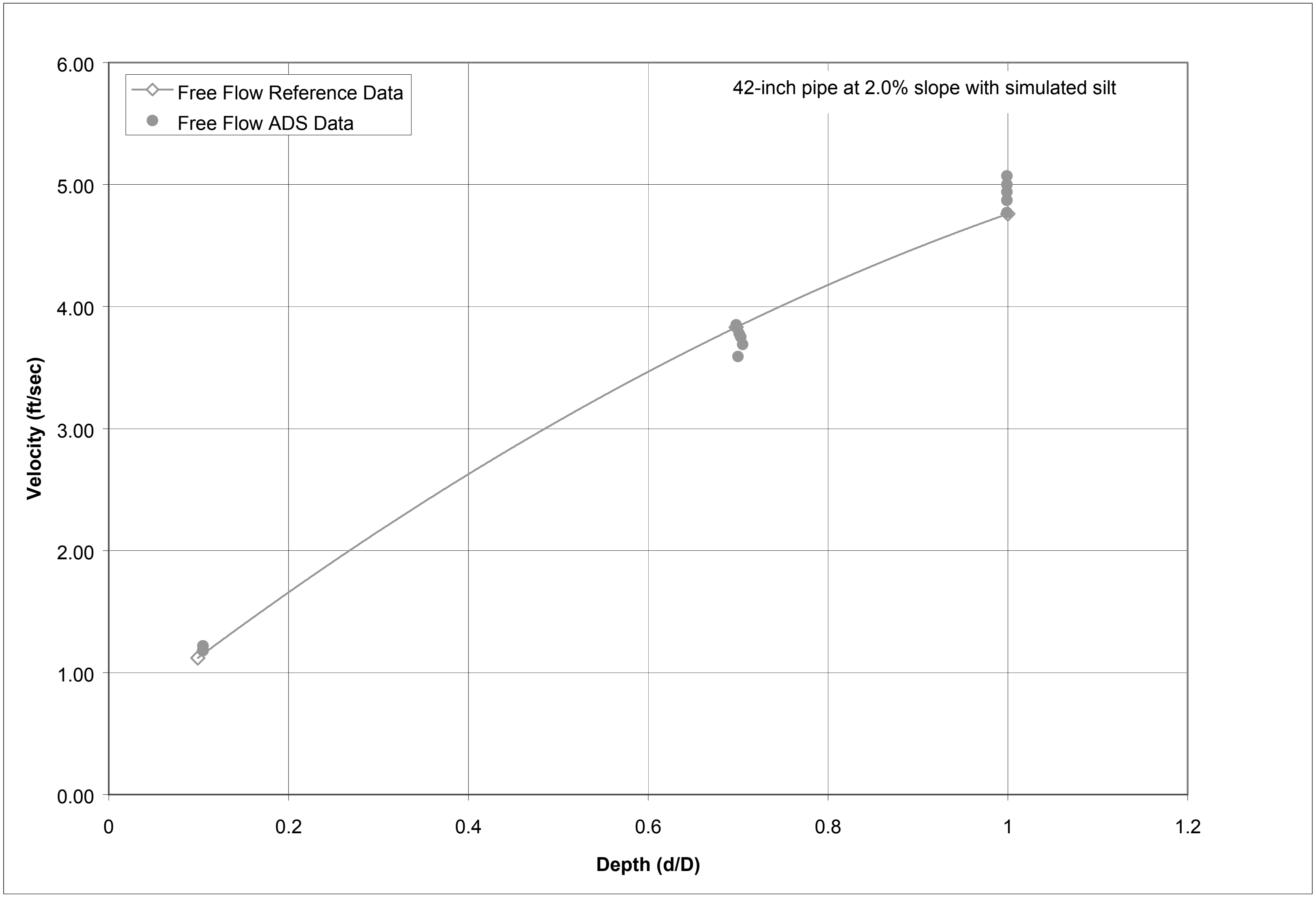


Figure 3-28. Scatter-graph for 42-inch pipe test at 0.2 percent slope with silt.

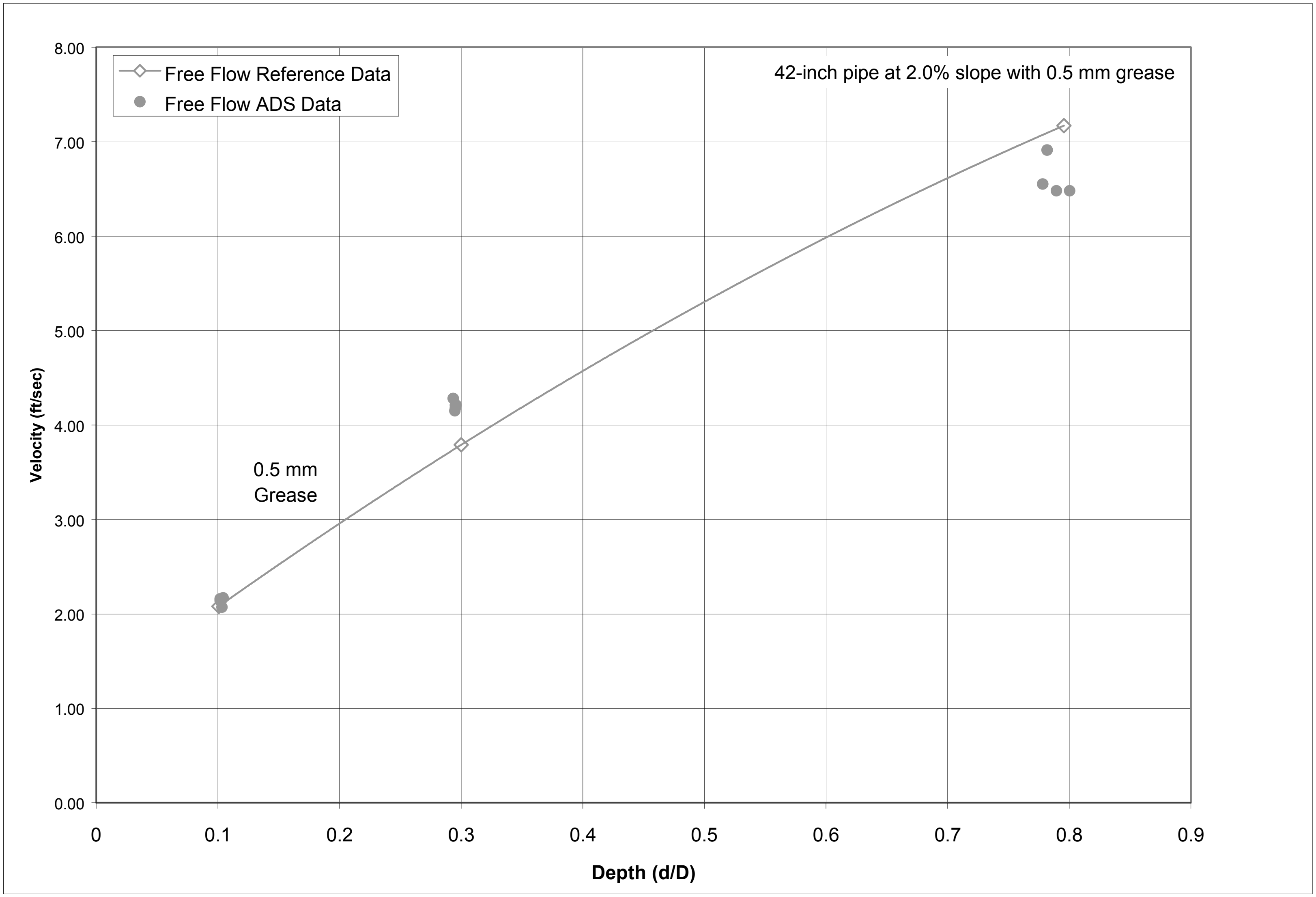


Figure 3-29. Scatter-graph for 42-inch pipe test at 0.2 percent slope with 0.5mm grease.

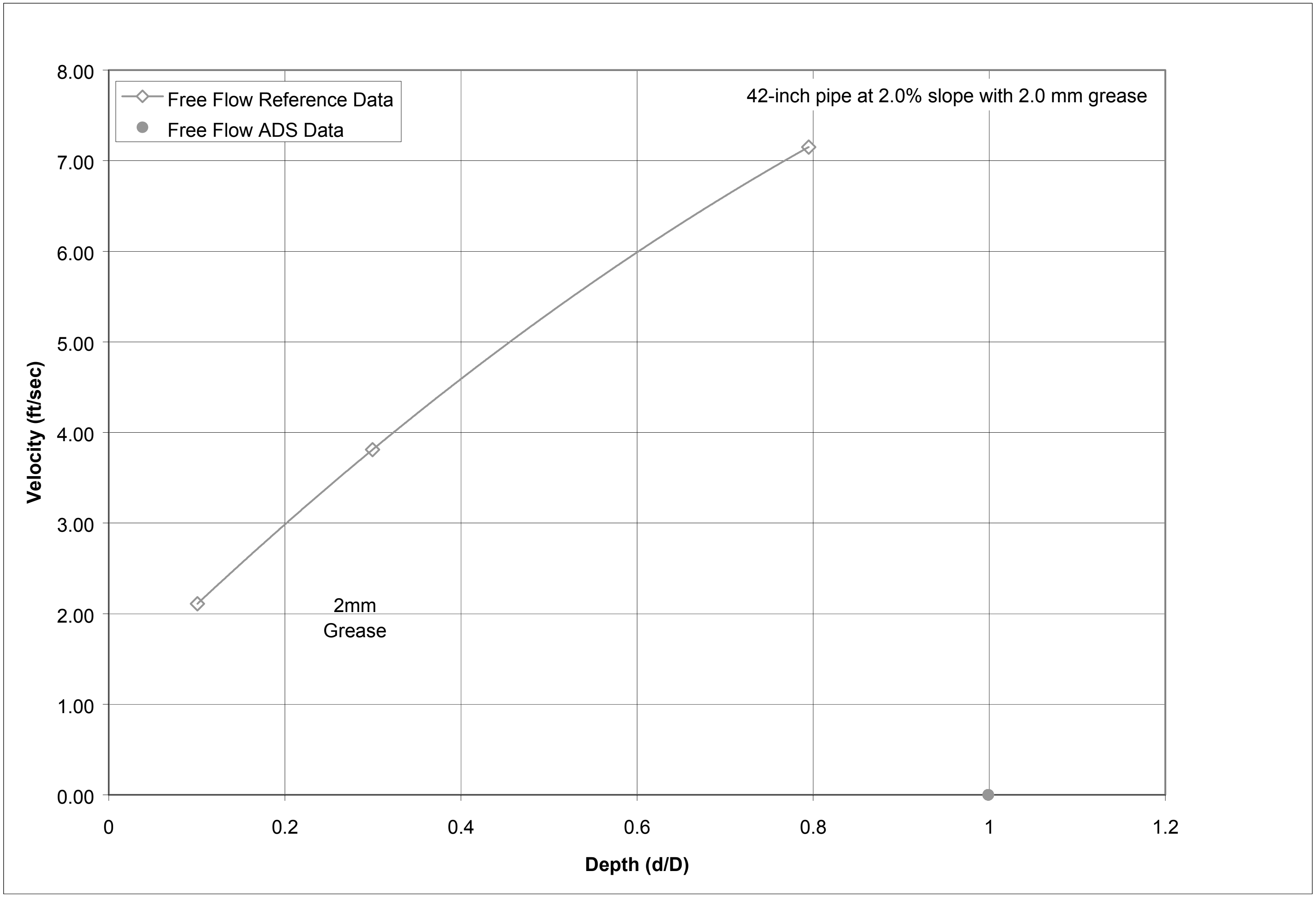


Figure 3-30. Scatter-graph for 42-inch pipe test at 0.2 percent slope with 2.0mm grease.

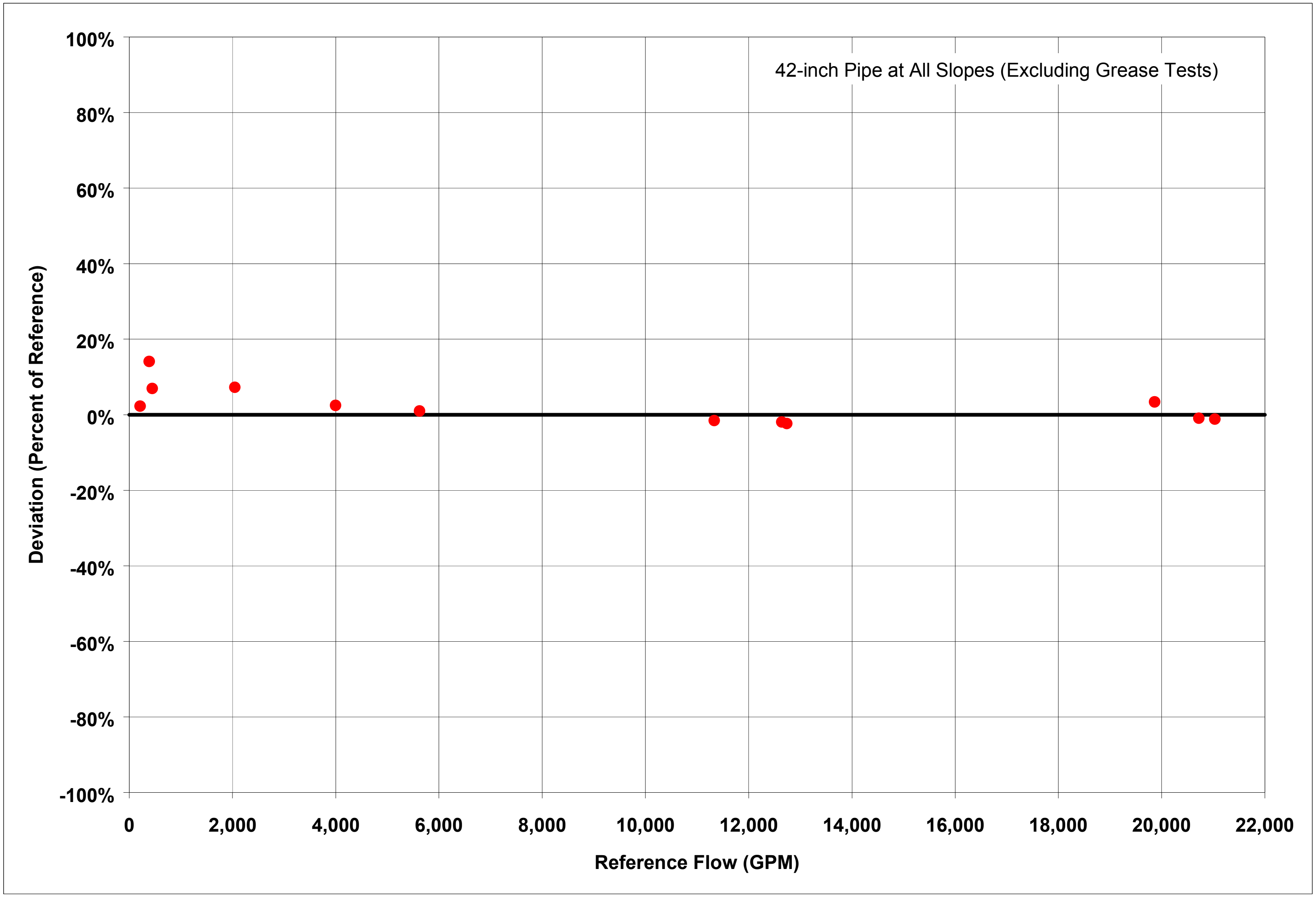


Figure 3-31. Deviation of meter flow to reference flow for 42-inch pipe.

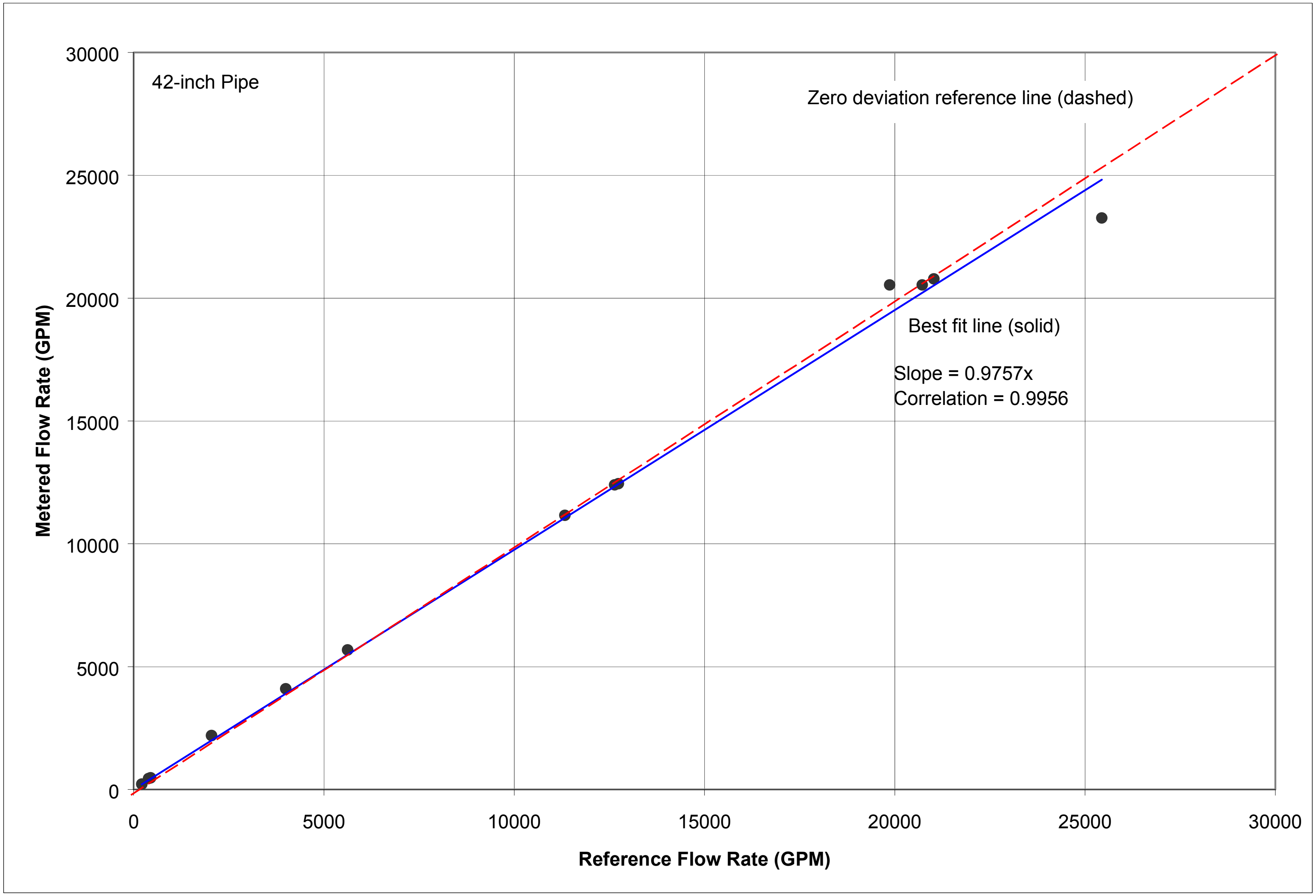


Figure 3-32. Plot of reference flow versus meter flow in 42-inch pipe.

Appendices

A Laboratory Equipment Calibrations and Information
B Raw Laboratory Test Notes and Data
C Operational Procedure and Data Logging Method
D Laboratory Test Data

Glossary

Accuracy - a measure of the closeness of an individual measurement or the mean of a number of measurements to the true value and includes random error and systematic error.

Bias - the systematic or persistent distortion of a measurement process that causes errors in one direction.

Comparability – a qualitative term that expresses confidence that two data sets can contribute to a common analysis and interpolation.

Completeness – a qualitative term that expresses confidence that all necessary data have been included.

Precision - a measure of the agreement between replicate measurements of the same property made under similar conditions.

Protocol – a written document that clearly states the objectives, goals, scope, and procedures for the study. A protocol shall be used for reference during vendor participation in the verification testing program.

Quality Assurance Project Plan – a written document that describes the implementation of quality assurance and quality control activities during the life cycle of the project.

Representativeness - a measure of the degree to which data accurately and precisely represent a characteristic of a population parameter at a sampling point, a process condition, or environmental condition.

Wet Weather Flows Stakeholder Advisory Group - a group of individuals consisting of any or all of the following: buyers and users of flow monitoring technologies, developers and vendors, consulting engineers, the finance and export communities, and permit writers and regulators.

Standard Operating Procedure – a written document containing specific procedures and protocols to ensure that quality assurance requirements are maintained.

Technology Panel - a group of individuals with expertise and knowledge of flow monitoring technologies.

Testing Organization – an independent organization qualified by the Verification Organization to conduct studies and testing of flow monitoring technologies in accordance with protocols and Test Plans.

Vendor – a business that assembles or sells flow monitoring equipment.

Verification – to establish evidence on the performance of flow monitoring technologies under specific conditions, following a predetermined study protocol(s) and test plan(s).

Verification Organization – an organization qualified by EPA to verify environmental technologies and to issue verification statements and verification reports.

Verification Report – a written document containing all raw and analyzed data, all quality assurance/quality control (QA/QC) data sheets, descriptions of all collected data, a detailed description of all procedures and methods used in the verification testing, and all QA/QC results. The test plan(s) shall be included as part of this document.

Verification Statement – a document that summarizes the Verification Report reviewed and approved and signed by EPA and NSF.

Verification Test Plan – a written document prepared to describe the procedures for conducting a test or study according to the verification protocol requirements for the application of flow monitoring technology. At a minimum, the test plan shall include detailed instructions for sample and data collection, sample handling and preservation, precision, accuracy, goals, and QA/QC requirements relevant to the technology and application.

December 2003
03/13/WQPC-WWF
EPA/600/R-04/034

Environmental Technology Verification Report

Wet Weather Flow Monitoring Equipment

ADS Environmental Model 4000 Open Channel Flow Monitor

Part II – Field Test Results

Prepared by

NSF International

Under a Cooperative Agreement with
U.S. Environmental Protection Agency

THE ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM

U.S. Environmental Protection Agency

NSF International

ETV Joint Verification Statement

TECHNOLOGY TYPE:	**AREA/VELOCITY FLOW MONITORS**	
APPLICATION:	**FLOW METERING IN SMALL- AND MEDIUM (10- to 42-inch) SEWERS**	
TECHNOLOGY NAME:	**ADS ENVIRONMENTAL SERVICES MODEL 4000 OPEN CHANNEL FLOW METER**	
TEST LOCATION:	**QUEBEC CITY, QUEBEC, CANADA, AND LOGAN, UTAH**	
COMPANY:	**ADS ENVIRONMENTAL SERVICES**	
ADDRESS:	**5030 BRADFORD DRIVE BUILDING 1, SUITE 210 HUNTSVILLE, AL 35805**	PHONE: **(800) 633-7246** FAX: **(256) 430-6633**
WEB SITE:	**http:\\www.adsenv.com**	
EMAIL:	**info@adsenv.com**	

NSF International (NSF) manages the Water Quality Protection Center (WQPC) under the U.S. Environmental Protection Agency's (EPA) Environmental Technology Verification (ETV) Program. NSF evaluated the performance of the Model 4000 Open Channel Flow Meter manufactured by ADS Environmental Services. Utah Water Research Laboratory (UWRL) in Logan, Utah, and BPR of Quebec City, Canada, both NSF-qualified testing organizations, performed the laboratory and field verification testing, respectively.

EPA created the ETV Program to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV program is to further environmental protection by accelerating the acceptance and use of improved and cost-effective technologies. ETV seeks to achieve this goal by providing high-quality, peer-reviewed data on technology performance to those involved in the design, distribution, permitting, purchase, and use of environmental technologies.

ETV works in partnership with recognized standards and testing organizations; stakeholder groups consisting of buyers, vendor organizations, and permitters; and with the full participation of individual technology developers. The program evaluates the performance of innovative technologies by developing test plans that are responsive to the needs of stakeholders, conducting field or laboratory tests (as appropriate), collecting and analyzing data, and preparing peer reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance protocols to ensure that data of known and adequate quality are generated, and that the results are defensible.

TECHNOLOGY DESCRIPTION

The following technology description is provided by the vendor and does not represent verified information.

Area/velocity flow meters are commonly used in wastewater collection, storm sewer, and combined sewer systems. The ADS 4000 flow meter utilizes a quad-redundant ultrasonic sensor that measures the time required for an ultrasonic pulse to travel from the sensor face to the surface of the water and back to the sensor. The meter converts the travel time to distance by calculating the speed of sound through air and adjusting for temperature, which is measured by two sensors inside the ultrasonic sensor head. The depth of the flow is then calculated using the pipe diameter and the range measured by the ultrasonic sensor. A pressure-depth sensor is also installed at the bottom of the pipe to measure surcharge levels and to provide a redundant depth reading when used with the ultrasonic level sensor. Doppler velocity measurements are made by transmitting an ultrasonic signal upstream using a submerged velocity sensor and measuring the frequency shift in the sound waves reflected by the moving particles in the water. The depth and velocity sensor readings are stored in the flow meter's memory until the data can be downloaded to a computer through either a voice-grade telephone line or a cellular network. The computer software calculates flow rates using the depth and velocity readings.

The ADS 4000 flow meter system includes the flow meter unit, sensors, and installation hardware. The flow meter unit is housed in a waterproof, marine-grade aluminum housing. The submersible pressure sensor, ultrasonic level sensor, and velocity sensor are attached to a circular stainless steel band installed around the inner circumference of the sewer pipe. Waterproof cables with sealed connectors convey power and signals between the flow meter unit and the sensors. The system is battery-powered, and can power the unit for about one year at a standard 15-minute measurement interval. According to vendor claims, after the unit is installed, minimal operation and maintenance (O&M) or unit calibration is required; the most common O&M procedure is cleaning the sensors.

VERIFICATION TESTING DESCRIPTION

Laboratory Test Site

The laboratory testing was completed at the Utah Water Research Laboratory (UWRL), at Utah State University in Logan, Utah. The flow meter was installed in three nominal pipe sizes: 10-inch, 20-inch, and 42-inch. The straight lengths were sized so they were at least 40 times the pipe diameter for the 10- and 20-inch pipes and at least 22 times for the 42-inch pipes. Pipe slopes were adjustable to allow the flow meter to be evaluated under different slope conditions. Sluice gates at both ends of the pipes were used to regulate appropriate flow, head, and obstruction during testing. Reference devices were directly traceable to the National Institute of Standards and Technology (NIST), and were regularly calibrated. Uncertainty for the reference devices was less than 0.25 percent.

Field Test Site

Field verification testing was conducted in a section of the Quebec Urban Community's (QUC) sewer network, located in the City of Sainte-Foy, Quebec, Canada. The ADS flow meter and reference meters were installed in a 41.7-inch diameter interceptor pipe, near the downstream of a straight run of pipe that had an average slope of 0.169 percent. The reference devices, which consisted of a bubbler for a reference level measurement, a reference flow monitor, and an Accusonic 4-path flow monitor, were installed downstream of the ADS 4000 flow meter. Upstream and downstream sluice gates were used to create the required flow conditions.

Validation of the reference flow monitor and bubbler were performed by lithium tracer dye tests. Flow rates under the upstream and downstream gates were also calculated using standard hydraulic equations for a redundant check of flow data.

Methods and Procedures

Laboratory evaluation of the flow meters consisted of collecting depth, velocity, and flow data from the ADS meter and comparing it to the depth, velocity, and flow data from the reference devices. These tests were performed under normal operating conditions of uniform flow, backwater flow, full pipe (manhole surcharged), and simulated silt. Water transmission through the pipes, as a ratio of flow depth versus the pipe diameter (d/D), ranged from 10 to 250 percent (surcharged conditions). Tests were also performed under the abnormal operating conditions of reverse flow and grease accumulation.

Field evaluation of the ADS flow meter at the Quebec site consisted of a general evaluation of the flow meter (Test A) and the performance of the meter under varying flow conditions. Testing consisted of collecting depth, velocity, and flow data at regular time intervals and comparing the data to the corresponding depth, velocity, and flow data from the reference devices. Four test scenarios were used:

1. Test B—accuracy under dry weather flow (approximately 1.71 million gallons per day [MGD]), with back-flow conditions;
2. Test C—accuracy under wet weather flow (1.71–29.7 MGD), without back-flow conditions;
3. Test D—accuracy under wet weather flow (1.71–29.7 MGD), with back flow-conditions; and,
4. Test E—accuracy under short-term (26-day) continuous operation, with various flow rates.

Three conditions were identified during testing that created an unintended challenge to the ADS flow meter:

1. The water used in the testing at UWRL did not contain the particulate concentrations of normal sewage, so small quantities of coffee creamer were added to the water on some test runs. The operating principle utilized by the ADS flow meter requires particles in the water to serve as reflectors for sound waves. The vendor maintained that the coffee creamer additive provided a level of reflectivity, but the particulate concentration in the test water did not approach that of sewage and could be a source of measurement error.

2. During each field test, a portion of the ADS flow meter data collected at one-minute intervals was not recorded. ADS personnel indicated that this happened because the flow meter was configured for maximum error checking and sensor refiring. They further indicate that the ADS 4000 flow meter can be reconfigured to collect data at one-minute intervals by reducing the level of real-time error checking.

3. The field testing results include data in which it appears that standing waves and troughs were present beneath the ADS 4000 flow meter's ultrasonic depth sensor. During portions of the testing, the depth sensor was likely affected by standing waves and troughs up to $\pm$5 inches. The ADS flow meter measures depth with a downward-looking, narrow-beam ultrasonic sensor mounted on the top of the pipe, so depth measurements would be susceptible to influence by waves. Based on a review of the field data, it appears that waves were most prevalent at higher depths and flow rates.

No editing was allowed on the metered data during field or laboratory testing. In actual applications, the flow monitoring service provider may implement post-monitoring quality control measures to attempt to improve the accuracy of final data. According to ADS, the company typically bundles flow meter sales with post-monitoring quality control and reporting services.

VERIFICATION OF PERFORMANCE

System Operation

The testing organizations found the equipment durable and easy to use, and that it required minimal maintenance. The flow meter operation and data retrieval software programs were easy to learn. The ultrasonic sensors and stainless steel band did not promote accumulation of debris during testing.

Laboratory Testing Results

The mean deviation and the 95-percent confidence intervals under normal operating conditions (i.e., all test conditions except grease tests and reverse flow) are presented in Table 1. The width of the 95-percent confidence interval is a function of the variation in instrument deviation and of the number of test runs in each reported category. Categories with a fewer number of runs show wider confidence intervals. The calculations exclude "abnormal condition" tests, where grease was applied to the sensors or where reverse-flow conditions were created. The mean deviation for the abnormal operating conditions was 1.3 percent for the 0.5-mm grease tests, -69.5 percent for the 2.0-mm grease tests, and –62.4 percent for the reverse-flow tests.

Table 1. Deviation and 95-Percent Confidence Interval by Test Configuration for Lab Testing

Pipe size (inches)	Deviation (percent)	95-percent confidence interval (percent)
10	4.7	-6.5 – 15.8
20	-0.7	-7.9 – 6.6
42	-0.9	-10.8 – 9.0
Pipe slope (percent)		
0.1	4.7	-4.2 – 13.5
0.2	-0.9	-10.8 – 9.0
0.5	-0.8	-10.9 – 9.4
1.25	2.3	-10.8 – 15.4
2.0	0.2	-30.1 – 30.4
Percent full (d/D, percent)		
10	-0.1	-22.2 – 20.3
30	1.1	-13.5 – 15.8
50	5.4	-1.6 – 12.5
80	1.9	-7.4 – 11.2
150	-4.6	-28.8 – 19.6
250	3.3	-6.7 – 13.2
Condition		
Free flow	2.7	-4.3 – 9.7
Backwater	0.2	-7.5 – 8.0
All conditions	**1.2**	**-4.0 – 6.5**

The overall accuracy of the ADS 4000 flow meter under normal operating conditions (i.e., all test conditions except grease tests and reverse flow) is shown in Figure 1. The meter deviation is segregated into two components—bias and precision. Overall bias was 1.6 percent, as calculated by the slope of the best-fit line. Precision, as calculated with the correlation coefficient (r^2), was 0.74 percent.

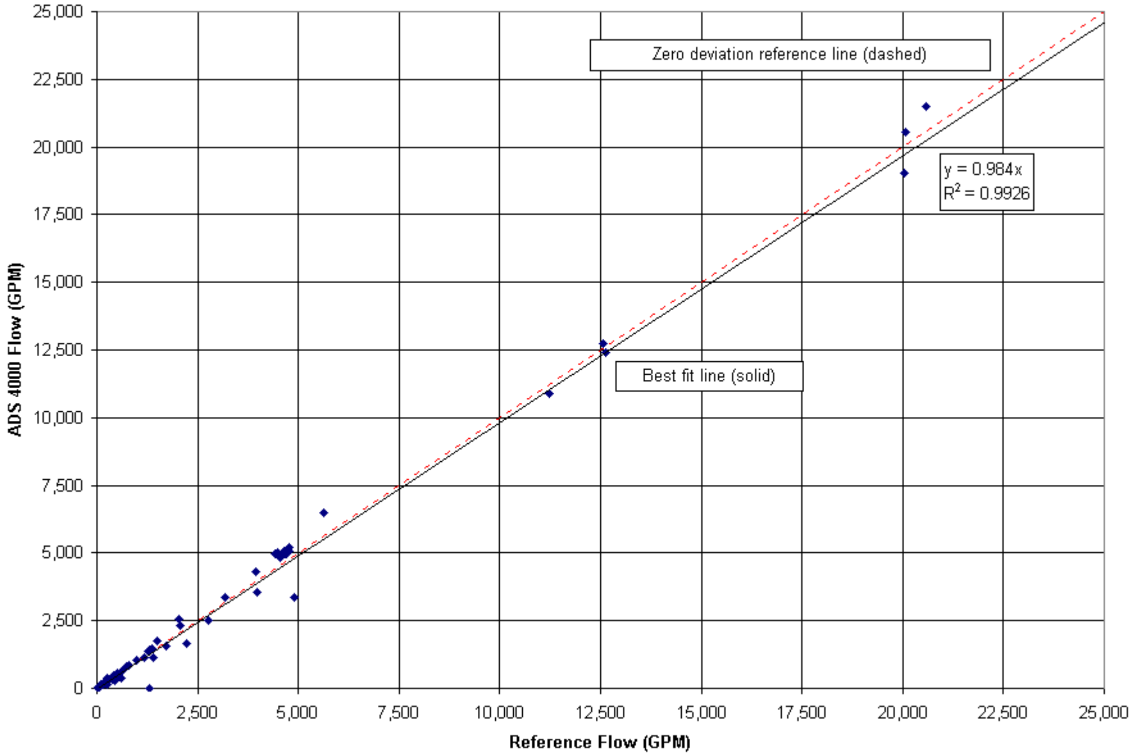


Figure 1. Laboratory-metered flow rate versus reference.

Field Testing Results

Table 2 summarizes the field testing results in two categories: mean deviation and trimmed mean deviation. The mean deviation is the arithmetic mean of all of the one-minute–interval data. The trimmed mean deviation is calculated by eliminating values greater than ±99 percent, making it less susceptible to skewing from large outliers, such as those produced when the ADS flow meter recorded zero velocity.

Table 2. Deviation from Reference Flow: Tests B, C, and D.

Flow regime	Mean deviation (percent)	Trimmed mean deviation (percent)
Test B	-14.5	-0.9
Test C	14.0	14.5
Test D	-0.8	8.3
Test B-D combined	**-0.4**	**3.8**
Simulated low flow	0.5	9.5
Simulated wet flow	-1.3	-1.0
Combined flows	**-0.4**	**3.8**

Analysis of the data collected during Test B (low flow) revealed that in nearly one-fourth of the samples the deviation was –100 percent. This occurred when the ADS 4000 flow meter recorded zero velocity and calculated the flow to be zero. This occurred most frequently when the pipe experienced back-flow conditions. The data collected during Tests C and D shows a significantly lower occurrence of data with deviations exceeding ±99 percent.

Test E (not included in Table 2) evaluated the performance of the flow meter over an extended (26-day) time period. Generally, the data collected during Test E closely correlated with the reference flow monitor data. Spikes were noted in water level measurements collected toward the end of the test, which may have been the result of accumulated condensation on the ultrasonic depth probe. No debris accumulation was observed on the equipment, and, aside from a thin film of grease on the probes, the equipment was in good condition and did not require maintenance.

QUALITY ASSURANCE/QUALITY CONTROL

A complete description of the quality assurance/quality control procedures and findings are included in the verification reports. Calibration records were maintained by the testing organizations and validation of the reference flow devices fell within control limits. NSF completed a data quality audit of at least 10 percent of the test data to ensure that the reported data represented the data generated during testing. Audits of the field and laboratory testing were conducted by NSF with no significant issues noted.

Original Signed by
Lee A. Mulkey *March 31, 2004*

Lee A. Mulkey Date
Acting Director
National Risk Management Laboratory
Office of Research and Development
United States Environmental Protection Agency

Original Signed by
Gordon Bellen *April 26, 2004*

Gordon Bellen Date
Vice President
Research
NSF International

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Availability of Supporting Documents

Copies of the *Draft 4.0 – Generic Verification Protocol, Flow Monitors for Wet Weather Flows Applications in Small- and Medium-Sized Sewers, September, 2000,* the verification statement, and the verification report (NSF Report #03/13/WQPC-WWF) are available from:

ETV Water Quality Protection Center Program Manager (order hard copy)
NSF International
P.O. Box 130140
Ann Arbor, Michigan 48113-0140
NSF web site: http://www.nsf.org/etv (electronic copy)
EPA web site: http://www.epa.gov/etv (electronic copy)

(NOTE: Appendices are not included in the verification report. Appendices are available upon request from NSF.)

Environmental Technology Verification Report

WET WEATHER FLOW MONITORING EQUIPMENT VERIFICATION

ADS ENVIRONMENTAL MODEL 4000
OPEN CHANNEL FLOW MONITOR

PART II: FIELD TEST RESULTS
QUEBEC URBAN COMMUNITY TEST SITE

Prepared for:

NSF International
Ann Arbor, Michigan

Prepared by:

BPR
Quebec City, Quebec, Canada

December, 2003

Under a cooperative agreement with the U.S. Environmental Protection Agency

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Notice

The U.S. Environmental Protection Agency (EPA) through its Office of Research and Development has financially supported and collaborated with NSF International (NSF) under a cooperative agreement. This verification effort was supported by the Water Quality Protection Center operating under the Environmental Technology Verification (ETV) Program. This document has been peer-reviewed and reviewed by NSF and EPA and recommended for public release.

Foreword

The following is the final report on an Environmental Technology Verification (ETV) test performed for NSF International (NSF) and the United States Environmental Protection Agency (EPA) by BPR-CSO, in cooperation with ADS Environmental Services for the Model 4000 Open Channel Flow Monitor. The test protocol for flow monitors requires both laboratory and field testing. The final report for this verification is divided into two parts to address both portions of testing.

This part of the report (Part II) describes the testing and summarizes the data from the field testing. Part I: Laboratory Test Results, describes the testing and summarizes the data of the laboratory testing. Both parts of the report are available on the NSF and EPA websites.

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

Contents

Tables

Figures

Acronyms and Abbreviations

ADS	ADS Environmental Services, a division of ADS Corporation
avg	Average
BPR	BPR, Quebec, Canada
cfs	Cubic feet per second
CSO	Combined sewer overflow
EPA	United States Environmental Protection Agency
ETV	Environmental Technology Verification
ft	Foot or feet
gpm	Gallons per minute
in.	Inch
kPa	Kilopascal
Lb	Pound
LCQ	Laboratoire de l'environnement LCQ Inc.
TO	testing organization
mA	milliamps
MGD	Million gallons per day
mg/L	Milligrams per liter
m	Meter
mm	Millimeter
NIST	National Institute of Standards and Technology
NSF	NSF International (formerly National Sanitation Foundation)
PC	Personal computer
PLC	Programmable logic controller
psi	Pounds per square inch
QA	Quality assurance
QAPP	Quality Assurance Project Plan
QUC	Quebec Urban Community
SD	Standard deviation
sec	Second
TO	Testing organization
UWRL	Utah Water Research Laboratory
VTP	Verification test plan
WWF	Wet Weather Flow
WWTP	Wastewater treatment plant

Chapter 4
Field Report

4.1 Description of Test Site

The test site for the field testing component of the verification of the ADS Model 3600 Open Channel Flow Monitor (ADS Model 3600) was a section of the Quebec Urban Community's (QUC) sewer network. The site is located in the City of Sainte-Foy, along the east side of the Chaudière Blvd, approximately between the Bombardier and Mendel Streets. Figures 4-1(a) through 4-1(c) present a schematic layout of the complete test site and Figure 4-2 presents details about the portion of the sewer where the ADS Model 3600 was installed and tested.

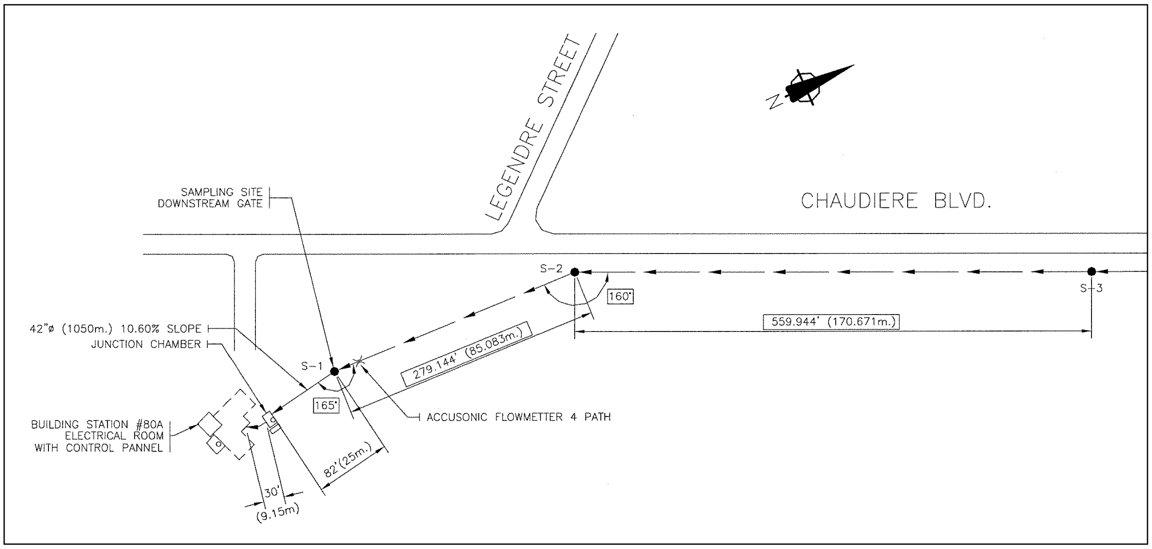
4.1.1 Test Site Infrastructure Description

The test site was defined on the upstream side (north) by the Versant-Sud tunnel, which was controlled at its downstream end by a regulation chamber (Station #100) equipped with a sluice gate. This gate was referred as the "upstream gate" of the test site. The sluice gate was used to control the flow under the gate and the volume of wastewater in the Versant-Sud tunnel when performing tests under high flows. A retention volume of 2.9 million gallons (11,000 m^3) was available from this 96-inch (in.) (2,466 millimeters [mm]) nominal diameter tunnel.

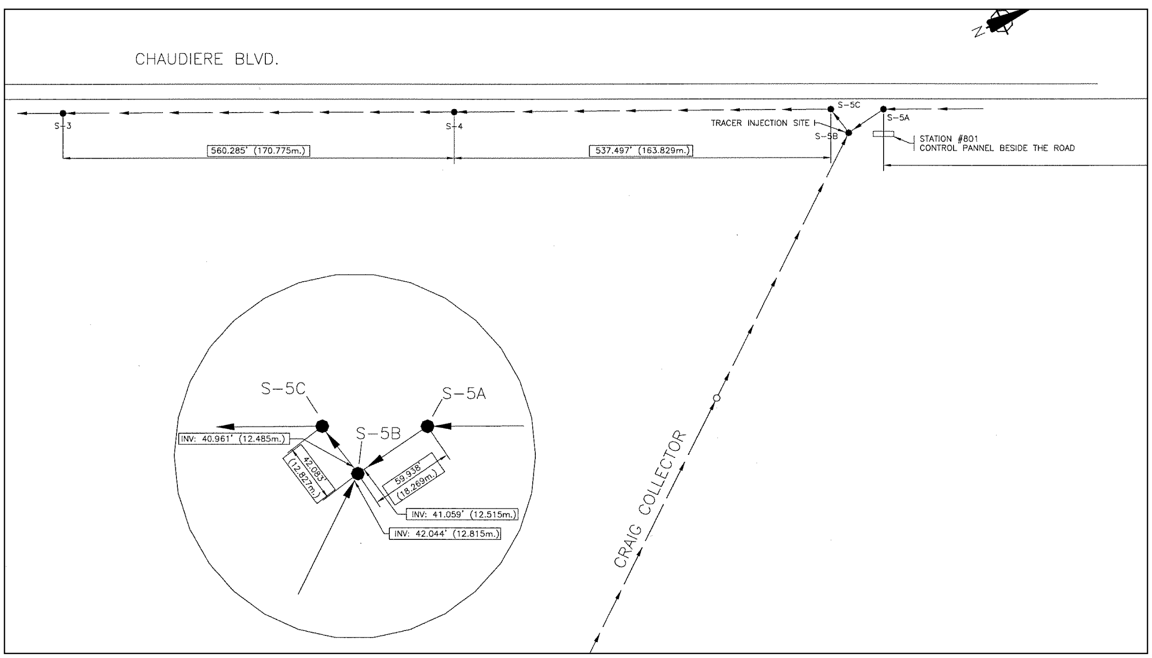
The test site was defined on the downstream side (south) by the west junction chamber (Station #80A), which was the last chamber before the effluent tunnel that leads to QUC's West Wastewater Treatment Plant (WWTP). The test site's "downstream gate" was located just upstream of the west junction chamber.

As shown in Figures 4-1(a) to (c), the test site was an interceptor pipe 41.7 in. (1,059 mm) in diameter. There was approximately 3,620 feet (ft) (1,103 meters (m)) between the downstream gate near which the ADS flow meter was installed and the upstream gate where the flow was controlled. The interceptor pipe between manholes S-1 to S-2 is 279.1 ft (85.1 m) long on an average slope of 0.169 percent. The pipe between manholes S-2 and S-3 is 559.9 ft (170.7 m) long on an average slope of 0.181 percent. The pipe changes direction by 20 degrees at the S-2 manhole and by 15 degrees at the S-1 manhole. Downstream from the S-1 manhole, the pipe sloped 10.6 percent over a distance of 82 ft (25 m) before reaching Station #80A.

As shown in Figure 4-1(b), the Craig Collector coming from the southeast joined the interceptor pipe at manhole S-5B, approximately 1,968 ft (600 m) upstream of manhole S-1. Manhole S-5B was the injection site for the lithium dilution tests. The last section of pipe of the Craig Collector had a 36 in. (910 mm) nominal diameter and was 421 ft (128.4 m) long, with an average slope of 0.417 percent. The Craig Collector was a small pseudo-sanitary uncontrolled flow collector, in which a bubbler level meter was installed 8.6 ft (2.6 m) upstream of manhole S-5B. The electrical panel for this instrument is located nearby on Chaudière Boulevard and the measurements were transmitted to Station #100 by a radio link to take into account the uncontrolled flow in the upstream flow management.

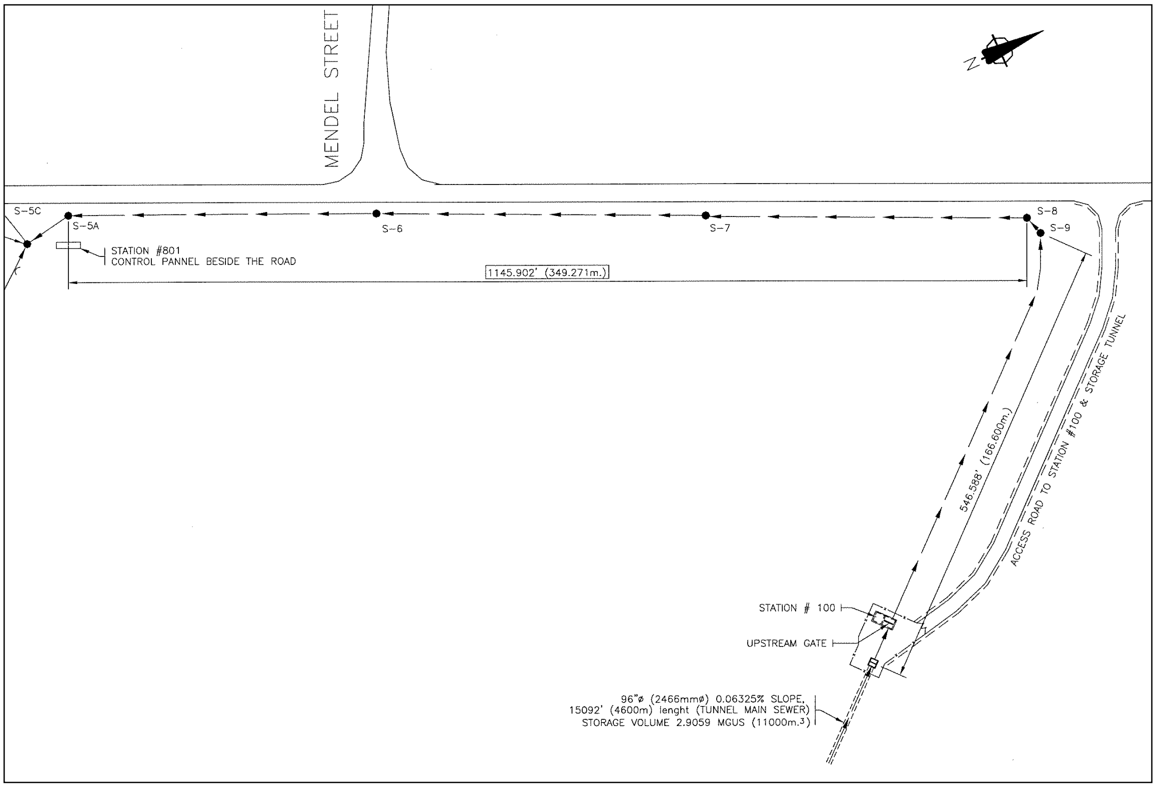


(a)



(b)

Figure 4-1. Test site plan view.



(c)

Figure 4.1 (cont'd). Test site plan view.

As shown on Figure 4-2, the reference bubbler and ultrasonic level meters were installed 4.0 ft (1.24 m) and 7.52 ft (2.30 m) upstream of the S-1 manhole, respectively, and the reference flow meter was installed in a pipe section from 5.4 ft (1.65 m) to 9.2 ft (2.80 m) upstream of the S-1 manhole. This manhole is made of concrete with a nominal diameter of 6.8 ft (2.1 m). It was covered with a concrete roof with two circular 28.5-in. (724-mm) diameter access covers. One access was downstream from the control gate. The other access was just upstream and was equipped with a trap to facilitate the access to the sewer for meter installation and operation.

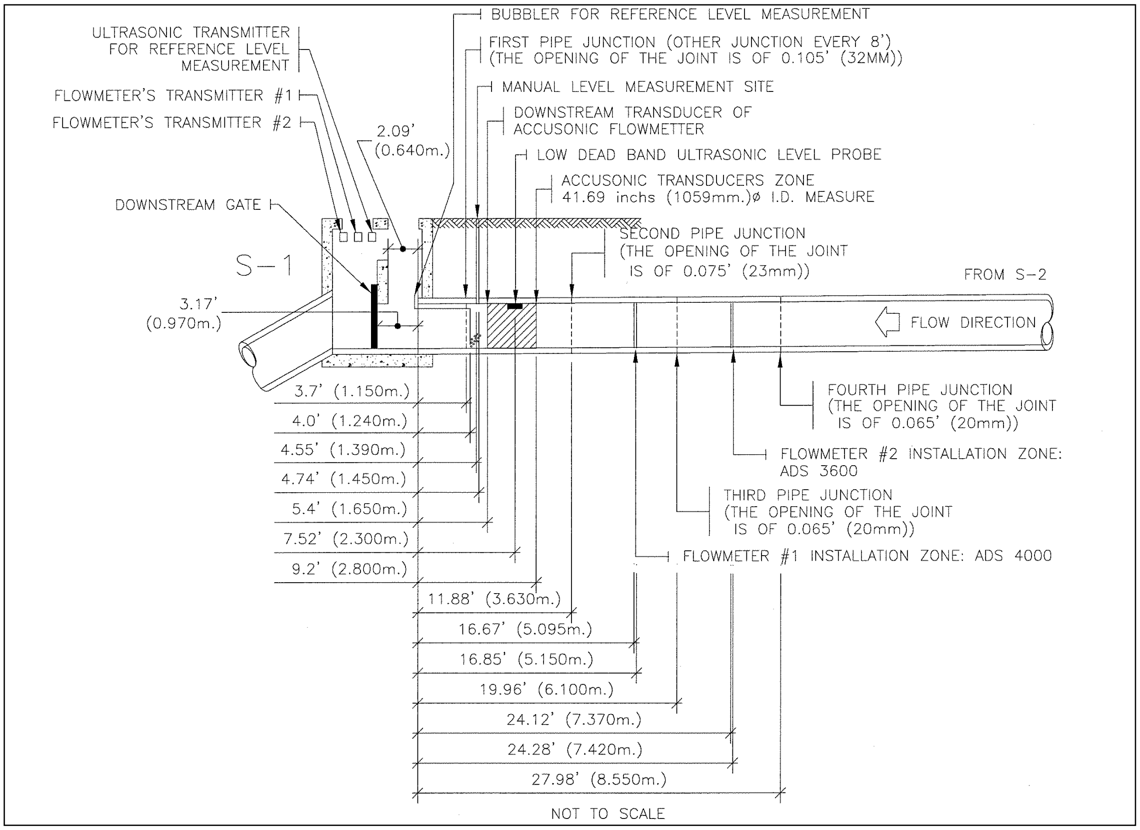


Figure 4-2. Test site profile view of downstream gate site.

There was an electrical room adjacent to the west junction chamber where the transmitters of the reference flow meter and the reference bubbler level meter were located. The transmitter for the reference ultrasonic level meter was hung in manhole S-1. This manhole was also the sampling site for the lithium dilution tests and was the nearest access to the flow meters under test, the reference meters, and the downstream gate.

Construction of the main interceptor pipe was completed around 1991, with the remainder of the site constructed between November 1998 and June 2000. The newest parts of the system are the control gate downstream from manhole S-1 and the ultrasonic level meter at the reference flow meter site.

4.1.2 Pipe Configuration

The normal flow condition in the interceptor pipe was free surface flow. Neither accumulation of solids nor surface foam was observed in the pipe. The flow delay between the test site's upstream and downstream control gates was 12 to 15 minutes. Figure 4-3 shows the profile of the last 13 pipe sections. All sections were 8 ft (2.44 m) long, except the last section, which was 3.7 ft (1.15 m) long. A survey of the invert pipe profile was performed with a 100 ft (30.5 m) long by 0.5 in. (13 mm) diameter water hose and rulers graduated every 0.039 in. (1 mm). This method provided an accuracy of approximately ±0.079 in. (±2 mm). As in all sewers, the slope of every pipe section was slightly different. Four major elements had a hydraulic impact on the test site:

- There was a 2.2 in. (55 mm) bump at the end of the last pipe section due to an excess of concrete at the bottom of manhole S-1. The consequence of this bump, although not the purpose, was that the lowest path of the reference flow meter was always submerged.
- The last pipe section had a negative slope of approximately 1.2 in. (31 mm).
- The coupling of the last two pipe sections was not very good and the last pipe has a negative elevation of approximately 0.55 in. (14 mm).
- The large cross-section of the downstream manhole S-1 and its sluice gate could create slower wastewater velocity and an upstream surge. The impact of these elements was reduced since the velocity increased in the manhole due to the steep slope (10.6 percent) in the downstream pipe.

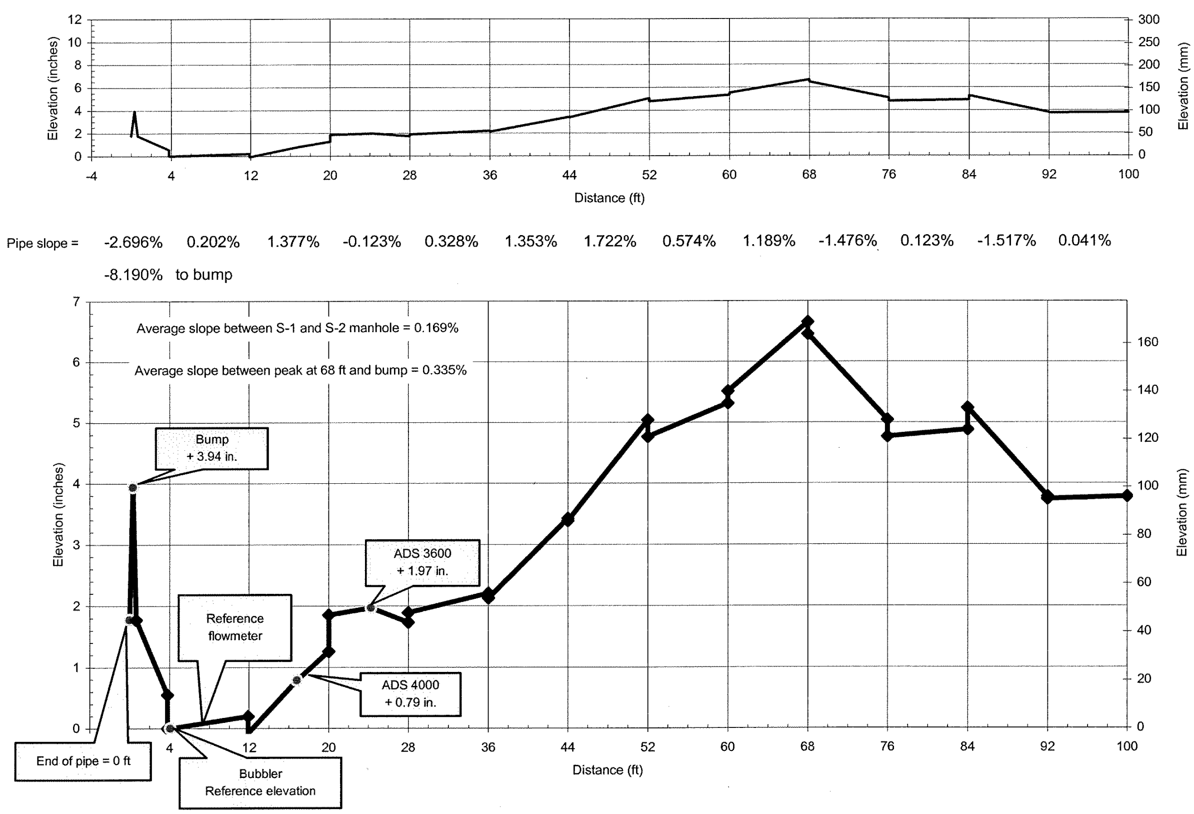


Figure 4-3. Test site pipe invert profile.

The difference in elevation between the invert elevation at the ADS 3600 testing site and at the reference level meter (bubbler) was approximately +1.97 in. (50.0 mm). Since there is a slope of -3.97 in. (-101 mm) between the invert at the bubbler and the bump described earlier, the back flow caused by the bump had a hydraulic impact up to approximately 23 ft (7 m) upstream of the ADS 3600 testing site. For this reason, the hydraulic profile was not exactly the same at the reference meters location and at the ADS 3600 location. The water level was lower and the velocity was higher at the ADS 3600 location than at the reference meters location.

No back flow could occur downstream of the downstream gate, because the maximum level over the overflow weir in the downstream west junction chamber is approximately 20 in. (500 mm) under the invert of manhole S-1. When required during a test, it was possible to create back-flow conditions by closing the test site's downstream gate. The water level could then be raised up to 14 in. (350 mm) over the crown of the pipe at the reference level meter location.

4.1.3 Waves in the Test Pipe

Waves in sewer pipes are common, and result from a variety of different factors (Figure 4.4). Waves are commonly caused by the roughness of the pipe walls, poor coupling of the pipe sections, or surge caused by a change of direction, slope, cross-section or velocity. Because of these waves, the measurement of the water level in sewers is not easy, even for a technician measuring with a ruler. The following were some of the conditions that make level measurements difficult:

- High flows (sometimes present on this test site);
- High energy slopes (sometimes present on this test site);
- Location near a change of direction (not significant on this test site);
- Location near a change of slope (present at some places on this test site);
- When pipe couplings are not very good, resulting in open junctions, steps, uncoupled junctions, etc. (present at some places on this test site).

(a) Open joint. **(b) Closed joint.**

Figure 4-4. Pipe joint conditions in test system.

There were different sizes and kinds of waves on the water surface. Depending on the water level and flow rate, waves have different behaviors. Three kinds of waves were observed at the test site (surface disturbances caused by surges are considered waves):

1. Short, local dynamic waves: Small waves with lengths of 1 to 3 in. (25 to 75 mm) that created small ripples in all directions on the water surface, as on any river or lake. These waves were present everywhere. Their amplitude, approximately 0.5 to 1 in. (13 to 25 mm), is a function of the flow rate and water level (Figure 4-5). They were visual signs of surface turbulence.

2. Short, local standing waves: Small waves with lengths 3 to 6 in. (75 to 150 mm) that stood at a specific location on the water surface, without moving forward or upward. Their amplitude, approximately 1 to 3 in. (25 to 75 mm), was also a function of the flow rate and water level. These waves were rare (two or less per pipe section) and were mostly asymmetric in the pipe (Figure 4-5). They were visual signs of surge. At the test site, the negative slope, the downstream manhole, or the reference flow meter probes could have caused short local standing waves.

3. Long, standing waves: Long waves with lengths of several feet. Their number and amplitude (>2 in. [>50 mm]) were a function of the flow rate, water level and wave length. Most of these waves were symmetric in the pipe.

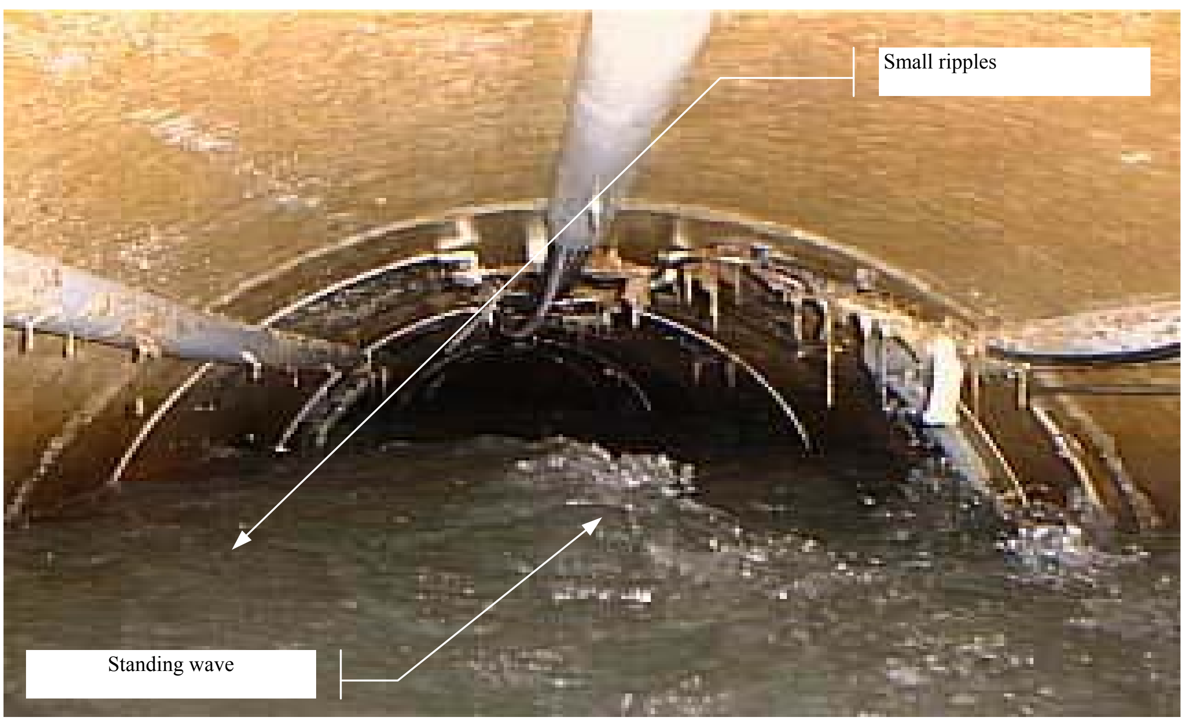


Figure 4-5. Waves in test pipe.

On June 27, 2001 ADS reviewed data recorded during a high-flow trial the previous day and noticed a large and unexpected aberration in the depth-velocity flow relationship in the pipe. Analysis in the field conducted by ADS suggested that a hydraulic jump or large waves were the likely cause of the aberration. Both BPR and NSF were notified of the concern and a request was made to re-run the high-flow trial to verify if large waves were present.

The high-flow trial was re-run and an ADS field person with a camera was suspended over the flow at the access manhole. Figure 4-5 was taken during the high-flow trial and it captures an asymmetrical standing wave in the reference meter section just upstream of the access manhole. Although not visible in Figure 4-5, the photographer reported seeing several similar waves farther upstream.

Area and velocity flow meters are designed to function in sewers with uniform flow conditions such that depth and velocity are constant as flow passes through the metering area. The ADS flow meter measures depth with a downward-looking, narrow beam ultrasonic sensor installed on top of the pipe. Based on this configuration, it was expected that depth measurements were more susceptible to influence by waves. Local wave peaks and troughs would affect the depth measurement by the narrow-beam depth sensor when they occurred immediately below the sensor. Therefore an important consideration in selecting a site in which an area and velocity flow meter is to be installed is to identify a location where the adverse effects of standing waves are minimized or eliminated.

Determining if standing waves were present at the ADS meter location was difficult without visual confirmation of the waves. During high flow conditions, it was extremely difficult to safely access the test site to make a visual determination of the presence of standing waves. Based on the specific characteristics of the test pipe and the photographic documentation of the standing wave, there exists the potential for standing waves under certain flow conditions in the test pipe area.

If there was a standing wave below the flow meter's ultrasonic depth sensor and the flow meter was working properly, the depth readings would be influenced by the presence of the wave. A comparison of the flow meter data with the reference data would show a larger than normal deviation between the flow meter depth readings and the reference depth readings.

Figure 4-6 presents a scatter plot of the velocity deviation (the difference in velocity readings between the test and reference meters) versus depth deviation (the difference in depth readings between the test and reference meters). These observations are for the period June 28 through July 4, though the apparent wave conditions were observed throughout the testing period. Three distinct clusters of observations were apparent. The clustering suggests that for certain flow conditions the difference in velocities are relatively constant (2 ft/sec) while the difference in depth changes up to 5 in. (-3 to -8 in.). This clustering was repeatable throughout the test, which suggests the effect was due to standing waves. The cluster of data points on the right side of the plot appears to be generated when wave peaks influenced the depth measurement, while the cluster of data points on the left side of the plot appears to be generated when wave troughs influenced the depth measurement.

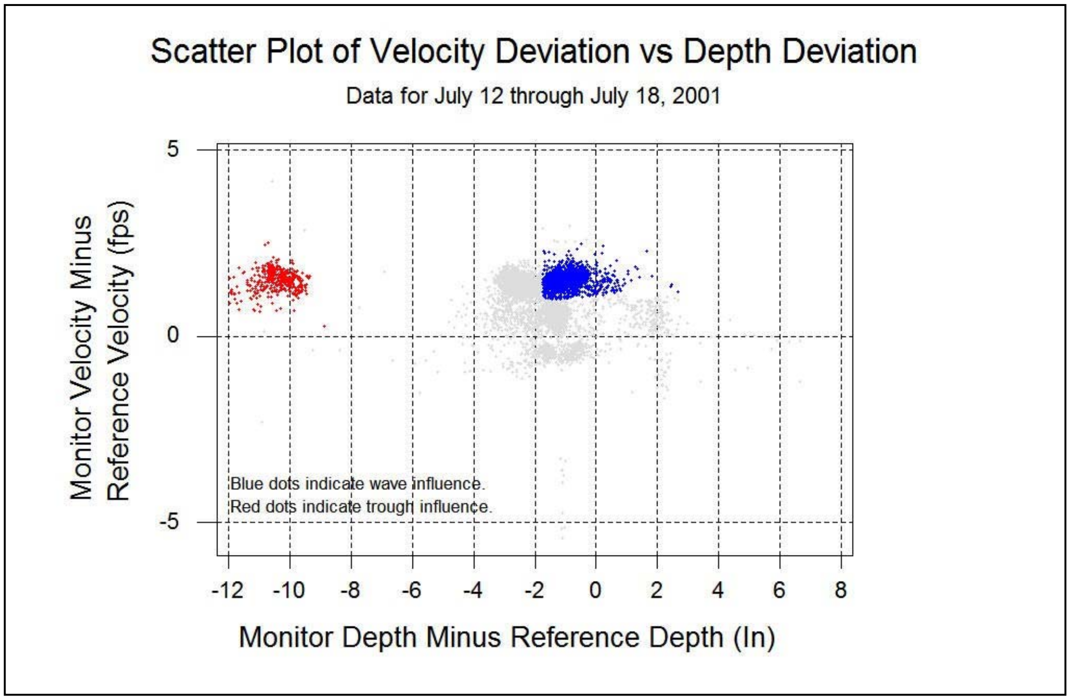


Figure 4-6. Scatter-plot showing possible standing wave and trough influence.

The presence of local wave peaks under the depth sensor would result in incorrectly high measurements and correspondingly high flow rate calculations. Conversely, the presence of a local trough under the depth sensor would result in incorrectly low depth measurements and low flow rate calculations. Figure 4-7 shows that deviations from reference flow rates appear to correlate with the influence of waves.

Consistent with the protocol for this field test, accuracy for each of the several flow conditions is reported as a single value. The reader should be aware that this single value might contain large deviations resulting from waves. Figure 4-8 displays the deviation distribution of data from June 28 to July 4 and the tri-modal nature of the error pattern is apparent. The bars clustered to the right of the center cluster represent data under the influence of wave peaks, while the cluster of bars left of the center cluster represent data under the influence of wave troughs. Together the waves appear to widen the range of deviation. Because of the uncertainty associated with these conditions, ADS recommends against installing flow meters in locations with large standing waves.

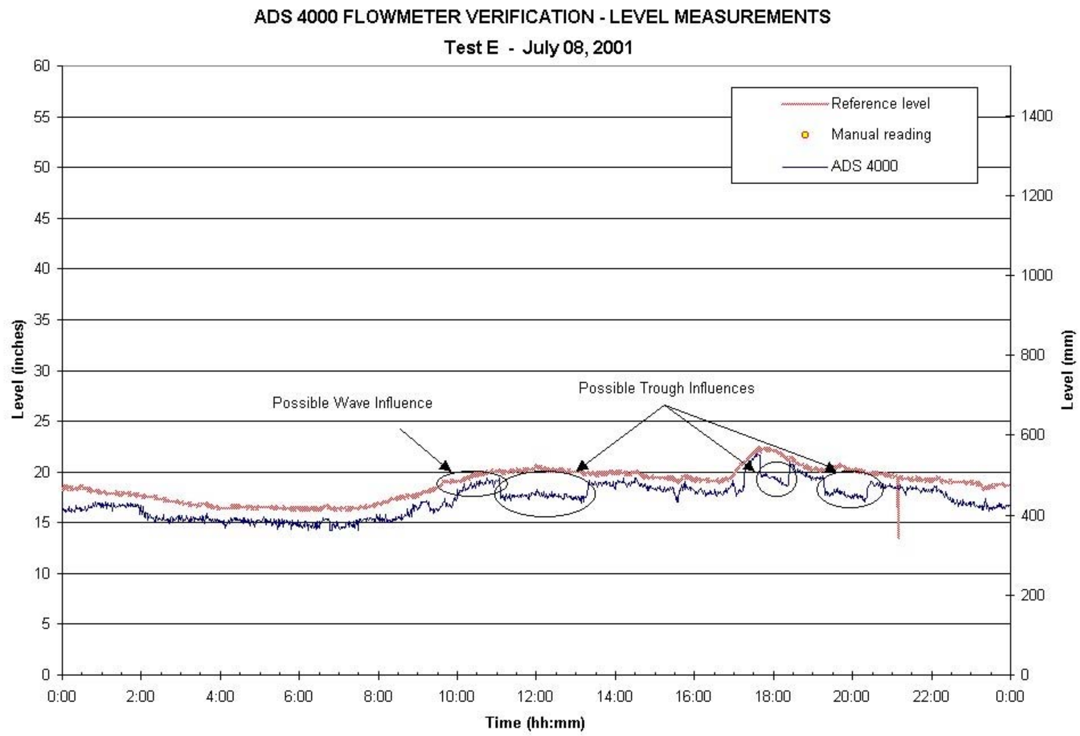


Figure 4-7. Flow graph with possible wave and trough influences shown.

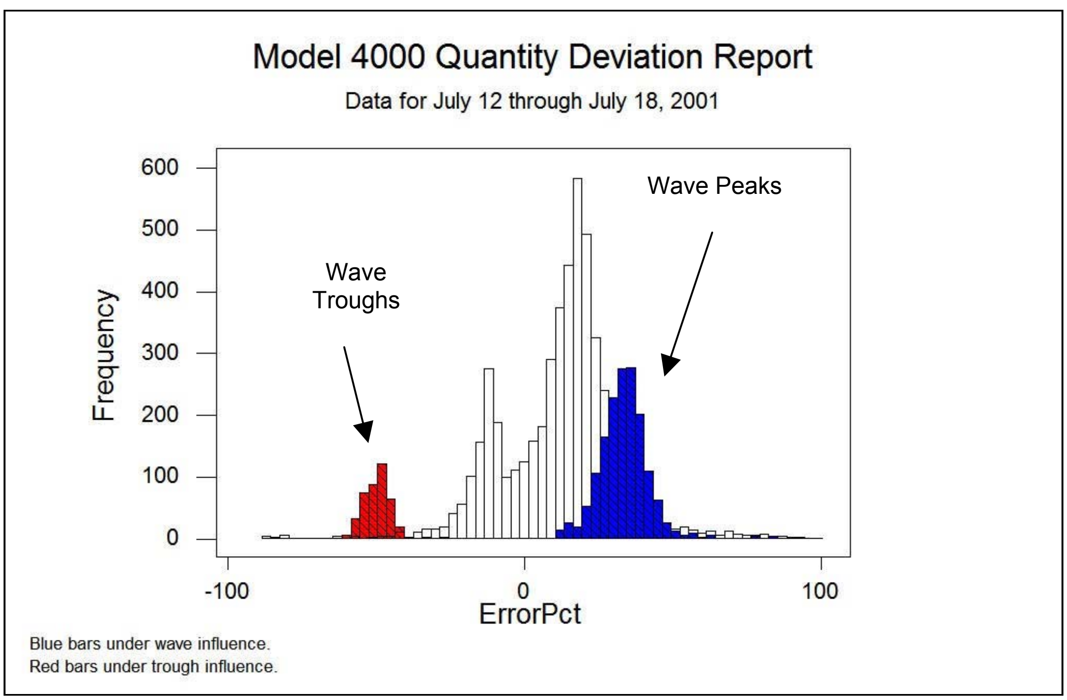


Figure 4-8. Tri-nodal nature of deviation pattern is consistent with presence of waves.

4.2 Description of Test Equipment

4.2.1 Downstream Gate Site

The downstream gate site was the primary site for the verification of the flow meters. The ADS 4000 and the reference meters were installed at this site. This is also where the level of back flow was controlled using the downstream gate, where the diluted tracer samples were collected and the manual level readings taken. Figure 4-9 shows the downstream gate site during a tracer dilution test, while one technician was taking manual level readings and another was collecting diluted samples.

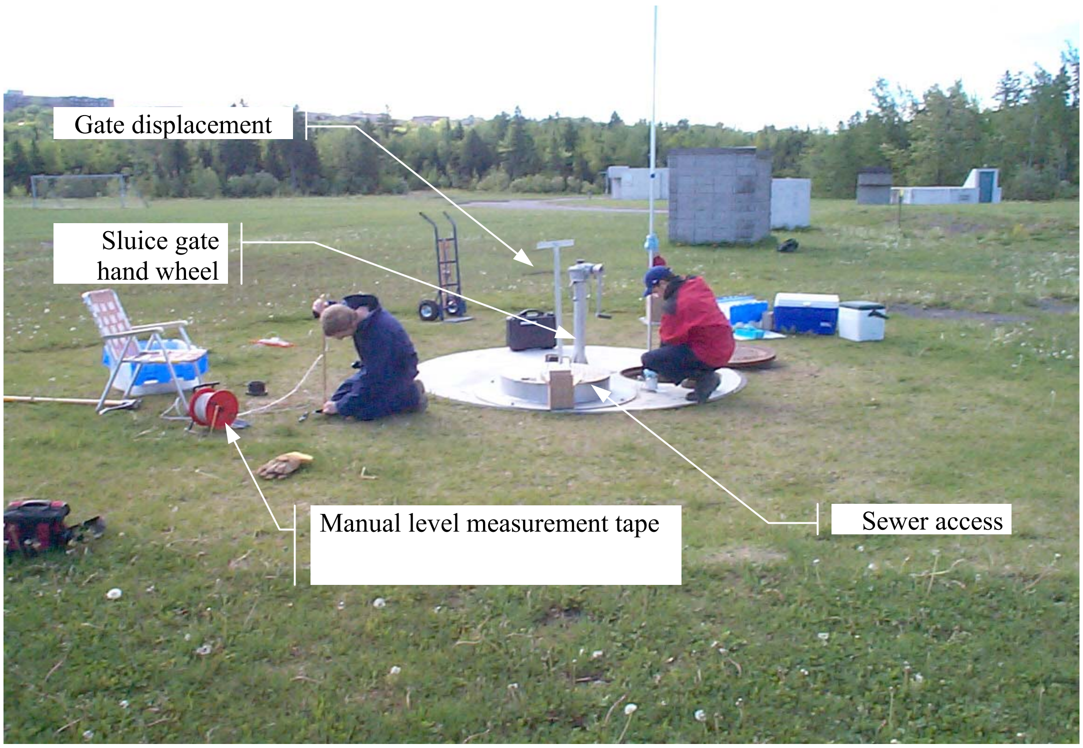


Figure 4-9. General view of the downstream test site.

4.2.1.1 Verified Flow Meter: ADS 4000

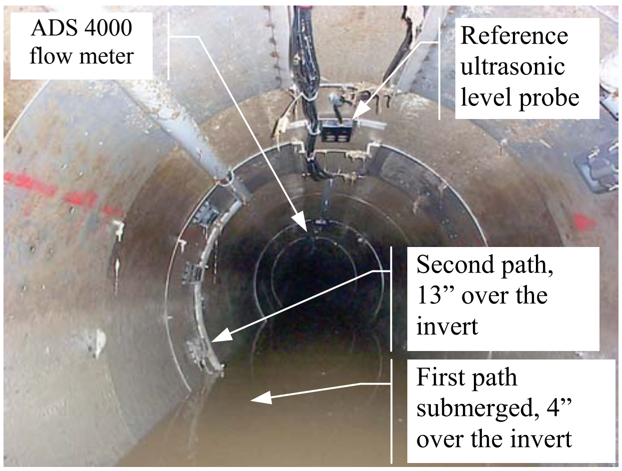
As shown in Figure 4-2, the ADS 4000 flow meter was installed 16.7 ft (5.1 m) upstream of manhole S-1. The flow meter is composed of a transmitter and a pressure level probe, an ultrasonic level probe and a velocity probe, as shown in Figure 4-10. All probes were pre-installed on a stainless steel band, which was installed in the sewer using a bender that extends the diameter of the band to squeeze it on the pipe wall, as shown in Figure 4-11. The transmitter was hung on the ladder in the manhole. The submersible pressure probe was at the bottom of the pipe and the velocity probe was close to it, slightly off-center. Wires for the submerged probes were attached using tie-wraps on the downstream side of the stainless steel band. The probes were small and had a good hydrodynamic profile, causing no discernable disturbance to the flow pattern.

Figure 4-10. ADS 4000 flow meter components.

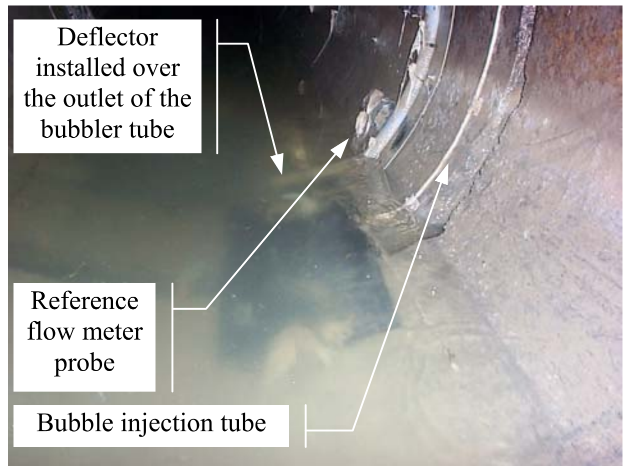
Figure 4-11. ADS 4000 flow meter installed in pipe.

4.2.1.2 Transit-Time Reference Flow Meter

The reference flow meter transducers (probes) were installed in a pipe section from 5.4 ft (1.65 m) up to 9.2 feet (2.80 m) upstream of manhole S-1 (Figure 4-12(a)). The transmitter was located in the electrical room of Station #80A approximately 130 ft (40 m) from manhole S-1. A description of the operating principle for the reference flow meter is provided in Appendix A, along with details of its configuration and installation drawings.



(a) Reference flow meter.



(b) Bubbler installation.

Figure 4-12. Reference flow devices installed in the test pipe.

4.2.1.3 Reference Flow Meter Bubbler

The injection pipe for the bubbler level meter was located 16.1 in. (410 mm) downstream from the reference flow meter transducers described in Section 4.2.1.2. To avoid a venturi effect due to high velocities at the outlet of the injection pipe, a deflector plate was installed at the end of the pipe, as shown in Figure 4-12. This instrument transmitted the water level measurements via the local programmable logic controller (PLC) to the reference flow meter. A periodic, 100 pound per square inch (psi) air purge lasting three seconds was automatically triggered to keep the end of the pipe clear. Specifications for the bubbler system are included in Appendix A.

4.2.1.4 Ultrasonic Reference Level Meter

This meter provided redundancy of the level measurement of the reference bubbler level meter. The meter’s probe was located in the 42 in. pipe, 7.52 ft (2.3 m) upstream of manhole S-1, above all the paths of the reference flow meter. Mounted on the crown of the pipe, the probe had an intrinsic dead band of approximately two in. (50.8 mm), allowing the meter to measure from approximately 0 to 40 in. The transmitter was hung in manhole S-1. Additional information about the meter is provided in Appendix A.

4.2.1.5 Downstream Gate

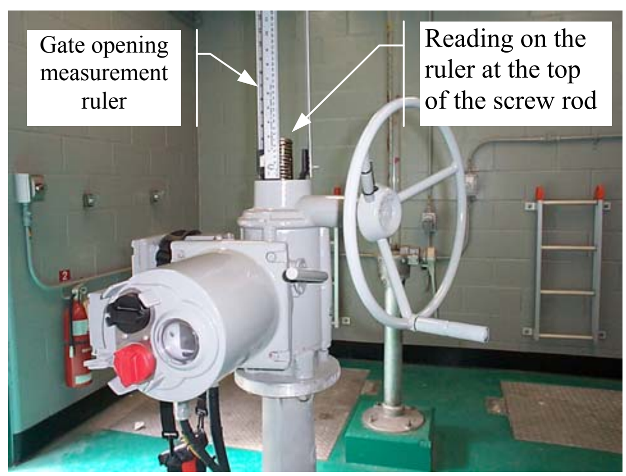
Manhole S-1 is equipped with a manual sluice gate to control the water level in the pipe where the reference flow meter and the ADS 3600 flow meter were installed. The gate could be closed to create back-flow conditions in the upstream pipe, but the pipe would return to free surface flow when the gate was fully opened (Figure 4-2). The manual actuator for the gate permitted vertical movement of one inch (25 mm) for four turns of crankshaft. The vertical displacement of the downstream gate was measured manually using a fixed aluminum ruler graduated every 1/16 in. (2 mm). The ruler was attached vertically to the top of the gate and passed through the roof of the chamber in a standard floor valve box. The displacement was measured using a fixed point on the side of the floor valve box.

4.2.2 Upstream Gate Site

4.2.2.1 Electrical Control Room

The tests were directed from the electrical control room of the upstream gate. The technician at that site logged all information and measurements taken during the test into the computer (Figure 4-13(a). The technician at the upstream gate site was in continuous telephone communication with the technician at the downstream gate and used radio communication with the technician at the injection site during tracer dilution.

(a) Test operator entering data.



(b) Upstream gate actuator.

Figure 4-13. Upstream gate site arrangements.

4.2.2.2 Upstream Gate

The upstream control gate at Station #100 permitted water retention in the Versant-Sud tunnel to control flows during rainfall events. It was used during the tests to simulate of a wide range of flow conditions. When fully closed, only flow from the Craig Collector would remain in the pipe at the flow meter location.

The gate was equipped with an electrical actuator, but most gate movements were done with the hand wheel (Figure 4-13(b)). Flow control was made using a mathematical model of the flow under the gate that used the downstream bubbler level meter reading, the average value of the two upstream ultrasonic level meter readings, and the gate opening reading made directly on a ruler on the gate actuator.

4.3 Description of Reference Methods

Area-velocity flow meters have two measurable components, depth and velocity, which are evaluated independently. Reference measurements were required to evaluate the accuracy of depth and velocity readings from the flow meter under test. The flow rates for the flows under the upstream and downstream gates were also used to verify the accuracy of the reference flow meter. A reference instrument that recorded depth, velocity, or flow in the same interval as the ADS meter was preferred over manual measurements, since the test and reference data sets were then comparable in size.

4.3.1 Reference Depth Measurement

4.3.1.1 Manual Depth Measurement

Manual measurements of the water depth were made using a standard Solinst level meter tape with a stainless steel probe at the location specified in Figure 4-2. The probe was modified to ensure that both contacts touched the water surface at the same time to avoid dragging the tape, which would result in a higher water level reading. A metallic tape, graduated in millimeters, was attached to the plastic tape since plastic bends more easily than metal.

During the challenge tests (tests B, C, and D), three manual measurements were taken at the site of the reference depth meter, roughly every five minutes. The first measurement was taken 30 seconds before the target time, the second 15 seconds before the target time, and the third at the target time. During the passive test (test E), five consecutive manual measurements were made on most weekdays at 60-second intervals.

4.3.1.2 Reference Depth Meters

Two reference instruments were used to record depths. The bubbler on the Accusonic meter was the primary reference meter. The secondary depth meter was the ultrasonic depth meter. Depth readings from the ADS Model 3600 were compared with depth measurements obtained from the Accusonic bubbler. The ultrasonic depth meter and the manual depth readings provided calibration data for the bubbler. Depth measurements from both instruments were logged at one-minute intervals, whereas manual readings were taken approximately every five minutes during challenge tests. The reference depth meters were calibrated prior to initiation of the verification testing to ensure their accuracy.

4.3.2 Reference Velocity Measurement

4.3.2.1 Reference Velocity Computed from Tracer Dilution

Whenever possible, reference velocities were compared to calculated velocities based on the tracer dilution flow rates and on the flow sections computed from the bubbler depth readings.

4.3.2.2 Reference Velocity Meter

The reference flow meter used during verification was a 4-path Accusonic flow meter. Because this instrument did not provide the average velocity on the modbus signal (a serial link to output data), reference velocities were computed from the reference flow rates divided by the flow sections. The flow sections were computed from the bubbler depth readings. To demonstrate their accuracy and the fact that they exhibit no bias, the reference flow meter and depth meter were tested prior to ADS verification testing.

4.3.3 Reference Flow Measurement

Three reference flow measurement methods were used for testing and evaluation of the test data:

1. Tracer dilution was used during two of the three replicas of Test C.
2. A reference flow meter (Accusonic) was used continuously for all tests.
3. The flow rate under the downstream gate was calculated during tests B and D, when back-flow conditions were present, and the flow rate under the upstream gate was calculated during tests C0 and C3 (to verify accuracy of reference meters).

4.3.3.1 Tracer Dilution Method

Tracer dilutions performed during the verification were based on the guidelines presented in the protocol. The major elements were:

- Due to the variation in suspended solids concentrations in combined sewers, lithium chloride was used for the tracer dilution tests.
- For two of the replicates of Test C, tracer dilution was performed to verify the accuracy of the reference meter. The first tracer dilution was done before the first replicate and the second was performed during the third replicate, near the end of the challenge tests.
- No dilution was performed on the day before a non-working day to ensure faster analysis of samples. Samples were brought to the laboratories at the end of the day. Samples from the dilution performed Sunday, July 15, 2001 were put in a cooler with ice packs and brought to the laboratories the following morning.
- Samples were analyzed for lithium content by an accredited laboratory in accordance with Method SM-3111B, from *Standard Methods for the Examination of Water and Wastewater* (American Public Health and Association, 20th Edition, 1998) and MA 200-Method 1.0, from Quebec Environment Ministry–Laboratory Expertise Center.

- To increase the accuracy of the analysis of the concentrated samples, each sample was analyzed five times by the laboratories (five separate dilutions) and the laboratories provided the results for each analysis.

While laboratories may have good in-house accuracy and low variability results (±3 percent for diluted samples and ±2 percent for averaged concentrated samples), deviations of more than ±10 percent between laboratories may occur. This is not a problem as long as the difference for both laboratories remains constant considering the calculation of the tracer dilution flow rate.

4.3.3.1.1 At the Injection Site

A leveled table with the flow injection control system was installed at the injection site. The flow injection control system consisted of two cylinders for flow injection control, two metering pumps and a set of pipes and valves (Figures 4-14 and 4-15). The cylinders were used one at a time, with one in use while the other was refilled and prepared for the next flow injection control. Three quarters of a cylinder was injected over a period of 15 minutes, then the technician switched to the other cylinder. One metering pump was used, with the second being available in case of failure. Specifications of the equipment used in the injection control system are provided in Appendix A.

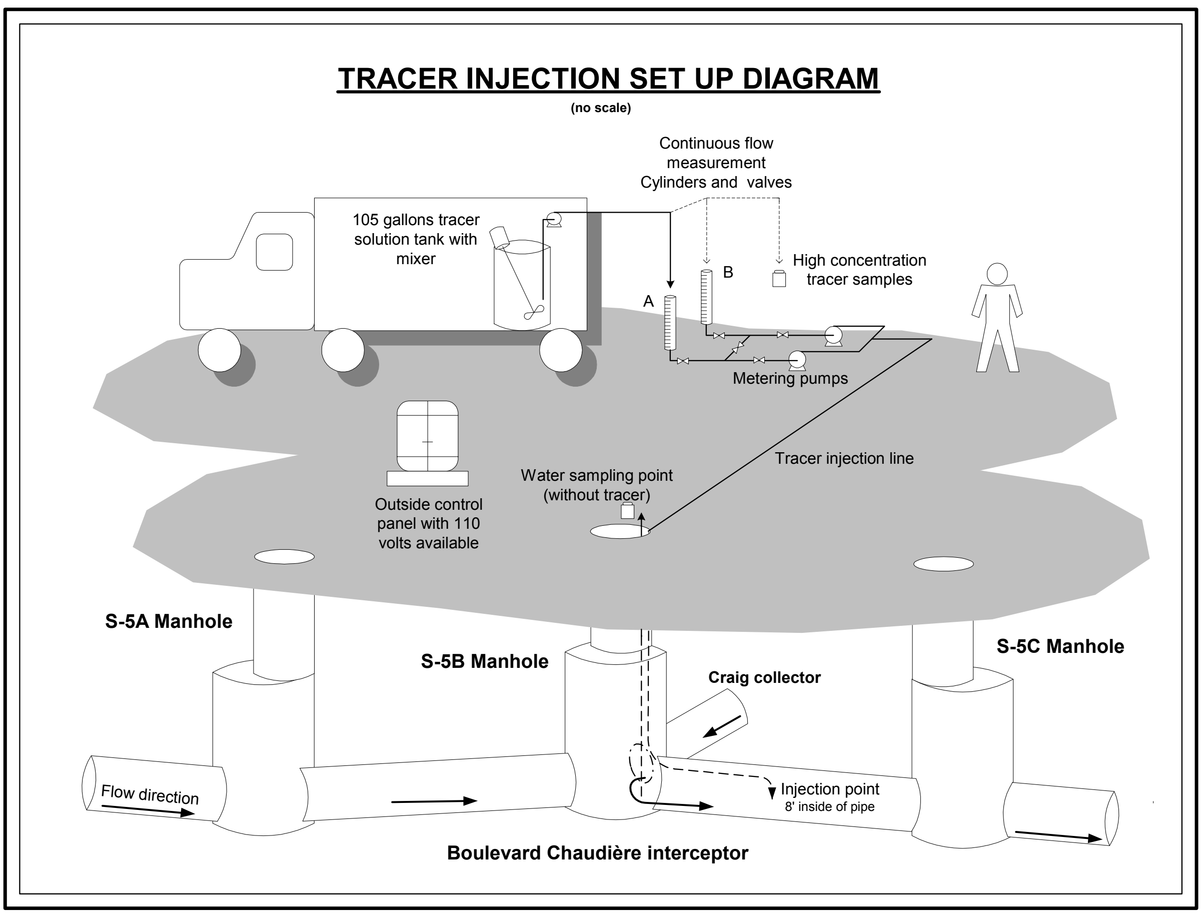


Figure 4-14. Tracer injection diagram.

(a) Lithium injection control system.

(b) Mobile unit.

(c) Injection point inside pipe

Figure 4-15. Lithium injection system.

The tank containing the concentrated lithium solution was located in the injection mobile unit. The solution was prepared a few days before the test and agitated continuously during the test (Figure 4-15(b)). The concentrated lithium was injected eight feet (2.4 m) downstream of manhole S-5B through a 0.5 in. (13 mm) diameter pipe installed along the crown of the pipe (Figure 4-15(c)). The injection pipe had a counter-pressure foot valve to minimize the variation in the injection flow rate under surcharge flow conditions.

Blank samples were collected every 30 minutes, with one additional blank collected at the end of the test. A sample of the concentrated lithium solution was taken every two hours, and at the end of the test. The concentrated samples were collected with the peristaltic pump from the automatic water sampler used to refill the cylinders. Blank samples were taken using a sampling rod (Figure 4-16) on which the bottles were installed. After sampling, preprinted labels were applied to the bottles.

Figure 4-16. Blank sampling site.

4.3.3.1.2 At the Sampling Site

Diluted samples were taken every five minutes at the downstream gate sampling site. Samples were placed into the cooler in a plastic bag to separate them from the blanks and concentrated samples that were collected at the injection site.

4.3.3.2 Reference Flow Meter

Reference flow measurements were logged at one-minute intervals.

4.3.3.2.1 Flow Under the Gate

The flow rates under the upstream and downstream gates were calculated from a standard hydraulic equation and were used as a redundant method to verify the accuracy of the reference meter. The calculation depended on depths upstream and downstream of the gate and the height of the gate opening. The downstream gate was never submerged because of a steep slope, so the depth downstream of the gate was not required for the computation. The following two sections describe particularities of the application for both gates.

4.3.3.2.2 Upstream Gate

The flow rate under the upstream gate was calculated for tests C0 and C3, to provide an estimation of the flow rate measurement at the downstream gate. Graphs showing the flow rate measurements for these tests are included in Appendix H. The calculation depends on the upstream and downstream depths, the gate opening, the flow rate of the Craig Collector, and the transit time from the upstream gate to the downstream gate. An estimation of the flow rate at the downstream gate was computed by delaying the summation of the flow rate at the upstream gate and the flow rate of the Craig Collector by 15 minutes because of the distance between the gates.

The flow rate of the Craig Collector was generally inconsequential and therefore not measured. The dry weather flow rate curve was used as the flow rate control during active tests. Based on the observations made during these last tests, the precision on this flow rate is estimated to ±0.23 MGD (±10 L/sec).

The equation of the flow rate under the upstream gate was calibrated for this site during the installation of the real-time control system of the QUC. The methods used for these measurements are discussed in Section 4.2.1.

4.3.3.2.3 Downstream Gate

The downstream gate was used to create back flow conditions in the section of pipe used for the verification testing. Prior to the testing, preliminary calculations were completed by the TO to estimate the approximate gate positions needed to achieve different back flow conditions in the pipe. Because there is a steep slope downstream of the gate, the calculation depends only on the upstream depth and the gate opening.

4.4 Experimental Procedures

This section describes the tests conducted as part of the flow meter verification. The tests can be classified as either general evaluations or performance evaluations, and are summarized in Table 4-1. The general evaluation of the flow meter included:

- Software evaluation (Test A);
- Ease of operation and maintenance (Test E);
- Potential for debris accumulation (Test E); and
- Data retrieval (Test E).

The performance evaluation for accuracy of depth and velocity measurements and accuracy of the flow calculation included tests:

- Under a controlled range of flow conditions (Tests B, C, and D);
- During simulated rainfall events (Tests C and D); and
- Under short-term continuous operation (Test E).

Test F, operation and maintenance under extended operations, was not performed, as noted in the verification test plan (VTP).

Table 4-1. Flow Meter Verification Test Overview

Test	Objectives	Evaluation General	Evaluation Performance
Flow meter software	User-friendliness, functionality, and flexibility	A	-
Accuracy under dry weather flow with back-flow conditions	Accuracy of depth and velocity measurements and accuracy of the flow calculation under controlled range of flow conditions	-	B
Accuracy under wet weather flow	Accuracy of depth and velocity measurements and accuracy of the flow calculation under controlled range of flow conditions	-	C
Accuracy under wet weather flow with back-flow conditions	Accuracy of depth and velocity measurements and accuracy of the flow calculation under controlled range of flow conditions	-	D
Accuracy under short-term continuous operation	- Ease of operation and maintenance - Potential for debris accumulation - Data retrieval - Accuracy of the flow calculation under controlled range of flow conditions	E	E

4.4.1 General Evaluation (Test A: Flow Meter Software)

The objective of this test was to evaluate the software provided by the flow meter manufacturer for user-friendliness, functionality, innovation, and compatibility.

4.4.1.1 Procedures

This was a qualitative evaluation, parts of which were performed in the field during configuration, calibration and data collection. Other parts were completed in the TO's office after the flow meter was removed from the sewer.

The two flow meter software programs were installed on a PC provided by the testing organization and on a PC provided by ADS. The specifications for the PCs used for this evaluation are included in Table 4-2.

4.4.1.2 Measurements

All of the elements that the vendor had indicated were available at the beginning of the verification were tested. The elements were rated as "possible" or "not possible," according to the ability of the flow meter software to process them. Relevant comments concerning the evaluated elements were noted by the TO.

Table 4-2. Personal Computers Used in Flow Meter Software Evaluation

	Testing Organization PC	ADS PC
Manufacturer	Toshiba	Dell
Processor	Pentium 2-400 MHz	Pentium
Hard Disk	6.4 GB, > 1 GB disk free	> 1 GB disk free
Disk Drives	CD ROM	CD ROM, 3.5 in. floppy
Operating System	Windows 95	Windows 95

4.4.2 Performance Evaluation

In the following procedures, the waiting period to reach steady flow and tracer concentration conditions was established by experimentation.

4.4.2.1 Test B: Accuracy under Dry Weather Flow with Back-Flow Conditions

Test B verified the accuracy of depth and velocity measurements and flow calculations during field-simulated dry weather flow conditions (low flow), and when subjected to back-flow conditions caused by a downstream obstruction. This test was run three times.

4.4.2.1.1 Procedures

For every trial of Test B, the following procedure was applied:

1. Adjust the upstream gate to a position corresponding to a flow of approximately 1.71 MGD (75 L/sec) at the flow meter location.

2. Initiate the reference flow, velocity and depth measurements; manually verify the reference depth measurements.

3. Wait 45 minutes to establish a steady flow at the flow meter location and maintain this steady flow condition for 30 minutes.

4. Close the downstream gate as necessary to establish a flow of approximately 0.86 MGD (37.5 L/sec); hold the flow for about five minutes to accumulate a head of water equal to 18 ± 2 in. at the flow meter location.

5. Open the downstream gate as necessary to establish a steady flow of 1.71 MGD (75 L/sec) and a head of water equal to 18 ± 2 in. at the flow meter location. A steady

flow and depth was established at the flow meter location approximate 60 minutes after step 4; maintain this flow rate for 60 minutes.

6. Close the downstream gate for about 25 minutes to accumulate a head of water equal to 36 ± 4 in. at the flow meter location.

7. When a head of 36 in. is reached, open the downstream gate to establish a steady flow of 1.71 MGD (75 L/sec) and a head of water equal to 36 ± 4 in. at the flow meter location. A steady flow and depth was established at the flow meter location approximately 90 minutes after the beginning of step 6; maintain this flow rate for 60 minutes.

8. Collect data from the ADS 3600 and reference meters.

4.4.2.1.2 Measurements

During the testing under Test B, measurements were taken in the following manner:

1. Log the depth, velocity and flow of the ADS 3600 and the reference meters each minute.

2. Log every gate manipulation, with the corresponding time and the depths upstream and downstream of the gate, for the upstream gate.

3. Log every gate manipulation for the downstream gate, with the corresponding time and depth upstream of the gate.

4. Record noteworthy events and the corresponding times.

5. Take manual depth measurements at five minute intervals for comparison with values recorded by the reference depth meter. Each time measurements are taken, measure the depth three times at 15-second intervals, the third measurement to be taken at the exact time that the data is reported. For example: the first reading at 10:19:30, the second at 10:19:45, and the third at 10:20:00, the mean value of the three readings to be reported at 10:20:00.

4.4.2.2 Test C: Accuracy Under Wet Weather Flow Without Back Flow Conditions

Test C verified the accuracy of depth and velocity measurements and flow calculations during field-simulated wet weather flow conditions (normal and high flow). This test was run three times.

4.4.2.2.1 Procedures

For every trial of Test C, the following procedure was applied:

1. Adjust the upstream gate to a position corresponding to a flow of approximately 1.71 MGD (75 L/sec) at the flow meter location. Start the tracer injection when applicable.

2. Initiate reference flow, velocity, and depth measurements; manually verify reference depth measurements.

3. Wait 45 minutes to establish a steady flow (and tracer concentration when applicable) at the flow meter location and maintain flow (and concentration when applicable) conditions for 30 minutes.

4. Progressively open the upstream gate during a 10-minute period to establish a flow equal to 17.1 MGD (750 L/sec) ± 1.14 MGD (50 L/sec) at the flow meter location. A steady flow (and tracer concentration, when applicable) was established at the flow meter location approximately 45 minutes after beginning this step. Maintain this flow rate for 30 minutes.

5. Close the upstream gate during a five-minute period to establish a flow equal to 8.56 MGD (375 L/sec) ± 1.14 MGD (50 L/sec) at the flow meter location. A steady flow (and tracer concentration, when applicable) was established at the flow meter location approximately 45 minutest after beginning this step. Maintain the flow rate for 30 minutes.

6. Open the upstream gate during a ten-minute period to establish a flow equal to 29.7 MGD (1,300 L/sec) ± 1.71 MGD (75 L/sec) at the flow meter location. A steady flow (and tracer concentration, when applicable) was established at the flow meter location approximately 45 minutes after beginning this step. Maintained the flow rate for 30 minutes.

7. Close the upstream gate during a ten-minute period to establish a flow equal to 8.56 MGD (375 L/sec) ± 1.14 MGD (50 L/sec) at the flow meter location. A steady flow (and tracer concentration, when applicable) was established at the flow meter location approximately 45 minutes after beginning this step. Maintain the flow rate for 30 minutes.

8. Close the upstream gate during a five-minute period to establish a flow of 1.71 MGD (75 L/sec) at the flow meter location. A steady flow (and tracer concentration, when applicable) was established at the flow meter location approximately 45 minutes after beginning this step. Maintain the flow rate for 30 minutes.

9. Stop the tracer injection, when applicable.

10. Collect data from the ADS 3600 and the reference meters.

4.4.2.2.2 Measurements

Measurements made during testing under Test C were taken in the same manner as for Test B. Refer to Section 4.4.2.1.2 for more detail.

4.4.2.3 Test D: Accuracy Under Wet weather flow With Back flow Conditions

Test D verified the accuracy of depth and velocity measurements and flow calculations during simulated wet weather flow (high flow) when subjected to back-flow conditions caused by a downstream obstruction. This test was run three times.

4.4.2.3.1 Procedures

For every trial of Test D, the following procedure was applied:

1. Adjust the upstream gate to a position corresponding to a flow of approximately 1.71 MGD (75 L/sec) at the flow meter location, according to the calibrated upstream gate equation.

2. Initiate reference flow, velocity, and depth measurements; manually verify reference depth measurements.

3. Wait 45 minutes to establish a steady flow at the flow meter location and maintain this steady flow condition for 30 minutes.

4. Open the upstream gate during a five-minute period to establish a flow equal to 8.56 MGD (375 L/sec) ± 1.14 MGD (50 L/sec) at the flow meter location, according to the calibrated upstream gate equation. A steady flow was established at the flow meter location approximately 45 minutes after beginning this step. Maintain the flow rate for 30 minutes.

5. Open the upstream gate to establish a flow of approximately 11.4 MGD (500 L/sec) at the upstream gate to accumulate a head of water equal to 54 ± 4 in. at the flow meter location.

6. Position the downstream gate at 2⅜ in. (60 mm) to establish a head of water equal to 54 ± 4 in. at the flow meter location. When the depth of water is close to 54 ± 4 in., operate the downstream gate to maintain a head of water equal to 54 ± 4 in. at the flow meter location.

7. Three minutes after the beginning of step 5, close the upstream gate as necessary to establish a flow equal to 8.56 MGD (375 L/sec) ± 1.14 MGD (50 L/sec) at the flow meter location, according to the calibrated upstream gate equation. A steady flow and depth was established at the flow meter location approximately 60 minutes after the beginning of step 5. Maintain this flow rate for 30 minutes.

8. Open the upstream gate during a five-minute period to establish a flow equal to 17.1 MGD (750 L/sec) ± 1.14 MGD (50 L/sec) at the flow meter location, while adjusting the downstream gate to maintain a head of water equal to 54 ± 4 in. at the flow meter location. A steady flow and depth was established at the flow meter location approximately 60 minutes after beginning this step. Maintain this flow rate for 30 minutes.

9. Open the upstream gate as necessary during a ten-minute period to establish a flow equal to 29.7 MGD (1,300 L/sec) ± 1.71 MGD (75 L/sec) at the flow meter location, while adjusting the downstream gate to maintain a head of water equal to 54 ± 4 in. at the flow meter location. A steady flow and depth was established at the flow meter location approximately 60 minutes after beginning this step. Maintain the flow and depth for 30 minutes.

10. Maintain the downstream gate position. Progressively close the upstream gate as necessary during a 10-minute period to establish a flow equal to 1.71 MGD (75 L/sec) at the flow meter location, according to the calibrated upstream gate equation. A steady flow was established at the flow meter location approximately 60 minutes after beginning this step. Maintain the flow and depth for 30 minutes.

11. Collect data from the ADS 3600 and the reference meters.

4.4.2.3.2 Measurements

Measurements made during testing under Test D were taken in the same manner as for Test B. Refer to Section 4.4.2.1.2 for more detail.

4.4.2.4 Test E: Accuracy Under Short-Term Continuous Operation

Test E verified the accuracy of depth and velocity measurements and flow calculations over a 21-day period of continuous operation.

4.4.2.4.1 Procedures

1. There was one period following completion of tests B, C, and D, during which flow data were not retrieved during seven consecutive days of data collection.

2. The TO was responsible for the proper operation and maintenance of the flow meter in accordance with the operating instructions. Any intervention required to maintain the flow meter in good operating order was authorized and done by the vendor. The TO recorded the nature and frequency of any operation and maintenance procedures required during a 21-day period of continuous operation.

3. The TO performed the procedures listed in Section 4.4.2.4.2 as well as other specific procedures specified in the ADS 3600 operating manual.

4. The personnel required for operation and maintenance procedures were also classified according to their qualifications as engineer, technician or general laborer.

5. The TO noted whether any specialized tool or equipment was required, and whether the need for such tools or equipment was indicated by the operation and maintenance instructions.

4.4.2.4.2 Measurements

The nature and frequency of operation and maintenance procedures required during a 21-day period of continuous operation were noted by the TO, and are reported in Section 4.5.2.3. Specifically, the TO completed the following measurements:

1. The numbers of hours (rounded to nearest whole hour) for each personnel classification were recorded for any field intervention to maintain the flow meter in operating order, in accordance with the operation manual or the procedures recommended by the flow meter manufacturer.

2. The time, depth, velocity, and flow were recorded by the flow meter under test and the reference meters during all periods of normal operation, including the periods covered under tests B, C, and D.

3. Manual depth measurements were taken at least once a day at the flow meter under test for comparison with values recorded by the verified depth meter. For each measurement time, the depths were measured five times at intervals of 60 seconds. During this visit, the depth and velocity probes were inspected to observe debris accumulation or other problems. The presence of accumulated debris on the probes was noted and documented by photographs.

4. After dismantling, the flow meter and probes were inspected for infiltration, broken, cracked, or scratched components. The extent and nature of the damage was described. Evidence of water infiltration or broken components was noted and documented with photographs.

5. Any unusual event occurring during the test was noted with its corresponding time.

4.5 ADS 4000 Evaluation Results

4.5.1 Software Evaluation

The ADS 4000 flow meter required two different software programs: Fieldscan™ V.3.1, released on March 28, 2001, and Profile V.1.4.1, released on April 6, 2001. ADS provided the TO with a portable computer using a Microsoft Windows 95™ operating system with the two software programs installed. The TO tested the installation and start-up procedures, along with the usual applications of the software as used during the flow meter testing period.

TO personnel received training on the flow meter software at the beginning of the test. This six-hour training, combined with the software user guide, allowed TO personnel to become familiar with the flow meter software and to accomplish the required tasks for the flow meter verification. Some complex operations performed afterward with the flow meter software required the help of the ADS analysts.

Fieldscan™ was used to set the parameters for the on-site installation as well as for the configuration and calibration of the flow meter. It can also collect data from the flow meter and allow real-time viewing of the monitor status and data.

When the Fieldscan™ installation was completed, the Profile software was used to collect data from the monitor, store it in a database, and view, analyze and export it. The Profile software cannot be used to modify set-up parameters on the flow meter. Fieldscan™ must be used to perform these tasks.

Fieldscan™ stores parameters and data in files while Profile uses a Microsoft Access database. Fieldscan™ data and parameters can be imported into the Profile database but not vice-versa. Both programs must be used during normal operation, but since they do not use the same source files, the user has to keep both sources of information updated.

The manufacturer first completed a checklist of available features and the TO verified their availability. A detailed evaluation of the features of both programs is presented in Appendix G.

Both programs were easy to learn, and quick and easy to use. Profile was a powerful analysis tool with a large variety of features. The procedure to collect data was simple and efficient, taking about 1.5 minutes to record data collected at one-minute intervals. A few additional minutes were required to view data on graphs and to make sure that the collection was complete. Considering that this task had to be performed frequently under difficult conditions, the features of Profile were a significant advantage.

The use of a database to store data was also a significant advantage. It allowed users to easily access data from several monitoring points and for any time period. It could also easily export data in ASCII or Microsoft Excel files for other uses. A disadvantage was that two software programs are needed to perform the required operations. The user had to learn both programs and keep both sources of information individually updated, which could become a source of problems.

One software issue was identified during testing. As tests commenced, the TO noted the program implemented in the flow meter would occasionally fail to store data points in its memory. The protocol required the flow meter to electronically collect mean velocity, ultrasonic depth, and pressure depth data, and compute flow rate at one-minute intervals. The ADS flow meter and laptop computer, as supplied and set up during testing, was not capable of retrieving, computing and storing all the data within the one-minute interval; it would respond by not storing any of the data at the particular time interval. The missing data points would typically be spread randomly throughout the dataset, with at most four or five consecutive missing data points.

True zero readings were represented on the graphs generated by the program while missing data were not. Data points around the missing data were simply connected. ADS personnel indicated the program settings could be modified to provide the one-minute readings. The quantity of data points retrieved was sufficient to provide verification of flow meter effectiveness.

The number of missing data points for each test was noted. The minimum number of missing data during a 24-hour period was 119, the maximum was 670 and the mean was 389 out of 1,440 data points. This represents 8 percent, 47 percent, and 27 percent of the daily data collection, respectively.

A complementary test was conducted by the TO on July 24 and 25, 2001 to further investigate the issue. During this test, data was logged at two-minute intervals instead of one-minute intervals for approximately 24 hours. During this test, no data points were missing from the time series. It was hypothesized that the root of the problem was the flow meter processor, and that the program implemented in the flow meter was not able to process and store the volume and frequency of data being provided by the ADS flow meter probes (one pressure probe, four ultrasonic probes and one velocity probe) or to calculate the flow rate.

The Utah Water Research Laboratory (UWRL) conducted laboratory testing with the same ADS flow meter equipment. They collected data at one-minute intervals, but did not have the problem with data collection and storage experienced at the field testing site.

4.5.2 Performance Tests

The performance tests were completed between June 28 and July 24, 2001 according to the procedures outlined in the VTP. Tests were performed on days without precipitation (morning, afternoon or evening), in no particular sequence except that the first and second to last tests were two of the three replicates of Test C, for which dilution tests were done. No data were collected for seven consecutive days (July 17 to 24) as specified in the protocol. The results from tests B, C, and D are summarized in Table 4-3.

Results of all performance tests are presented in graphical form with one-minute data for all instruments (Accusonic, bubbler, ADS 3600). Clocks from all instruments were synchronized and no more than a two-minute difference was observed for the duration of the tests.

Table 4-3. Deviation from Reference Flow—Tests B, C, and D

Flow regime	Average deviation (percent)	Trimmed average deviation (percent)[a]
Test B	-14.5[b]	-0.9
Test C	14.0	14.5
Test D	-0.8	8.3
Test B-D combined	**-0.4**	**3.8**
Simulated dry flow	0.5[b]	9.5
Simulated wet flow	-1.3	-1.0
Combined flows	**-0.4**	**3.8**

[a] The trimmed average deviation removes the deviations greater than 99 percent or less than –99 percent from the mean deviation, and then averages the remaining values. This computation mitigates the skewing caused by large outliers.

[b] The ADS 4000 flow meter read zero velocity during low-flow testing, resulting in a deviation of –100 percent and a skewing of the data.

The hydraulic conditions at the test site created a condition where water levels at the reference site (bubbler) and at the ADS 4000 flow meter were different. These two measuring sites were approximately 12.7 ft (3.88 m) apart, on a theoretical slope of 0.169 percent (elevation difference of 0.26 in., or 6.6 mm). The two pipe sections involved were on slightly different slopes, resulting in a measured elevation difference of 0.79 in. (20 mm). Furthermore, there was a 2.17-in. (55-mm) high concrete bump at the end of the pipe, approximately four feet (1.2 m) downstream from the bubbler, which caused a permanent back flow over both the bubbler and the ADS 4000 sites.

4.5.2.1 Scatter Plots

Two types of scatter plots are presented in this report: a system behavior (velocity versus depth) plot and a flow rate comparison plot. The system behavior scatter plot is shown in Figure 4-17. The figure presents the hydraulic conditions at the ADS 4000 testing site during the three replicas of Test C, when there was no back flow. There are 946 data points on this figure, which includes data from all three replicas: stable (698 data points), ebbing (178), and rising (70). There are 407 missing data points compared to the reference data set. There are fewer data points for the rising water profiles because the transition was more rapid under this condition.

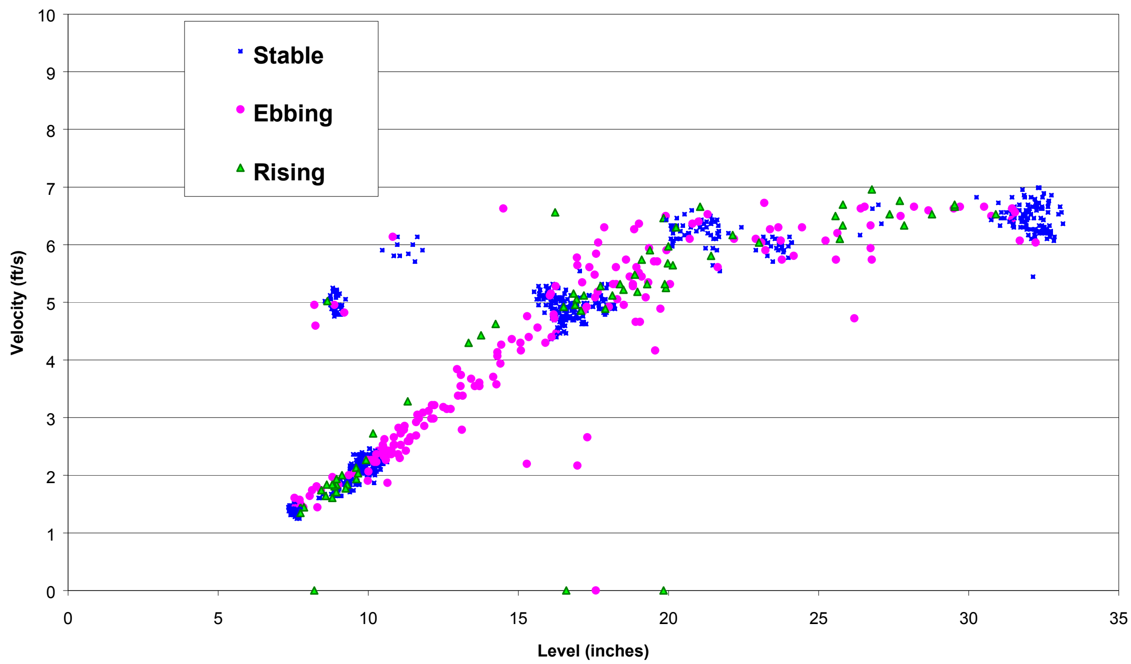


Figure 4-17. ADS 4000 system behavior—Test C.

Figure 4-18 presents the same scatter plot for the reference flow meter. Three observations can be made:

1. The four stable water profiles of Test C (1.71, 8.56, 17.1, and 29.7 MGD; 75, 375, 750, and 1,300 L/sec) are clearly defined;

2. The ebbing water profiles data points are generally over the best-fit curve drawn from stable conditions data points.

3. The rising water profiles data points are generally under the best-fit curve.

These conditions are not observed on Figure 4-17 for the ADS 4000.

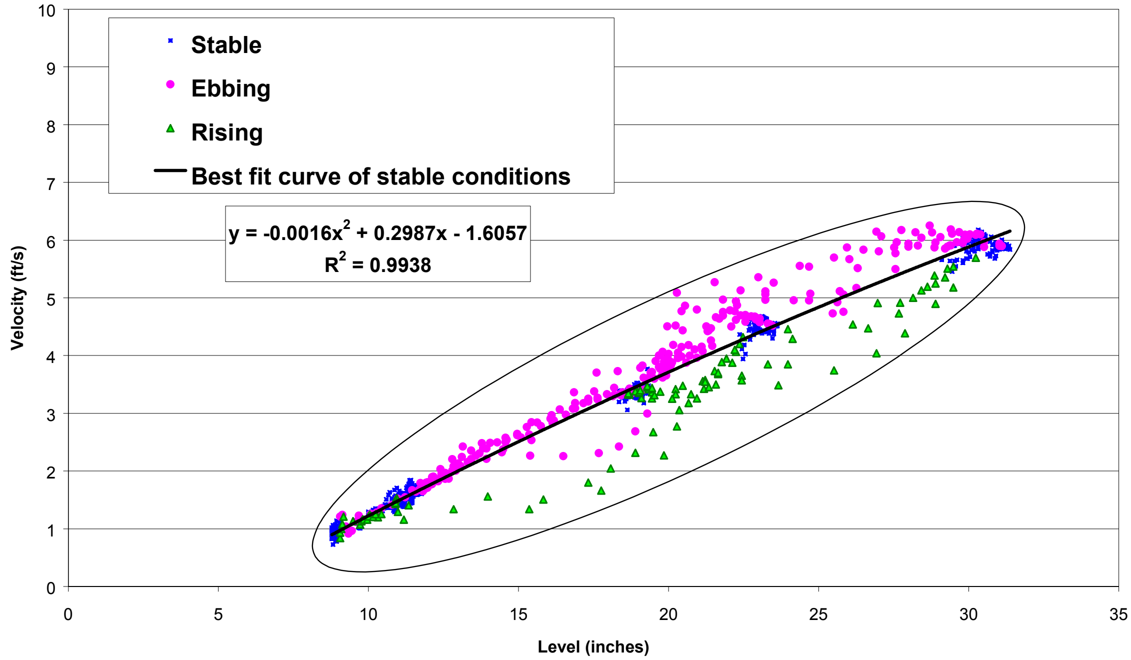


Figure 4-18. Reference meter system behavior.

Figure 4-19 presents a flow rate comparison plot between the ADS 4000 and the reference flow meter for all data from tests B, C, and D. The line on the figure represents a perfect fit between the two flow meters. The reference flow meter recorded 3,924 data points (five true zero readings and five true negative values) during those tests while the ADS 4000 recorded 3,309 data points (615 missing data points). The zero readings and negative values of the reference flow meter were recorded during a transition period during Test B just after the gate was closed and there was some counter-flow.

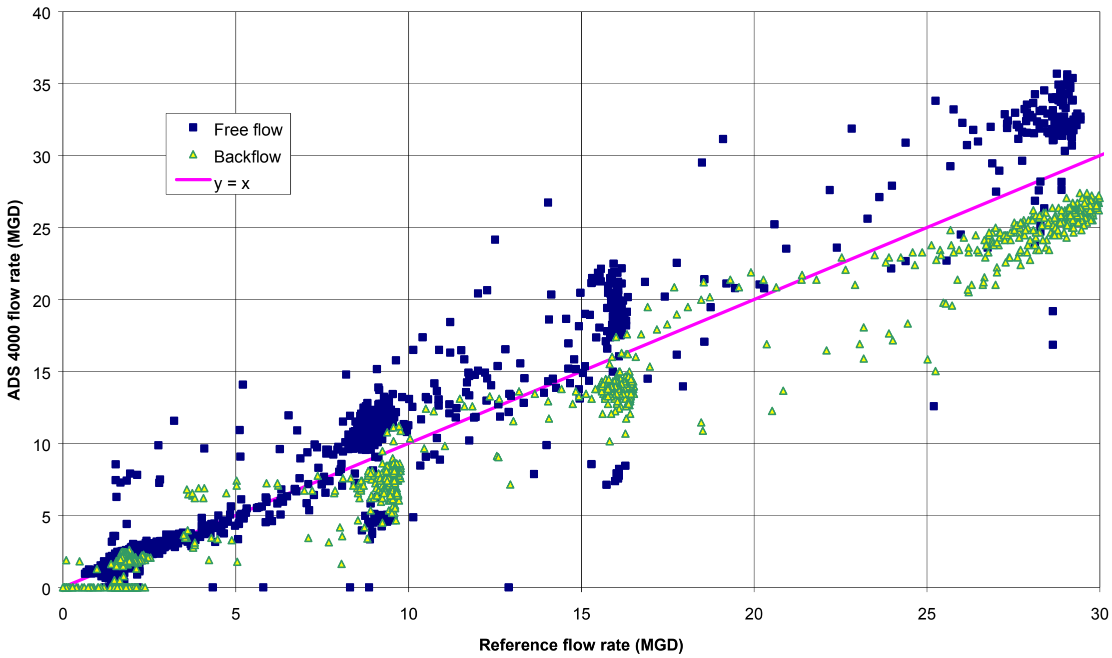


Figure 4-19. ADS 4000 flow vs. reference flow, Tests B, C and D.

Of the 3,309 matching data points between the ADS 4000 and the reference flow meter, the ADS 4000 had 157 true zero readings and no negative readings, while the reference flow meter had one true zero reading and three negative readings. Most (152) of the 157 true zero readings from the ADS 4000, 152 were recorded during Test B (low flow) with 36-inch back flow, while the reference flow meter recorded flow in the range of 1.37 to 2.05 MGD (60 to 90 L/sec). Under these conditions, velocities were in the range of 0.33 ft/sec (0.1 m/sec). The resolution of the velocity meter on the ADS 4000 was 0.0394 ft/sec (0.012 m/sec).

4.5.2.2 Deviation Distribution Plots

Figures 4-20 to 4-25 present the ADS 4000 flow deviation distributions. For all these plots, the +100 percent deviation bar groups all data equal or greater than 100 percent, whereas the –100 percent deviation bar groups all data points equal to zero (the ADS 4000 does not output negative flow rates). The deviation is presented in two-percent increments. Indicated on the figures are the :

- Margin of deviation (±*X* percent) that contains 95 percent of all measurements (i.e. standard ±2σ);
- Percentage of measurements within a margin of deviation of ±20 percent;
- Percentage of measurements within a margin of deviation of ±10 percent;
- Mean deviation of all measurements (influenced by very large positive deviations);

- Mean deviation of measurements within a margin of deviation of ±99 percent (to exclude very large deviations); and
- Median deviation (gives an indication of the spread).

Figure 4-20 presents the deviation distribution for Test B. It is a two-peak bell-shaped curve, with the peaks centered at approximately -2 percent and 24 percent. There is no distinct pattern to explain the two peaks. The high frequency (16.2 percent) of data points with an deviation of -100 percent is due to ADS 4000 flow rates recording zero when the velocity meter recorded velocities of zero (refer to discussion on Test B below). The zero flow data had a large impact on the mean deviation (-14.5 percent) compared to the median deviation (-3.5 percent). Two data points had deviations larger than +100 percent. These two data points were recorded during a transitional flow period, and are considered to be an artifact of testing. The data points were therefore removed from accuracy calculations.

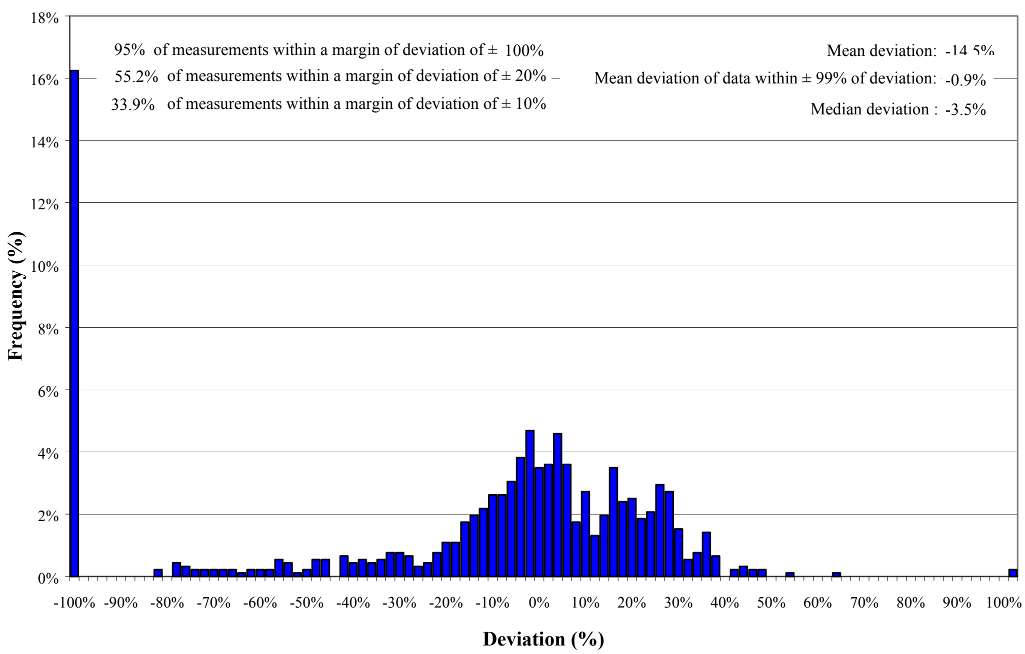


Figure 4-20. Flow deviation distribution—Test B.

Figure 4-21 presents the deviation distribution for Test C. It is a two-peak bell-shaped curve, with peaks centered at approximately 18 percent and -46 percent,. The small peak (deviations from –38 percent to –52 percent) was due to the large oscillations on the depth measurements during stable flow periods. There are seven data points with deviations larger than +100 percent recorded in the transition period between 1.71 to 17.1 MGD (75 to 750 L/sec) when there are large oscillations in velocity measurements. These two data points were recorded during a transitional flow period, and are considered to be an artifact of testing. The data points were therefore removed from accuracy calculations.

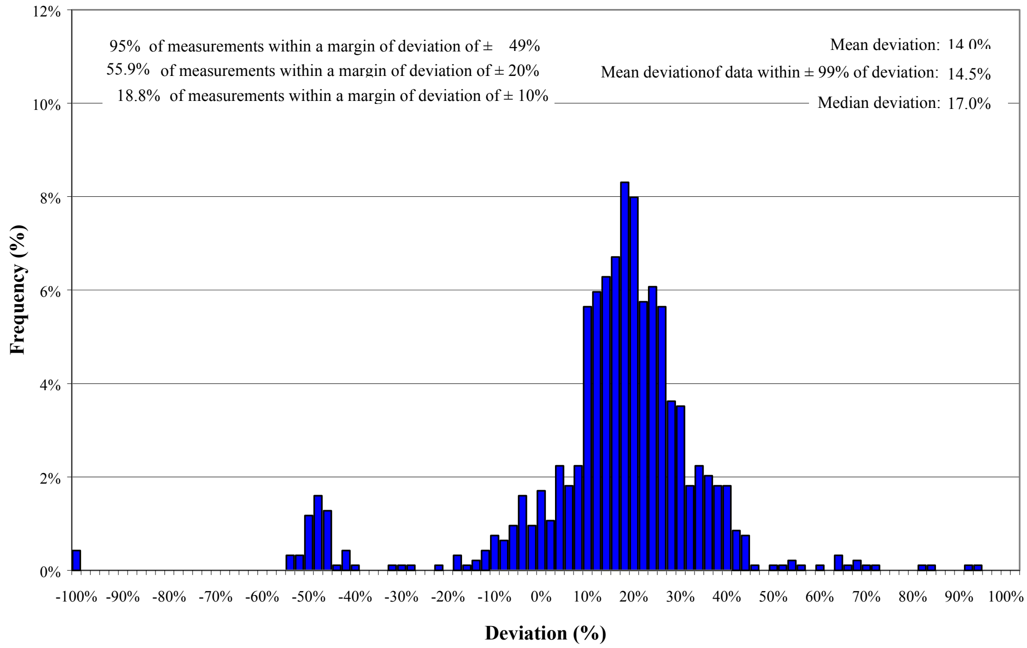


Figure 4-21. Flow deviation distribution—Test C.

Figure 4-22 presents the deviation distribution for Test D. It is roughly a two-peak bell-shaped curve, with peaks centered at approximately -10 percent and 26 percent. The peak centered at approximately 26 percent is due to the ADS 4000 calculating flow rates higher than reference flow rates during dry weather periods (1.71 MGD; 75 L/sec) while the other peak is due to the ADS 4000 calculating flow rates lower than reference flow rates during back flow. There are 11 data points with deviations larger than +100 percent (the largest being +388 percent) that were recorded during the transition period between 1.71 to 8.56 MGD (75 to 375 L/sec) at the beginning of the test. These two data points were recorded during a transitional flow period, and are considered to be an artifact of testing. The data points were therefore removed from accuracy calculations.

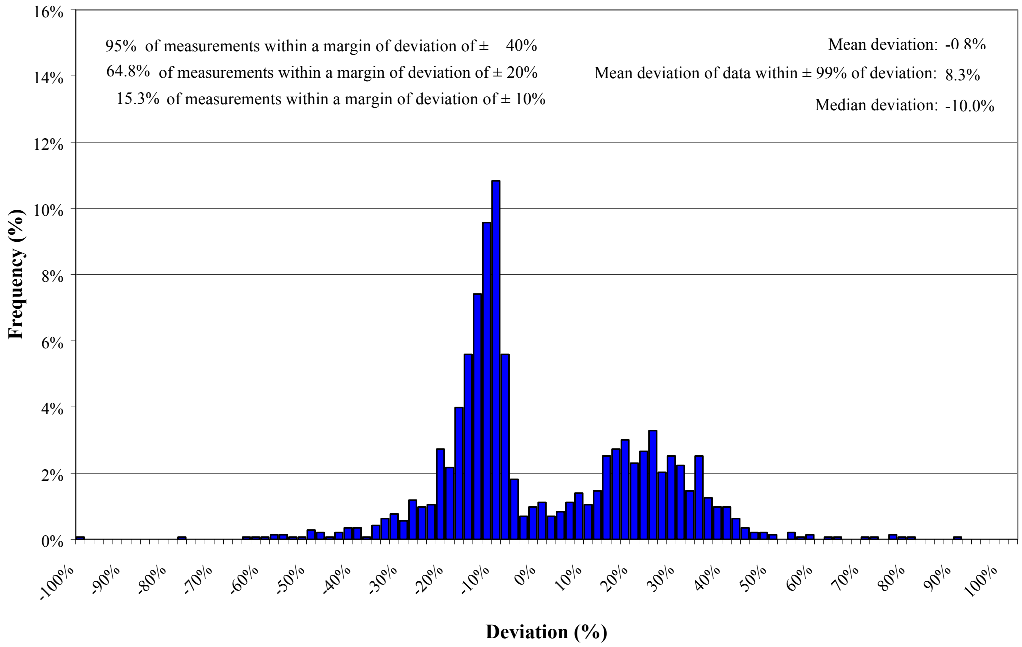


Figure 4-22. Flow deviation distribution—Test D.

Figure 4-23 presents the deviation distribution for tests B, C, and D combined. It is roughly a two-peak bell-shaped curve, with peaks centered at approximately -10 percent and 20 percent. The peak centered at approximately 20 percent is primarily due to over-estimations during low flow testing periods (1.71 MGD; 75 L/sec) and during Test C. The other peak is mainly due to underestimations during back flow during Test D. Data points with an deviation of -100 percent were due to the zero flows during Test B.

Figure 4-24 presents the deviation distribution for dry weather conditions and Figure 4-25 for wet weather conditions. The criterion for wet weather flow for a flow above 1.5 times maximal dry weather flow (1.71 MGD; 75 L/sec) or. 2.57 MGD (112.5 L/sec). Figure 4-11 shows a bell-shaped curve centered on a positive value (18 percent) while the wet weather flow plot is a two-peak bell-shaped curve (centered on -10 percent and 20 percent), showing the influence of Test D and Test C, respectively.

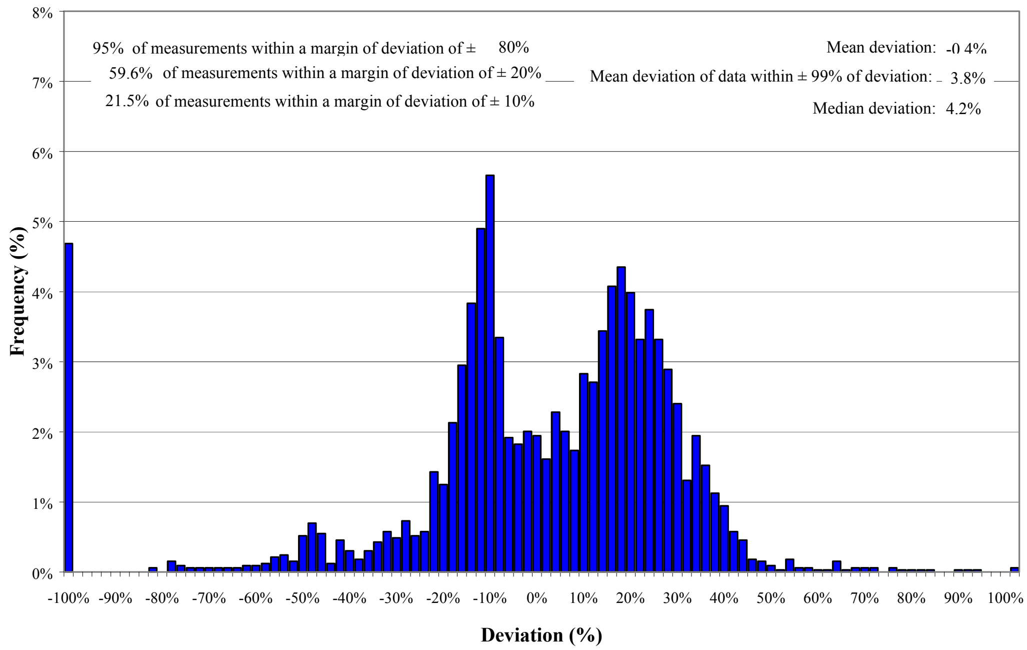


Figure 4-23. Flow deviation distribution—Tests B, C and D.

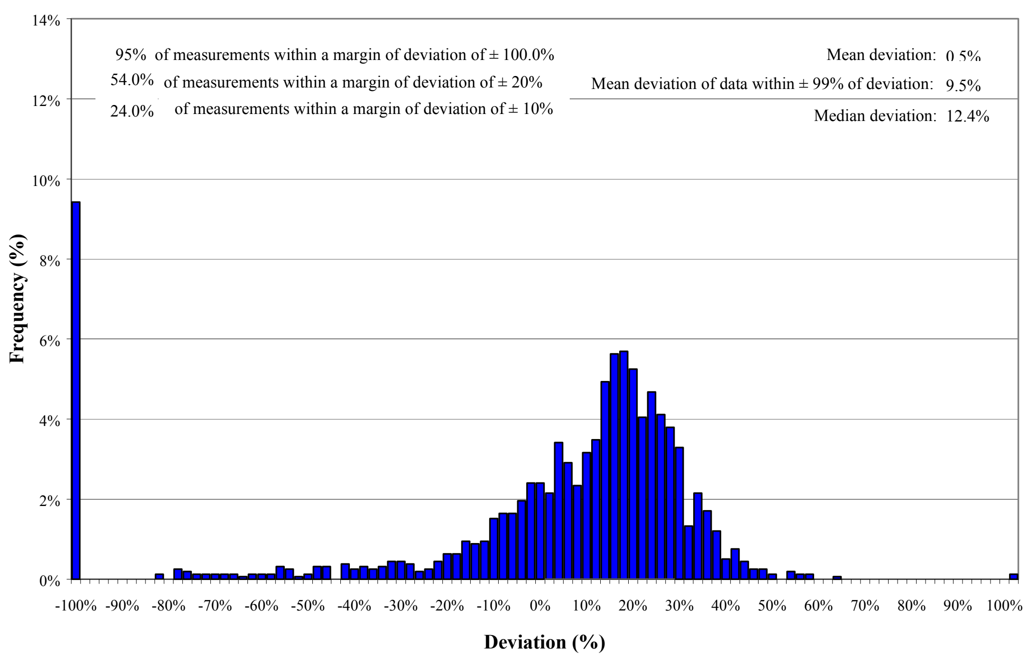


Figure 4-24. Flow deviation distribution—simulated dry weather conditions.

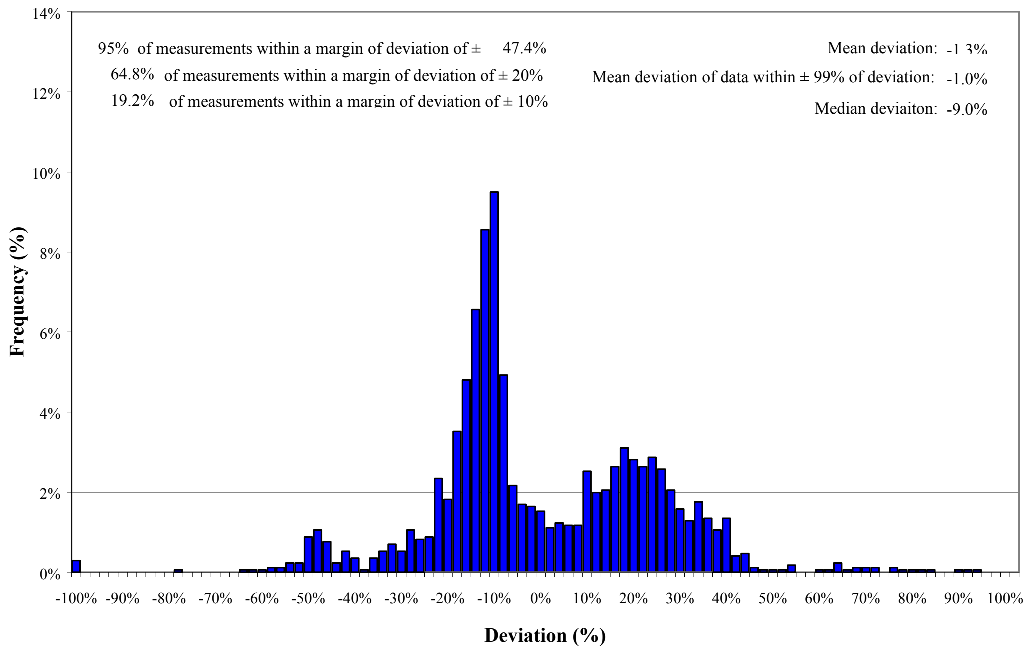


Figure 4-25. Flow deviation distribution—simulated wet weather conditions.

For tests B, C, D, and E, figures are presented in Appendix H in the following order: (1) flow rates; (2) water depths; and (3) velocities. While flow rates measured by the verified flow meter and the reference flow meter can be compared directly, water depths and velocities cannot, because the flow meters were not installed at the same location in the pipe. Since the pipe profile was known, it was possible to have a good appreciation of the quality of the water depth readings. It was much more difficult to evaluate the velocity readings on their own.

4.5.2.2.1 Test B

After some flushing of the sewer line, this test was conducted at maximal dry weather flow (1.71 MGD; 75 L/sec) with three consecutive hydraulic conditions:

1. no back flow;
2. with a back flow of 18 in. (457 mm); and
3. with a back flow of 36 in. (914 mm).

Figures H-1, through H-3 (Appendix H) present flow rates measured by the ADS 4000 and by the reference flow meter for each replica of Test B. Flow rates measured by both meters were close except during a 36-inch back flow condition for all replicas. During replicas B2 and B3, the ADS 4000 sporadically recorded velocities of zero, and thus calculated flow rates of zero. Table 4-4 gives an appreciation of the deviation between the flow rates (reference/ADS 4000) for samples of data points taken during stable periods (delimited by the indicated start and end times) for each replica and for the three hydraulic conditions of this test. Also shown in this table are the average reference flow rates, the standard deviations of the flow rate differences and the percentage these differences represent in comparison with the reference flow rates. Without back flow, flow rates are overestimated by 11 to 12 percent for replicas B1 and B2 and by 23 percent for replica B3. Under the 18-inch (457 mm) back flow, flow rates were within 5 to 6 percent for replicas B1 and B3, while they were underestimated by an mean of 31 percent for replica B2. Under the 36-inch (914 mm) back flow, flow rates were overestimated by an mean of 25 percent for replica B1.

Table 4-4. Flow Rate Comparison of Data Point Samples for the Three Replicas of Test B

Hydraulic Condition		Replica			Average (L/sec)
		B1	B2	B3	
Flow rate of 75 L/sec No back flow	Start time	9:40	9:40	19:40	
	End time	10:15	10:15	20:15	
	Mean reference flow rate (L/sec)	79.6	64.9	71.1	71.9
	Mean difference (L/sec)	-8.6	-8.1	-16.1	-10.9
	Standard deviation of difference	4.8	4.8	5.5	
	Difference/reference (percent)	-11	-12	-23	
Flow rate of 75 L/sec Back flow of 18 in.	Start time	10:30	10:30	20:30	
	End time	12:15	12:15	22:15	
	Mean reference flow rate (L/sec)	74.0	68.1	89.1	77.1
	Mean difference (L/sec)	4.6	21.4	4.7	10.2
	Standard deviation of difference	6.0	10.9	9.5	
	Difference/reference (percent)	6	31	5	
Flow rate of 75 L/sec Back flow of 36 in.	Start time	12:45	12:45	22:45	
	End time	14:45	14:45	00:45	
	Mean reference flow rate (L/sec)	78.2	77.7	83.6	79.9
	Mean difference (L/sec)	-19.5	50.1	35.0	21.9
	Standard deviation of difference	6.3	37.7	33.8	
	Difference/reference (percent)	-25	64	42	

Figures H-4 through H-6 present water depths measured by the ADS 4000 and by the reference depth meter (bubbler) for each replica of Test B. Considering the profile of the test site, a 0.79-inch (20.0-mm) difference in water depth was expected between the two sites under back-flow conditions, with the ADS 4000 water depths being lower. The ADS 4000 water depth readings are always lower with an average 1.04 in. (26.4 mm) (see Table C.4). Table 4-5 gives an appreciation of the difference between the two water depth readings (reference/ADS 4000) for data points collected during stable periods (delimited by the indicated start and end times) for each replica and for the three hydraulic conditions of this test. Also shown in this table are the average reference water depths and the standard deviations of the water depth differences. The differences in water depth vary between 1.02 to 1.37 in. (25.8 to 34.9 mm) under back-flow conditions. Since there is very low disturbance due to velocity under these conditions, these values should match the difference in slope, as expected.

Table 4-5. Water Level Comparison of Data Point Samples for Three Replicas of Test B

Hydraulic Condition		Replica			Average (mm)
		B1	B2	B3	
	Start time	9:40	9:40	19:40	
Flow rate of 75	End time	10:15	10:15	20:15	
L/sec	Mean reference level (mm)	273.1	259.6	267.5	266.7
No back flow	Mean difference (mm)	34.3	34.9	31.7	33.6
	Standard deviation of difference	1.6	2.1	2.7	
	Start time	10:30	10:30	20:30	
Flow rate of 75	End time	12:15	12:15	22:15	
L/sec	Mean reference level (mm)	445.4	464.2	513.5	474.4
Back flow of 18 in.	Mean difference (mm)	34.9	28.3	29.6	30.9
	Standard deviation of difference	3.5	4.0	2.3	
	Start time	12:45	12:45	22:45	
Flow rate of 75	End time	14:45	14:45	00:45	
L/sec	Mean reference level (mm)	908.2	926.5	919.9	918.2
Back flow of 36 in.	Mean difference (mm)	26.9	25.8	25.9	26.2
	Standard deviation of difference	2.2	2.2	2.2	

Figures H-7 through H-9 present velocities measured by the ADS 4000 and by the reference flow meter for each replica of Test B. Considering the difference in water depth, velocities measured by the ADS 4000 were expected to be higher than those measured by the reference meter. This was not the case for most of replica B2. Under the 36-inch (914-mm) back flow, reference velocities fell under 0.49 ft/sec (0.15 m/sec) and the ADS 4000 sporadically recorded zero velocities for replicas B2 and B3, although the velocity meter had a resolution of 0.0394 ft/sec (0.012 m/sec). The ADS 4000 velocity meter signal had more noise than the reference velocity meter.

4.5.2.2.2 Test C

After some flushing of the sewer line, this test was conducted at six consecutive flow rates with no back flow:

- 1.71 MGD (75 L/sec);
- up to 17.1 MGD (750 L/sec);
- down to 8.56 MGD (375 L/sec);
- up to 29.7 MGD (1,300 L/sec);
- back down to 8.56 MGD (375 L/sec); and
- back to 1.71 MGD (75 L/sec).

Figures H-10 through H-12 present flow rates measured by the ADS 4000 and by the reference flow meter for each replica of Test C. Flow rates were generally overestimated. There were large oscillations during the 17.1-MGD (750-L/sec) and second 8.56-MGD (375-L/sec) stable periods of replicas C2 and C3 and during the first 8.56-MGD (375 L/sec) stable period of replica C3 due to large oscillations on the depth measurements. The ADS 4000 recorded velocities of zero during the transition between 1.71 MGD (75 L/sec) and 17.1 MGD (750 L/sec) during all three replicas, generating calculated flow rates of zero. Table 4-6 gives an appreciation of the difference between the flow rates (reference versus ADS 4000) for samples of data points taken during stable periods (delimited by the indicated start and end times) for each replica and for the six hydraulic conditions of this test. Also shown in this table are the mean reference flow rates, the standard deviations of the flow rate differences and the percentage these differences represent in comparison with the reference flow rates. Both sets of maximal dry weather flow (1.71 MGD; 75 L/sec) data points are overestimated by roughly 18 percent, which is also the case at 29.7 MGD (1,300 L/sec). At 8.56 and 17.1 MGD (375 and 750 L/sec), the results are largely affected by the oscillations.

Figures H-13 through H-15 present water depths measured by the ADS 4000 and by the reference depth meter (bubbler) for each replica of Test C. Due to the profile of the test site, the ADS 4000 water depths are expected to always be lower than the reference, which they are, except at the highest flow rate (29.7 MGD; 1,300 L/sec). Table 4-7 gives an appreciation of the difference between the two water depth readings (reference versus ADS 4000) for samples of data points taken during stable periods (delimited by the indicated start and end times) for each replica and for the three hydraulic conditions of this test. Also shown in this table are the average reference water depths and the standard deviations of the water depth differences.

Figures H-16 through H-18 present velocities measured by the ADS 4000 and by the reference flow meter for each replica of Test C. Velocities measured by the ADS 4000 are higher than those measured by the reference meter as expected. Reference velocities are mostly in the range of 0.98 to 5.91 ft/sec (0.3 to 1.8 m/sec). Excluding data points at 1.71 MGD (75 L/sec), the span of reference velocities is greater (3.28 to 5.91 ft/sec; 1.0 to 1.8 m/sec) than for the ADS 4000 (4.59 to 6.56 ft/sec; 1.4 to 2.0 m/sec). The signal of the ADS 4000 velocity meter has more noise than the reference meter.

Table 4-6. Flow Rate Comparison of Data Point Samples for Three Replicas of Test C

Hydraulic Condition		Replica C1	Replica C2	Replica C3	Average (L/sec)
Flow rate of 75 L/sec	Start time	8:40	15:40	7:40	
	End time	9:30	16:30	8:30	
	Mean reference flow rate (L/sec)	69.9	82.8	41.4	64.7
	Mean difference (L/sec)	-11.1	-15.2	-6.5	-11.0
	Standard deviation of difference	4.8	5.0	4.9	
	Difference/reference (percent)	-16	-18	-16	
Flow rate of 750 L/sec	Start time	9:45	16:45	8:45	
	End time	10:30	17:30	9:30	
	Mean reference flow rate (L/sec)	700.0	704.7	687.6	697.4
	Mean difference (L/sec)	-178.3	-100.3	-256.4	-178.4
	Standard deviation of difference	17.9	16.0	20.9	
	Difference/reference (percent)	-25	-14	-37	
Flow rate of 375 L/sec	Start time	10:45	17:45	9:45	
	End time	11:45	18:45	10:45	
	Mean reference flow rate (L/sec)	395.9	404.8	411.2	404.0
	Mean difference (L/sec)	-105.9	-86.6	41.6	-50.3
	Standard deviation of difference	23.8	15.2	172.5	
	Difference/reference (percent)	-27	-21	10	
Flow rate of 1300 L/sec	Start time	12:00	19:00	11:00	
	End time	13:00	20:00	12:00	
	Mean reference flow rate (L/sec)	1224.6	1213.3	1213.9	1217.3
	Mean difference (L/sec)	-224.9	-144.5	-164.9	-178.1
	Standard deviation of difference	36.4	32.0	40.5	
	Difference/reference (percent)	-18	-12	-14	
Flow rate of 375 L/sec	Start time	13:30	20:30	12:30	
	End time	14:30	21:30	13:30	
	Mean reference flow rate (L/sec)	379.9	401.0	389.1	390.0
	Mean difference (L/sec)	-102.2	23.2	-53.1	-44.0
	Standard deviation of difference	20.9	153.4	24.7	
	Difference/reference (percent)	-27	6	-14	
Flow rate of 75 L/sec	Start time	15:00	22:00	14:00	
	End time	14:45	22:45	14:45	
	Mean reference flow rate (L/sec)	101.7	88.9	91.3	94.0
	Mean difference (L/sec)	-15.8	-15.8	-18.0	-16.5
	Standard deviation of difference	8.1	8.6	7.1	
	Difference/reference (percent)	-16	-18	-20	

Table 4-7. Water Level Comparison of Data Point Samples for Three Replicas of Test C

Hydraulic Condition		Replica			Average (mm)
		C1	C2	C3	
Flow rate of 75 L/sec	Start time	8:40	15:40	7:40	
	End time	9:30	16:30	8:30	
	Mean reference level (mm)	262.2	279.5	228.5	256.8
	Mean difference (mm)	28.8	33.2	35.3	32.5
	Standard deviation of difference	1.7	2.6	2.6	
Flow rate of 750 L/sec	Start time	9:45	16:45	8:45	
	End time	10:30	17:30	9:30	
	Mean reference level (mm)	582.7	585.5	591.3	586.5
	Mean difference (mm)	38.8	70.5	-9.9	33.1
	Standard deviation of difference	6.4	6.0	4.9	
Flow rate of 375 L/sec	Start time	10:45	17:45	9:45	
	End time	11:45	18:45	10:45	
	Mean reference level (mm)	475.2	480.4	485.2	480.3
	Mean difference (mm)	46.9	73.8	257.4	126.1
	Standard deviation of difference	9.6	3.7	3.2	
Flow rate of 1,300 L/sec	Start time	12:00	19:00	11:00	
	End time	13:00	20:00	12:00	
	Mean reference level (mm)	778.6	761.8	760.1	766.8
	Mean difference (mm)	-30.8	-52.0	-40.9	-41.2
	Standard deviation of difference	7.8	6.7	9.1	
Flow rate of 375 L/sec	Start time	13:30	20:30	12:30	
	End time	14:30	21:30	13:30	
	Mean reference level (mm)	468.0	481.5	476.0	475.1
	Mean difference (mm)	48.9	168.5	61.8	93.1
	Standard deviation of difference	9.2	100.5	6.4	
Flow rate of 75 L/sec	Start time	15:00	22:00	14:00	
	End time	15:45	22:45	14:45	
	Mean reference level (mm)	291.1	285.6	288.9	288.5
	Mean difference (mm)	28.3	36.3	35.5	33.4
	Standard deviation of difference	2.0	2.7	2.6	

4.5.2.2.3 Test D

Test D was completed with varying flow rates and back flow conditions, as described in Section 4.4.2.3. In summary, the six hydraulic conditions used during the test included:

- 1.71 MGD (75 L/sec) with no back flow;
- 8.56 MGD (375 L/sec) with no back flow;
- 8.56 MGD (375 L/sec) with a back flow of 54 in;
- 17.1 MGD (750 L/sec) with a back flow of 54 in;
- 29.7 MGD (1,300 L/sec) with a back flow of 54 in; and
- 1.71 MGD (75 L/sec) with no back flow.

Figures H-19 through H-21 present flow rates measured by the ADS 4000 and by the reference flow meter for each replica of Test D. Flow rates were overestimated under conditions without back flow and underestimated under back-flow conditions. There was some instability associated with the closing of the gate to create the back flow. Table 4-8 gives an appreciation of the difference between the flow rates (reference/ADS 4000) for samples of data points taken during stable periods (delimited by the indicated start and end times) for each replica and for the six hydraulic conditions of this test. Also shown in this table are the mean reference flow rates, the standard deviations of the flow rate differences and the percentage these differences represent in comparison with the reference flow rates. Differences in flow rates at maximal dry weather flow were higher than in Test C (21 percent compared to 17 percent). Under back-flow conditions, flow rates were underestimated by 20 percent, 15 percent and 11 percent for the three flow rates (8.56, 17.1, and 29.7 MGD; 375, 750, and 1,300 L/sec).

Figures H-22 through H-24 present water depths measured by the ADS 4000 and by the reference depth meter (bubbler) for each replica of Test C. Due to the profile of the test site, the ADS 4000 water depths were expected to always be lower than the reference ones, which they were, except at the highest flow rate (29.7 MGD; 1,300 L/sec) during replica D1. There was some instability before closing the gate during replica D2. Table 4-9 gives an appreciation of the difference between the two water depth readings (reference/ADS 4000) for samples of data points taken during stable periods (delimited by the indicated start and end times) for each replica and for the six hydraulic conditions of this test. Also shown in this table are the average reference water depths and the standard deviations of the water depth differences. Under back-flow conditions the mean water depth difference was 0.85 in. (21.5 mm), which was close to the difference in slope (0.79 in.; 20.0 mm), as expected. Under maximal dry weather flow, the average difference was roughly 1.39 in. (35.3 mm), which was similar to results obtained at the same flow rate for tests B (1.32 in.; 33.6 mm) and C (1.30 in.; 33.0 mm).

Figures H-25 through H-27 present velocities measured by the ADS 4000 and by the reference flow meter for each replica of Test D. Velocities measured by the ADS 4000 are higher than those measured by the reference meter (as expected) for all conditions without back flow. Under back flow, ADS 4000 velocities are always below the reference ones, which invariably leads to underestimation of the flow rates. The signal of the ADS 4000 velocity meter has more noise than the reference meter.

Table 4-8. Flow Rate Comparison of Data Point Samples for the Three Replicas of Test D

Hydraulic Condition		Replica			Mean
		D1	D2	D3	(L/sec)
Flow rate of 75 L/sec	Start time	8:45	8:45	19:45	
	End time	9:30	9:30	20:30	
	Mean reference flow rate (L/sec)	63.2	68.2	66.7	66.0
	Mean difference (L/sec)	-11.7	-12.0	-16.5	-13.4
	Standard deviation of difference	4.9	8.2	5.5	
	Difference/reference (percent)	-19	-18	-25	
Flow rate of 375 L/sec	Start time	9:45	9:45	20:45	
	End time	10:30	10:30	21:30	
	Mean reference flow rate (L/sec)	379.2	382.8	387.4	383.1
	Mean difference (L/sec)	-107.2	-69.1	-123.0	-99.8
	Standard deviation of difference	26.3	12.6	18.8	
	Difference/reference (percent)	-28	-18	-32	
Flow rate of 375 L/sec Back flow of 36 in.	Start time	11:00	11:00	22:00	
	End time	15:00	15:00	2:00	
	Mean reference flow rate (L/sec)	400.1	413.2	414.4	409.2
	Mean difference (L/sec)	81.3	96.8	69.3	82.5
	Standard deviation of difference	19.7	31.5	17.9	
	Difference/reference (percent)	20	23	17	
Flow rate of 750 L/sec Back flow of 36 in.	Start time	12:15	12:15	23:15	
	End time	13:30	13:30	00:30	
	Mean reference flow rate (L/sec)	711.8	710.7	696.7	706.4
	Mean difference (L/sec)	104.0	111.9	88.1	101.3
	Standard deviation of difference	22.1	23.8	15.4	
	Difference/reference (percent)	15	2	13	
Flow rate of 1,300 L/sec Back flow of 36 in	Start time	14:00	14:00	01:00	
	End time	15:00	15:00	02:00	
	Mean reference flow rate (L/sec)	1285.3	1272.5	1262.5	1273.4
	Mean difference (L/sec)	138.1	139.2	142.3	139.9
	Standard deviation of difference	19.2	24.4	22.3	
	Difference/reference (percent)	11	11	11	
Flow rate of 75 L/sec	Start time	15:45	15:45	02:30	
	End time	16:00	16:00	03:30	
	Mean reference flow rate (L/sec)	86.9	93.8	71.8	84.1
	Mean difference (L/sec)	-18.6	-20.1	-17.5	-18.8
	Standard deviation of difference	6.0	5.4	9.2	
	Difference/reference (percent)	-21	-21	-24	

Table 4-9. Water Depth Data Point Sample Comparison for the Three Replicas of Test D

Hydraulic Condition		Replica			Average (mm)
		D1	D2	D3	
Flow rate of 75 L/sec	Start time	8:45	8:45	19:45	
	End time	9:30	9:30	20:30	
	Mean reference level (mm)	262.7	269.5	270.0	267.4
	Mean difference (mm)	34.9	36.7	32.4	34.6
	Standard deviation of difference	1.9	4.7	4.7	
Flow rate of 375 L/sec	Start time	9:45	9:45	20:45	
	End time	10:30	10:30	21:30	
	Mean reference level (mm)	471.4	477.1	475.5	473.4
	Mean difference (mm)	40.2	56.6	29.0	42.0
	Standard deviation of difference	10.2	12.6	5.5	
Flow rates of 375, 750, and 1,300 L/sec; Back flow of 54 in	Start time	11:00	11:00	22:00	
	End time	15:00	15:00	02:00	
	Mean reference level (mm)	1458.5	1440.2	1420.0	1429.6
	Mean difference (mm)	10.6	36.8	17.1	21.5
	Standard deviation of difference	12.9	10.4	8.1	
Flow rate of 75 L/sec	Start time	15:45	15:45	02:45	
	End time	16:30	16:30	03:30	
	Mean reference level (mm)	280.3	298.8	264.8	281.3
	Mean difference (mm)	33.5	37.3	37.0	35.9
	Standard deviation of difference	2.0	3.5	3.4	

4.5.2.2.4 Test E

This test was conducted over a minimum of 21 days, including a period of seven days without data collection. It comprises results obtained from the three replicas of tests B, C, and D. Test E was conducted over 26 days (June 28 to July 24, 2001), with no data collection from July 18 to 24, 2001. Flow rates outside periods of active testing do not vary much and are generally between 6.85 to 15.98 MGD (300 to 700 L/sec). Continuous operation was useful to identify shifts in the depth and/or velocity measurements.

Figures H-28 through H-54 (Appendix H) present flow rates measured by the ADS 4000 and by the reference flow meter for each 24-hour period of Test E. Flow rates measured by the ADS 4000 are generally larger than the reference rates. Spikes and shifts (up and down) in the ADS 4000 signal can be linked to the water depth measurements. Flow rates of zero are due to the zero velocities.

Figures H-55 through H-81 present water depths measured by the ADS 4000 and by the reference depth meter (bubbler) for each 24-hour period of Test E. As expected, considering the configuration of the test site, ADS 4000 water depths are lower than the reference depths. It is only periodically that the ADS 4000 depths are higher. Manual readings at the verified flow meter location are presented on the figures as they were taken (before each active test and almost daily on working days). Table 4-10 presents all the manual readings taken during the tests.

Table 4-10. Daily Manual Level Measurements – ADS 4000

Verification of level measurement									
Site and location	Time	Meter reading	Manual reading	Gap	**Site and location**	Time	Meter reading	Manual reading	Gap
	(hh:mm)	(mm)	(mm)	(percent)		(hh:mm)	(mm)	(mm)	(percent)
Date : 2001/06/28					**Date : 2001/07/09**				
Reading #1	6:58:10	226	240	-5.9	Reading #1	6:57:00	196	207	-5.2
Reading #2	6:59:10	227	240	-5.3	Reading #2	6:58:00	198	207	-4.2
Reading #3	7:00:10	228	244	-6.7	Reading #3	6:59:00	200	209	-4.5
Reading #4	7:01:10	229	242	-5.2	Reading #4	7:00:00	198	209	-5.1
Reading #5	7:02:10	228	242	-6.0	Reading #5	7:01:00	188	209	-10.1
Extra reading					Extra reading				
Average reading :		228	242	-5.8	Average reading :		196	208	-5.8
Comments	Everything seems ok				**Comments**	Condensation on Ultrasonic probe. Everything seems ok			
Date : 2001/06/29					**Date : 2001/07/10**				
Reading #1	7:23:00	300	315	-4.8	Reading #1	18:29:00	443	480	-7.7
Reading #2	7:24:00	292	308	-5.2	Reading #2	18:30:00		460	
Reading #3	7:25:00	284	300	-5.4	Reading #3	18:31:00	404	440	-8.2
Reading #4	7:26:00	280	295	-5.1	Reading #4	18:32:00	385	420	-8.3
Reading #5	7:27:00		290		Reading #5	18:33:00		400	
Extra reading					Extra reading				
Average reading :		289	302	-4.2	Average reading :		411	440	-6.6
Comments	-				**Comments**	Little condensation on Ultrasonic probe (less than usual). Everything seems ok			
Date : 2001/07/03					**Date : 200-07/13**				
Reading #1	7:36:00	248	260	-4.7	Reading #1	7:39:00	344	340	1.2
Reading #2	7:37:00	246	260	-5.2	Reading #2	7:40:00	354	352	0.6
Reading #3	7:38:00	250	257	-2.6	Reading #3	7:41:00	362	361	0.3
Reading #4	7:39:00	248	260	-4.7	Reading #4	7:42:00	354	370	-4.2
Reading #5	7:40:00	221	262	-15.6	Reading #5	7:43:00	374	378	-1.2
Extra reading					Extra reading				
Average reading :		243	260	-6.6	Average reading :		358	360	-0.7
Comments	Everything seems ok				**Comments**	Condensation on Ultrasonic probe. Everything seems ok			
Date : 2001/07/05					**Date : 2001/07/15**				
Reading #1	7:39:00	282	298	-5.3	Reading #1	5:47:00	231	258	-10.5
Reading #2	7:41:00	265	283	-6.3	Reading #2	5:48:00	228	253	-10.0
Reading #3	7:42:00	263	280	-6.2	Reading #3	5:49:00	223	248	-10.0
Reading #4	7:43:00	261	277	-5.9	Reading #4	5:50:00	198	242	-18.0
Reading #5	7:44:00	241	272	-11.5	Reading #5	5:51:00	196	238	-17.6
Extra reading	7:40:00	276	293	-5.8	Extra reading				
Average reading :		265	284	-6.8	Average reading :		215	248	-13.1
Comments	Everything seems ok. We took photo.				**Comments**	A few drops under the ultrasonic probes			

Table 4-10 (cont'd)

Verification of level measurement									
Site and location	Time	Meter reading	Manual reading	Gap	**Site and location**	Time	Meter reading	Manual reading	Gap
	(hh:mm)	(mm)	(mm)	(percent)		(hh:mm)	(mm)	(mm)	(percent)
Date : 200107/16					**Date : 2001/07/22**				
Reading #1	7:02:00	307	312	-1.5	Reading #1	6:39:00	193	212	-9.1
Reading #2	7:03:00	311	318	-2.2	Reading #2	6:40:00	192	210	-8.8
Reading #3	7:04:00	315	320	-1.7	Reading #3	6:41:00	190	207	-8.3
Reading #4	7:05:00	308	326	-5.6	Reading #4	6:42:00	177	205	-13.6
Reading #5	7:06:00	316	325	-2.9	Reading #5	6:43:00	175	207	-15.6
Extra reading					Extra reading				
Average reading :		311	320	-2.8	Average reading :		185	208	-11.0
Comments	Condensation on Ultrasonic probe. Debris accumulated on the bender. Everything seems ok				**Comments**	No accumulation on the bender.			
Date : 2001/07/18					**Date : 2001/07/23**				
Reading #1	20:01:00		470		Reading #1	6:41:00	215	235	-8.7
Reading #2	20:02:00	431	468	-8.0	Reading #2	6:42:00	213	232	-8.4
Reading #3	20:03:00		460		Reading #3	6:43:00	218	232	-6.0
Reading #4	20:04:00	418	450	-7.1	Reading #4	6:44:00	194	230	-15.6
Reading #5	20:05:00	372	435	-14.4	Reading #5	6:45:00	196	230	-14.6
Extra reading					Extra reading				
Average reading :		407	457	-10.9	Average reading :		207	232	-10.6
Comments	-				**Comments**	Condensation on the ultrasonic probe. Debris on the bender.			
Date : 2001/07/20					**Date : 2001/07/24**				
Reading #1	7:52:00	533	518	2.8	Reading #1	7:22:00	235	255	-7.9
Reading #2	7:53:00	548	532	2.9	Reading #2	7:23:00	233	253	-7.9
Reading #3	7:54:00	563	553	1.9	Reading #3	7:24:00	232	250	-7.0
Reading #4	7:55:00		567		Reading #4	7:25:00		250	
Reading #5	7:56:00	592	580	2.1	Reading #5	7:26:00	211	250	-15.5
Extra reading					Extra reading				
Average reading :		559	550	1.6	Average reading :		228	252	-9.4
Comments	2 last photo. Condensation on the ultrasonic probe				**Comments**	-			
Date : 2001/07/21					**Date :**				
Reading #1	7:46:00	248	275	-10.0	Reading #1				
Reading #2	7:47:00	243	272	-10.6	Reading #2				
Reading #3	7:48:00	235	263	-10.5	Reading #3				
Reading #4	7:49:00		260		Reading #4				
Reading #5	7:50:00	202	255	-20.6	Reading #5				
Extra reading					Extra reading				
Average reading :		232	265	-12.4	Average reading :				
Comments	Two or three drops on the ultrasonic probe				**Comments**	-			

Periodic air purges to flush debris at the end of the bubbler injection tube can be observed in the data. Downward spikes (amplitude of roughly five to ten in.) around 11:00, 17:00, and 21:00 on June 29 represent air purges, which have no impact on the flow rate. Small shifts (up and down) can be observed almost daily in the ADS 4000 signal. Spikes become very frequent from July 10 through 15, after which they become more sporadic until July 19 to the end of the testing period, when they become frequent. According to ADS staff, this is due to condensation under the ultrasonic probe. It should be noted that sewers typically have a humidity of 100 percent, and condensation is likely to occur. There is generally more noise in the signal of the ADS 4000 depth meter than for the reference meter.

Figures H-82 through H-108 present velocities measured by the ADS 4000 and by the reference flow meter for each 24-hour period of Test E. There are occasional zero readings of the ADS 4000 velocity meter, some of which occur when the reference velocity increases rapidly. There is generally more noise in the signal of the ADS 4000 velocity meter than for the reference meter.

Figures H-109 through H-117 present comparisons between water depths output by the reference depth meter (bubbler) and three water depth readings output by the ADS 4000: the pressure depth, mean ultrasonic depth, and final depth. The final depth is either the pressure depth or the average ultrasonic depth. A built-in proprietary algorithm selects the reading to be used, so it is always superimposed on either curve. The decision is not always a good one: for example, in Figures 4-113 and 4-114, the pressure depth is more stable than the mean ultrasonic depth but the final depth is mostly the average ultrasonic reading.

4.5.2.3 General Verification Tests

Test E was composed of two parts: the performance evaluation and the general evaluation. Appendix C presents a day-to-day description of the tests.

4.5.2.3.1 Installation, Configuration and Calibration

ADS staff, composed of a project manager, a field manager, a field technician, and an analyst, completed field installation of the ADS 3600. The TO helped the ADS field manager with the underground installation and supervised all activities of ADS during configuration and calibration. The ADS team performed almost all the fieldwork. A complete crew (except the project manager) was on-site from June 18 to July 7, 2001; the field analyst who could perform any sewer intervention stayed on-site July 7 - 17, 2001.

The installation activities of ADS were performed as follows:

- The analyst beside the manhole linked a laptop computer to the ADS 4000 transmitter.
- The project manager beside the manhole managed the safety harness.
- One ADS technician entered the pipe, supervised by TO personnel, and installed the equipment.
- A second technician entered the manhole to assist the technician already in the pipe.

The time spent by the TO staff was not accounted in the observed number of person-hours required to install the flow meter shown in Table 4-11. Four individuals could have performed the same job in the same amount of time during a normal installation.

Table 4-11. Time Estimate Required to Install, Operate and Service Flow Meter

Activities	Work class*	Estimate by ADS (person-hours)	Observed by tester team (person-hours)	Frequency (if applicable)
Installation, Configuration and Calibration				
Physical installation	Field Service Personnel	2	6	1
Configuration of the transmitter	Field Service Personnel	1	3	1
Initialization of the velocity measurement	Field Service Personnel	1	3	1
Initialization of the level measurement (Zeroing of the level probe)	Field Service Personnel	1	2	1
Start-up and trouble shooting	Field Service Personnel	1	48 hours	1
Replacement of a level probe	Field Service Personnel	1	3	Every 2-3 yrs
	Total*	7	65	N/A
Operation, Maintenance and Service				
Replacement of desiccant (SENSOR)	Field Service Personnel	1		Twice a year
Replacement of on-board memory battery	Field Service Personnel	N/A		Once a year
Replacement of the input board in the transmitter	Completed in the office by technician; not done in the field.	N/A		Several Years apart
Replacement of the output board in the transmitter	Completed in the office by technician; not done in the field.	N/A		Several Years apart
Replacement of the main board in the transmitter	Completed in the office by technician; not done in the field.	N/A		Several Years apart
Probes maintenance recommended by the manufacturer	Field Service Personnel		1	4

* The work class: project manager, field manager, field technician, data analyst

The installation, configuration, and calibration took approximately 16 person-hours (four people during half a day). The only problem met during this installation involved the bender on the stainless steel band. The first two benders moved away from the pipe wall when it was screwed, instead of pushing toward it, so the band was secured to the pipe wall at the crown of the pipe. Since the bender was not close to the pipe wall, debris accumulated (see Illustration 4-9). The problem was not major, but a bender closer to the pipe wall (pushing on it), would be required in a permanent installation.

Figure 4-26. Debris accumulation on ADS 4000's bender.

The installation took approximately eight person-hours. Configuration and calibration required another eight person-hours and involved four steps (Appendix F):

- Configuration and calibration of the ultrasonic depth meter;
- Configuration and calibration of the pressure depth meter;
- Configuration and calibration of the Doppler velocity probe;
- Configuration and calibration of flow computation options, like:
    - Depth measurement used;
    - Calibration or the pressure depth probe with the ultrasonic depth probe; and
    - Range of velocity expected (fast or slow);

The calibration of the reference flow meter required one specialized tool. A Marsh-McBirney Model 2000 portable velocity meter was used to measure the peak velocity in the pipe section. This value was required to calibrate the gain of the Doppler velocity probe.

After calibration with a maximal dry weather flow of 1.71 MGD (75 L/sec), the official test began June 20 with the test first replica of Test C. It was discovered after this test that the ultrasonic depth sensor was not measuring properly. It was decided to replace the sensor and restart the verification. Since tracer dilution was performed to verify the performance of the reference meters, the test was considered valid for the reference meters and renamed C0 instead of C1.

The ultrasonic depth probe was replaced and verification of the transmitter and probes was done to understand the behavior of the flow meter and try to find a better tuning. This was completed while waiting for the arrival of a spare component required for the other flow meter verified at the same time. The verification officially began on June 28, 2001.

4.5.2.3.2 Operation

The ADS 4000 operation and maintenance manual includes a chapter about unit maintenance. ADS recommends a local check at installation, during a monitor site visit and every four months or during battery replacement. In summary, the following elements have to be verified:

- Status of the casing;
- Status of the battery pack;
- Verification of the desiccant's color (for pressure probe);
- Verification of the stainless steel ring installation;
- Verification of grease or scum on the face of probes;
- Wiping the ultrasonic depth sensor with a clean moist cloth;
- Verification of the ultrasonic probe with a carpenter's level;
- Verification of debris accumulation on the ring or probes; and
- Verification of debris accumulation on cable.

The flow meter was inspected 16 times from June 28 to July 24, 2001 and no problem of debris accumulation was observed, except with the bender as shown in Figure 4-26. Debris on the bender was not removed because it had no impact on the measurements; it would have been removed every four months in a normal installation. Since the probes are thin and have a good hydraulic profile, they did not have a tendency to accumulate debris.

Except for a thin film of grease, the probes were clean at the end of the test. During verification in the sewer, drops of condensation were observed on the underside of the ultrasonic depth probe. Since there is always some condensation in sewers, the ultrasonic probe was not be wiped during verification.

4.5.2.3.3 Time for Data Retrieval

There was one period following completion of tests B, C, and D, during which data were not retrieved for seven consecutive days. The objective was to verify the time required to retrieve data during a normal data retrieval period.

For the period of seven days, it took approximately 1.3 minutes per day to log the one-minute data. This delay was reasonable for a seven-day period, but it may become restrictive for longer data collection intervals.

For retrieval of two to four days of data, the transmitter took approximately two to three minutes per day of one-minute data logging. This is probably due to the time required to establish communication with the transmitter (see Appendix C, Table C-3 for detailed results).

4.5.2.3.4 Dismantling

The probes and the transmitter were dismantled, cleaned and photographed on July 25. None of the components had been damaged or altered during the tests.

4.5.2.3.5 General Characteristics of the ADS 4000

The probes have a good hydraulic profile. The stainless steel band is well-designed. It is thin enough to fit the exact shape of the pipe and thick enough to have good strength. However, as stated, the bender must be pushed onto the pipe wall while securing its position.

The aluminum transmitter was well-designed for sewers and is easy to hang in the manhole. It had a handle on the top to facilitate manipulation and protect connectors. It is waterproof and protected against infiltration by pressurizing the casing at approximately 12 psi (82.7 kPa) of air pressure. There is no connector on the casing for external powering. The internal battery is not rechargeable, and it is expensive. According to the vendor, the battery can last up to one year while collecting 15-minute data, but such an infrequent logging period is not useful in many combined-sewer overflow (CSO) applications, such as modeling and diagnostic, which generally require a five-minute period. For data validation purposes, it may become useful to perform monitoring at a higher frequency to eliminate spikes caused by temporary local disturbances. When a long data-logging period is used, short local disturbances like standing waves, surge, or backwash can result in two logging intervals without valid measurements. These local disturbances are more frequent during high flows of a storm event compared to dry weather flows.

The ultrasonic depth probe has a specially designed sliding support to facilitate its installation and adjustment. Its low dead band (0.5 inch; 13 mm), low depth profile (0.875 inch; 22 mm), and its four probes incorporated in the same casing are characteristics that made this probe particularly well-adapted to sewer pipes. This probe is, however, more affected by local waves than the pressure probe, which performs an integration of the various depths over the probe.

The configuration of the transmitter has various options. For example, it is possible to compute the flow using the depth from the ultrasonic depth probe, the pressure probe, or the better of the two results according to an algorithm programmed into the flow meter. The ADS 4000 used during testing was configured using this last configuration.

ADS expressed concern about using a cable longer than that typically supplied with the Model 4000 (25 ft [7.6 m]) because of possible noise in the longer cable. The cable used during verification was the standard 25 ft length. This should be a consideration for permanent installations. It might be more convenient to install the transmitter in a control cabinet close to the street or in a service building. The length of the cable's probes, the data acquisition frequency, the powering options, and the packaging option are not well adapted to CSO real-time control applications.

The transmitter is available with a telephone modem option. With the modem and related software, the logging of many transmitters can be performed using a standard telephone line, instead of going on-site. The ADS 3600 also provides flexibility to connect a rain gauge and an automatic sampler for sampling proportional to the recorded transmitter flow.

4.6 Reference Meters

4.6.1 Scatter Plots

As with the presentation for the ADS 4000, three types of scatter plots are presented for the reference meter data: a system behavior (velocity versus depth) plot, flow rate comparison plots, and water depth comparison plots. These plots, showing the data collected for all of the reference meter runs, are presented in Appendix H.

The system behavior scatter plot was presented in Figure 4-18, showing the hydraulic conditions at the reference flow meter during Test C (no back flow). There are 1,353 data points on this figure, segregated in three groups: stable (984 data points), ebbing (261) and rising (108) water profiles. There are fewer data points for the rising water profiles because the transition is more rapid under this condition. Apart from the stable water profiles, there is no single relationship between velocity and water depth. The best-fit curve polynomial equation drawn from stable conditions data points is indicated on the figure, along with its coefficient of determination (R^2 = 0.9938).

The system behavior scatter plot was presented in Figure 4-18, showing the hydraulic conditions at the reference flow meter testing site during Test C (no back flow). There are 1,353 data points on this figure, segregated in three groups: stable (984 data points), ebbing (261) and rising (108) water profiles. There are fewer data points for the rising water profiles because the transition is more rapid under this condition. Apart from the stable water profiles, there is no single relationship between velocity and water depth. The best-fit curve polynomial equation drawn from stable conditions data points is indicated on the figure, along with its coefficient of determination (R^2 = 0.9938).

Figures H-121 to H-124 present water depth comparison plots between the reference depth meter (bubbler) and manual readings for tests B, C, and D respectively, and these three tests combined, along with the perfect fit line.

4.6.2 Deviation Distribution Plots

Figures H-125 to H-130 present the flow rate deviation distributions (reference flow meter compared to the flow rate calculated from the tracer dilutions) for all data of replicas C0 and C3. The deviation is presented in two-percent increments. Indicated on the figures are the:

- Margin of deviation (±*X* percent) that contains 95 percent of all measurements (i.e. standard ±2σ);
- Percentage of measurements within a margin of deviation of ±8.7 percent (wet-weather racer dilution error);
- Mean deviation of all measurements; and
- Median deviation (provides an indication of the spread).

Figure H-125 presents the flow error distribution for replicas C0 and C3. It is a bell-shaped curve centered on -0.9 percent. The largest negative error is -45.8 percent and the largest positive error is 20.5 percent, both of which occurred during dry-weather conditions (during replica C3 at 8:30 and 7:45, respectively). Replica C3 was performed on July 15, starting in the early morning when the flow rate was roughly 0.80 to 1.03 MGD (35 to 45 L/sec). At such low flow rates, the relative error tends to be larger since the flow meter resolution is 0.023 MGD (1 L/sec). Excluding these low flows, the largest negative error is -9.5 percent and the largest positive error is 19.7 percent. Both data points are during transition periods (during C3 at 10:55 and, C0 at 14:30 respectively). Of the measurements, 84.1 percent are within the margin of error of 8.7 percent, which is the tracer dilution error for wet-weather conditions, as indicated in the *Protocol for Flowmeters for Wet Weather Flow Applications in Small- and Medium-Sized Sewers (Draft 4.0, September 2000)* (protocol). The protocol referred to the fact that 95 percent of measurements should be within this margin of error. Figures H-126 and H-127 present the same data for C0 and C3 separately (used for the QAPP). Figures H-128 to H-130 present the same set of three figures but for stable condition data points only.

Figures H-131 to 4-133 present the water depth error distributions (reference depth meter compared to manual readings) for tests B, C, and D, respectively, while Figure H-134 presents all data from tests B, C, and D combined. These error distributions are presented in inches (mm) since the protocol referred to an acceptable error of two percent of full scale (full scale is 62.5 in. [1,586 mm]), which represents 1.25 in. (31.7 mm). The error is presented in 0.25 in. (6.4 mm) increments. Indicated on the figures are the:

- Margin of error (±*X* percent) that contains 95 percent of all measurements (i.e. standard ±2σ);
- Percentage of measurements within a margin of error of ±2 percent full-scale;
- Mean error of all measurements; and
- Median error (provides an indication of the spread).

Figure H-134 presents the water depth error distribution for all data of tests B, C, and D combined. It is a bell-shaped curve with a mean error of 0.13 in. The largest negative error is -3.74 in. recorded during replica D3 in the transition period of between 29.7 MGD (1,300 L/sec) with a 54-inch back flow to 1.71 MGD (75 L/sec) with no back flow (at 2:20). The largest positive error is +4.00 in. recorded during replica C1 in the transition period of between 17.1 MGD (375 L/sec) to 29.7 MGD (1300 L/sec) (at 12:00). The large positive and negative errors are due to waves at high flows (17.1 and 29.7 MGD [750 and 1,300 L/sec], respectively) since the manual readings are more affected by waves than is the bubbler.

Figure H-135 presents the water depth error distribution (reference bubbler depth meter compared to the reference ultrasonic depth meter) for all data from tests B, C, and D. It is roughly a centered bell-shaped curve. There are 12 data points outside ±5.0 in. The larger positive errors are during transition periods from 1.71 to 17.1 MGD (75 to 750 L/sec) and from 8.56 to 29.7 MGD (375 to 1,300 L/sec) while the larger negative errors are during the transition period between 29.7 to 8.56 MGD (1,300 to 375 L/sec). The overestimation at 29.7 MGD (1,300 L/sec) (all replicas) and underestimation at 17.1 MGD (750 L/sec) (replicas C0, C1 and C3) are due to the ultrasonic depth meter being more affected than the bubbler by waves caused by the high flows.

Figure H-136 presents the velocity error distribution (velocity calculated from the reference flow rate and water depth compared to velocity calculated from tracer dilutions) for replicas C0 and C3. The largest negative error is –45.8 percent and the largest positive error is 20.5 percent, both from replica C3 (at 8:30 and 7:45, respectively). Errors are largest at low flows and during transition periods. The error made on the velocity is the summation of the error made on flow rate and the one on water depth since it is the result of a calculation (velocity equals flow rate divided by area).

4.6.3 Tests B, C, and D

Only figures that supply new information are presented in this section since the bulk of the reference data is presented with the ADS 3600 flow meter data in Figures H-1 to H-108.

Figures H-137 through H-139 present flow rates from the reference flow meter and from the flow under the downstream gate equation for the three replicas of Test B, while Figures H-142 through H-144 present the same information for the three replicas of Test D. Figures H-140 and H-141 present flow rates from the reference flow meter, from tracer dilutions, and from the flow under the upstream gate with the Craig Collector flow rate added for replicas C0 and C3, respectively. On both figures, the largest differences between the reference flow meter and tracer dilutions are in the transition zones indicated by the square markers (rising and ebbing water profiles). As mentioned, replica C3 (Figure H-141) was performed on a Sunday, with a very low early-morning flow. From 11:30, there was not enough water in the Versant-Sud tunnel to maintain a stable flow rate of 29.7 MGD (1,300 L/sec) for the prescribed time.

Figures H-145 through H-154 present water depths from the reference depth meter (bubbler), manual readings and reference ultrasonic depth meter for the three replicas of Test B, four replicas of Test C, and three replicas of Test D, respectively. Water depths from all three instruments for the three replicas of both tests B and D (Figures H-145 through H-147, and H-152 through H-154) are practically identical. Water depths of the four replicas of Test C (Figures H-148 through H-151) vary more, principally due to the presence of waves during these tests. Replicas C0, C1, and C3 present the same pattern: manual readings are higher than the bubbler and the ultrasonic depths are lower during the 17.1 MGD (750 L/sec) stable period while the opposite is found in the 29.7 MGD (1,300 L/sec) stable period. Both manual readings and ultrasonic depths are affected by waves whereas the bubbler buffers the information over a larger volume of water. It should be noted that the manual readings are taken very close to the bubbler site.

Figures H-155 and H-156 present velocities calculated from the reference flow meter data and tracer dilution data for replicas C0 and C3, respectively. Since these velocities are calculated with the same water depths but different flow rates and because the errors on the water depths and flow rates are summed, there is simply more noise in the signal.

Chapter 5
Quality Assurance/Quality Control

The assessment of the accuracy, precision, and completeness of the flow meters undergoing testing requires the existence of reference data for comparison and validation. At the beginning of the project, it was decided that the reference flow rates would be produced using a 4-path Accusonic flow meter and reference water depths from a bubbler. The choice of a flow meter to assess the performance of other flow meters was not obvious. However, considering that a 4-path Accusonic flow meter has a theoretical uncertainty of ±4 percent for flows in open channel systems (this is smaller than the uncertainty associated with tracer dilution; refer to Appendix D-3) and that flow rates can be measured continuously in real time at a low cost, the choice of a 4-path Accusonic flow meter to generate the reference flow rates was justified.

Two reference depth meters were used: the bubbler and the ultrasonic. The bubbler was preferred as the primary reference for the following reasons.

- It exhibits no significant bias when properly installed and operated.
- It provides measurements for a large flow range.
- It is more reliable.
- It is the depth measurement linked with the reference flow meter.

The first step toward the use of the Accusonic flow meter as the reference flow meter was the validation of its measured flow rates. Lithium tracer dilutions were used to verify that the flow rates measured by the reference flow meter were accurate.

Validation of the data provided by the reference flow meter and the reference water depth meter was performed as rigorously as possible. Tight review of all the procedures used to collect and handle data was performed, and is described in the following sections. Such reviews are essential to assure that data quality conforms to protocol specifications. After the validation of the data collected in the field, described in Section 5.1, the Quality Assurance Project Plan (QAPP) was designed to verify the representativeness of the lithium concentrations measured by the standard laboratory. These concentrations were used to validate the flow rates measured by the reference flow meter. The final objective of the QAPP consisted of verifying that the measurements made by the reference devices, a reference flow meter and a bubbler depth meter, were representative of the true values considering the uncertainty margins associated with each measurement device. These validations are described in Sections 5.2 through 5.4.

5.1 Audits

Audits of the field testing and the reporting used in the testing were completed several times over the course of the verification testing.

5.1.1 Field Audits

During the course of the project, the QAPP representative visited the field several times. These visits were conducted without prior notice and included the injection site, the sampling site, and the control gate. The objectives of these visits were to ensure the conformity of the sites with respect to protocol specifications; and quality measurement procedures.

At each visit, the QAPP representative verified the measurement procedures followed by the field crew. In particular, the synchronization and frequency of measurements, the configuration of the measurement sites, the handling of the sampling bottles, and the injection procedure of the concentrated lithium were verified.

Observations made during field visits permitted observation of the methods used by the field crewmembers. It was observed that the steps required assuring good quality data were meticulously followed according to the VTP. All members knew exactly the tasks at hand, when to perform them and how to execute them. The following items were specifically observed:

- Crewmembers had a thorough knowledge of the hydraulics of the system. They were able to assess flow rates under the gates and had a good understanding of the flow delays between the injection and the sampling sites. Therefore, they could accurately control the flows in the sewer network and evaluate the time required to reach a steady-state flow.

- The existing communication procedure between the crewmembers was efficient, no matter where they were located. This guaranteed all members had real-time access to the available information. All collected data were quickly saved at a centralized location notwithstanding the fact that some were collected manually.

- The data collected were well synchronized. This validated the right to use paired sample data to assess the accuracy of time-varying measurements provided by different measurement devices or different laboratories.

- The measurement devices were properly configured and installed to provide measurements that were as accurate as possible. For example, manual water depth measurements were made using a homemade device designed to reduce variations that could be introduced by the flow turbulence observed at the sampling site during the wet weather flows of Test D.

- The procedure followed to label the sampling bottles helped ensure that no error could be made on location or on the time when samples were collected.

Field report check-ups conducted in conjunction with field visits verified that the procedures followed by the field crewmembers when collecting and handling data met the requirements of the QAPP. The field crewmembers were very careful and attentive to details to assure high quality data.

The field reports were completed with accuracy and included pertinent comments. The non-conformities noted were minor, mainly dealing with non-recorded departure times and the names of technicians. The collected data was appropriately handled, and the data in the spreadsheets used for validation and flow computations was found representative of the measurements made in the field.

The only negative observation concerned the handling of the sample bottles at the tracer injection site. The same individual collected the blank and the concentrated samples. This person took precautions to isolate the blank samples from the concentrated ones (e.g., changing gloves when manipulating new bottles, storing blank bottles in watertight bags). Nonetheless, the risk of contaminating the blank samples was not completely eliminated. It would have been safer to have a sampling site for the blanks that was geographically distant from the injection site.

5.1.2 Report Audit

The data collected in the field were transcribed according to the VTP in different field reports. One of the objectives of the audit was to verify if all required reports had been filled out and that no data was missing. To verify the completeness of the information gathered in the field, verification sheets were specially developed for the QAPP. A verification sheet was filled out for each report produced during the field tests. These verification sheets included:

Preliminary Tasks

- Instruments Calibration Report Verification
- Laboratory Report Verification

Test Tasks

- General Report Verification
- Test Report Verification: Daily General Verification
- Test Report Verification: Monthly General Verification
- Test Report Verification: Control Table of Test
- Injection Site Report Verification
- Sampling Site Report Verification
- Sampling Site Measurement Verification
- Tracing Sheet for Injection Site Verification
- Tracing Sheet for Sampling Site Verification
- Laboratory Results Verification
- Flow Meter Configuration and Calibration Verification
- Flow Meter Operation and Maintenance Verification
- Flow Meter Software Checklist Verification: Ease of Use
- Flow Meter Software Checklist Verification: Functionality and Flexibility
- Flow Meter Installation Report Verification
- Flow Meter Dismantling Report Verification

These verification sheets were designed to quickly assess whether the information contained in the field or laboratory reports was complete, as specified in the VTP. These sheets were designed to follow the data collection and handling sequences in chronological order and were divided into three sections:

Section 1 – General Information

The first section contained information such as the name of the test, the names of the technicians present during the test, the names of visitors, and the time of their visits.

Section 2 – Field Data

A part of this section was designed to check on the lithium tracer sampling frequencies, (i.e., blanks, concentrated and diluted samples for both the standard and control laboratories) and on the lithium concentration measured by the laboratories. The chronological sequence of the sheets enabled one to track all the sampling bottles collected during the tracer dilution tests (tests C0 and C3) from the collection sites to the laboratories. The injection and sampling sites verification sheets enabled one to verify if all lithium samples had been properly collected and labeled. The tracking sheets for injection and sampling sites confirmed that the standard and control laboratories received all samples. Finally, the laboratory results verification sheets guaranteed that all samples sent to the laboratories were analyzed and the results sent back to the TO for validation and flow computation.

This section was used to quickly verify that flow rates, velocities and water depths had been measured using the frequencies and the accuracy specified in the VTP. Particular attention was paid to the synchronization of the data saved in the data report spreadsheet since the data originated from several sources. Data on the sampling site measurement verification sheets included:

- Bubbler measurements (data transferred from the PLC to an industrial PC using software developed by the TO and then to a spreadsheet);
- Ultrasonic depth measurements (data transferred from the ADS data logger to a spreadsheet);
- Manual measurements (data directly recorded in a spreadsheet);
- Reference flow rates and velocity measurements (data transferred from the PLC to an industrial PC using a software developed by the TO and then to a spreadsheet); and
- ADS 3600 flow rate and water depth measurements (data transferred from the ADS data logger to a spreadsheet).

Time series related to flow computations under the upstream and downstream gates, including water depths and gate positions, were verified on the test report verification sheet, Control Table of Test.

Due to the large amount of collected data and its various sources, only a fraction of the data reported in the spreadsheet used for flow, water depth, and velocity validation were audited. These random audits indicated proper handling of the field data. For all testing, the data saved in the spreadsheets was identical to the raw measurements and was associated to the exact time collected. Moreover, the set of data saved in the spreadsheet was complete and respected the sampling frequency reported in the VTP.

The field data section allowed assessment of the completeness of the information related to the measurement devices. The information contained in the flow meter configuration and calibration verification sheet, the flow meter operation and maintenance verification sheet, the flow meter software checklist verification sheet, the flow meter installation verification sheet, and the flow meter dismantling verification sheet, verified that all reports related to flow measurement devices had been properly completed.

Section 3 – Non-Conformity Follow-Up

This section included questions required to complete the general information and the field data sections. Answers provided by the project manager or the crewmembers are also reported. This permitted good communication between the QAPP representative and the project manager in order to complete the field reports or to explain observations that were not in conformity with the VTP.

It was during the question-and-answer dialogue that the explanation of the existence of the C0 test was reported (this test was not planned in the original VTP). For this particular non-conformity, during the course of the original Test C1, the ADS 4000 flow meter worked properly, but the ADS 3600 flow meter did not. Since this test was done in conjunction with a tracer dilution test, it was decided to keep the dilution results, but to rename the Test C0 for the validation of the reference flow meter. Thereafter, Test C1 was repeated without dilution to get proper measurements with the ADS 3600 flow meter.

5.2 Validation of the Lithium Tracer Methods

Lithium dilution tests were used to validate the reference flow meter. Before using the tracer for the meter validation, the lithium concentrations provided by the standard laboratory needed to be validated. Validation of the results provided by the standard laboratory (Laboratoire de l'environnement LCQ Inc.) consisted of comparing the standard lithium concentrations with those measured by another laboratory, referred to as the control laboratory (Laboratoire de la qualité du milieu, Centre d'expertise en analyse environnementale du Québec). This process was conducted during the validation of the reference flow meter. Results showed that the concentrations measured by the standard laboratory were statistically equivalent to those measured by the control laboratory. Since the probability that the two laboratories measured the wrong concentrations is very low, it was concluded that the standard laboratory was providing concentrations that had the level of accuracy needed to validate the reference flow meter.

To analyze the performance of the verified flow meters, it was necessary to confirm the validation of the standard laboratory analyses previously conducted during the course of the validation of the reference flow meter. Two new lithium dilution tests were conducted to verify, using the same analysis tools, whether the standard laboratory was still providing concentration results representative of the real concentrations in the samples.

5.2.1 Sample and Data Handling

Before comparing the concentration results provided by the two laboratories, proper handling of the samples had to be guaranteed. Therefore, it was verified that all samples were properly collected and identified, they had been sent to the laboratories for analysis, and were returned with the concentration results.

The concentrations measured by the two laboratories were recorded in a spreadsheet for statistical analysis. In order to guarantee that the results used for the statistical analysis were valid, all the lithium concentrations recorded in the spreadsheet were crosschecked with the concentration results sent by the laboratories. Moreover, all the equations programmed into the spreadsheets (analysis results from standard and control laboratories) were validated according to the theory presented in Appendices D-1 and D-2.

5.2.2 Methods Used to Validate Lithium Concentrations

The lithium concentrations collected in the field and needed to compute the flow rates in the vicinity of the reference flow meter originate from three sources:

1. The concentrated samples collected in the injection cylinder. The concentrations at this site should match the lithium concentration of the prepared lithium mixture. For the duration of a given test, this concentration was assumed to be constant for the purpose of flow computation. The statistical analysis made for the validation of the concentrations measured by the standard laboratory would reflect this assumption.

2. Blank samples collected upstream of the lithium injection point. They were used to verify that lithium was conveyed in the QUC sewer network and to compute flow rates near the reference flow meter. These concentrations were assumed to be time varying and were treated as such when performing the statistical analyses.

3. Diluted samples collected near the reference flow meter, which were treated the same as the blank samples when performing hypothesis testing on the lithium concentrations.

5.2.2.1 Concentrated Samples

Two tests were used to validate the accuracy of the concentrated samples. The first test was a standard statistical test to compare the means of two normally distributed populations. In the literature, the test is referred to as a *"Two-population test of population means for normal populations with the same variance"* (Appendix D-1). This test compared the means of the concentrated samples, as measured by the standard and control laboratories, and verified whether their means differed significantly. A null hypothesis (the mean of the two populations are identical) and an alternate hypothesis (the mean of the two populations are different) were established, and a variable called the "test statistic" was computed using the null hypothesis. The probability of the test statistic being outside the acceptance range was given by the level of significance chosen. For this project, a level of significance of 0.05 was chosen to indicate the likelihood that the test statistic was outside the acceptance range was low (less than five percent).

If the test statistic was outside the acceptance range, the alternate hypothesis was accepted. Conversely, if the test statistic was inside the acceptance range, the null hypothesis was accepted.

Accepting the alternate hypothesis means that there was a strong presumption that the two laboratories did not measure the same mean concentrations. However, it does not mean that the mean concentration measured by the standard laboratory was not suited to compute flow rates at the sampling point. If the mean concentrations measured by the two laboratories were inside the accuracy margins specified by the standard laboratory, there was no reason not to use the mean concentration of the standard laboratory.

For the concentrated samples, the accuracy observed for the average concentration under normal conditions was ±0.02. The validation variable was defined as:

$$x_v = \frac{2(C_{sl} - C_{cl})}{(C_{sl} + C_{cl})} \qquad (5\text{-}1)$$

Where: C_{sl} is the mean concentration of the standard laboratory; and
C_{cl} is the mean concentration of the control laboratory.

x_v should be between ±0.04, assuming that the accuracy of the concentrations measured by the standard laboratory satisfied the expected accuracy (Appendix D-4). The validation chart of the concentrated samples is summarized in Table 5-1.

Table 5-1. Concentrated Samples Validation Chart

Result of hypothesis test	**Result of accuracy test** $-4\% < x_v > 4\%$	$-4\% > x_v < 4\%$
Null hypothesis accepted	Validation of the concentrated samples	Validation of the concentrated samples
Alternate hypothesis accepted	Validation of the concentrated samples	Rejection of the concentrated samples

If the concentrated samples are rejected for the two tests, the lithium test was not used to compute the flow rates needed to validate the performance of the reference flow meter.

5.2.2.2 Blank and Diluted Samples

For the concentrated samples, two validation tests were used to assess the accuracy of the blank and diluted samples measured by the standard laboratory. The first was a standard statistical called *"test on paired-sample data"* (Appendix D-2). Each number of a data set was associated with only one number in the other set. When the differences between the numbers in the pairs were the meaningful data, the two samples are called paired samples. The idea consists in verifying if the mean of the paired samples is significantly different from zero with a given level of significance assuming that the paired data population has a zero mean (the null hypothesis). The probability of the test statistic being outside the acceptance range is given by the level of significance chosen. As for the two-population test statistic, a 0.05 level of significance was used. If the test statistic is outside the acceptance range, since the probability of having such a result is little (less than five percent), it was concluded that the null hypothesis was wrong and the alternate hypothesis was accepted. Conversely, if the test statistic was inside the acceptance range, the null hypothesis was accepted and the alternate one was rejected.

Accepting the alternate hypothesis means that there was a strong presumption that the two laboratories are not measuring the same blank or diluted concentrations. However, it does not mean that the concentrations measured by the standard laboratory are not suited to compute the flow rates at the sampling point. If the mean concentration of the paired samples was very close to zero and the alternate hypothesis was accepted because of the small standard deviation of the paired samples, there was no reason not to use the blank and diluted concentrations of the standard laboratory since they allow the computation of flow rates that are similar to those computed using the concentrations measured by the control laboratory.

For the diluted samples, the accuracy observed for the measured concentrations under normal conditions was ±0.03 (value specified by the standard laboratory). The validation variable was defined as:

$$x_v = \sum_{i=1}^{n} \left[\frac{2\left(C_{sl_i} - C_{cl_i}\right)}{\left(C_{sl_i} + C_{cl_i}\right)} \right] / n \qquad (5\text{-}2)$$

Where: C_{sl} is the concentration of the standard laboratory; and
C_{cl} is the concentration of the control laboratory.

x_v should be between ±0.06, assuming that the accuracy of the concentrations measured by the standard and the control laboratories satisfied the expected accuracy (Appendix D-5).

For the blank samples, the accuracy was given in absolute values and was equal to ±0.01 mg/L for the standard laboratory and to ±0.005 mg/L for the control laboratory. The validation variable, as the mean difference of concentrations measured by the two laboratories, is defined as:

$$x_v = \sum_{i=1}^{n} (C_{sl_i} - C_{cl_i}) / n \qquad (5\text{-}3)$$

Where: C_{sl} is the concentration of the standard laboratory; and
C_{cl} is the concentration of the control laboratory.

The blank samples validation variable should be between ±0.015 mg/L, assuming that the accuracy of the concentrations measured by the standard and the control laboratories satisfied the expected accuracy (Appendix D-6). Converse to the concentrated samples, for the bland and diluted samples the validation variable was defined as a mean difference. For this reason, the acceptance of the measured concentration could not be restricted to the deviation of x_v from zero but also be related to the standard deviation (SD) observed. The concentration measured by the standard laboratory can be validated only when the mean difference of concentration between the two laboratories is small and when the hypothesis test is rejected due to a small variance. An acceptable value for the standard deviation is 0.05. The validation chart of the blank and diluted samples is summarized in Table 5-2.

Table 5-2. Validation Chart for the Blank and Diluted Samples

	Dilute samples		Blank samples	
Result	$-0.06 < x_v > 0.06$ and SD < 0.05	$-0.06 > x_v < 0.06$ or SD > 0.05	$-0.015 < x_v > 0.015$ and SD. < 0.05	$-0.015 > x_v < 0.015$ or SD > 0.05
Null hypothesis accepted	Validation	Validation	Validation	Validation
Alternate hypothesis accepted	Validation	Rejection	Validation	Rejection

If the blank or diluted samples were rejected for the two tests, the lithium test could not be used to compute the flow rates needed to validate the performance of the reference flow meter.

5.2.3 Validation Results for Test C0

Two lithium dilution tests were conducted during the course of the project. The first was performed during Test C0 and the second during Test C3. For Test C0, the standard and control laboratories analyzed 25 and five samples, respectively. The 25 samples analyzed by the standard laboratory originated from five different bottles, and each bottle was analyzed five times. The five samples analyzed by the control laboratory were produced from a single bottle.

The data from the 30 concentrated samples were used to validate the mean concentration computed using the results provided by the standard laboratory. The mean concentrations measured by the standard and control laboratories were 45,500 mg/L and 44,900 mg/L, respectively. The test statistic (Appendix D-1) gives a value of 1.91 using the two-population test, which was inside the acceptance range. Therefore, the concentrated samples measured by the standard laboratory were validated for Test C0.

Both laboratories analyzed two blank samples. For these samples, the standard laboratory results were lower than the detection limit of 0.01 mg/L, and the control laboratory results were 0.008 mg/L and 0.007 mg/L. Assuming that the blank concentrations measured by the standard laboratory are null for concentrations lower than 0.01 mg/L (this was the assumption made for the computation of flow rates when the concentration measured by the standard laboratory was lower to 0.01 mg/L), the hypothesis test on paired samples did not permit the validation of the blank concentrations (Table 5-3). However, the test on the mean differences verified the accuracy associated with the blank samples. Therefore, the blank concentrations measured by the standard laboratory during Test C0 were judged accurate enough to be used to validate the reference flow meter.

For the diluted samples, nine pairs of samples were collected for the validation of the concentrations measured by the standard laboratory. Results show that the paired samples did not stand up to the hypothesis that they have a zero mean assuming a significance level of five percent. However, the test on the mean value and standard deviation of the paired samples indicated that the concentrations measured by the two laboratories were within their accuracy margins. The mean concentration of the paired samples was equal to 0.06 mg/L with a standard deviation lower than 0.05 mg/L. Therefore, the diluted concentrations measured by the standard laboratory were considered accurate enough to be used to validate the reference flow meter.

Table 5-3. Validation Chart for Test C0

Samples	Hypothesis Test (mg/L)			Accuracy Test (mg/L)			Validation Result
	Lower Limit	Test Statistic	Upper Limit	Lower Limit	Value	Upper Limit	
Concentrated	-2.05	1.91	2.05	-0.04	0.013	0.04	Accepted
Blank	-12.7	-15.0	12.7	-0.015 (Mean)	-0.008 0.001	Mean 0.015 SD 0.05	Accepted
Diluted	-2.31	5.52	2.31	-0.06 (Mean)	0.06 0.032	Mean 0.06 SD 0.05	Accepted

5.2.4 Validation Results for Test C3

For Test C3, two analyses with the concentrated samples were done. In the first analysis, the standard laboratory analyzed 25 samples and the control laboratory analyzed five. The 25 samples analyzed by the standard laboratory originated from five different bottles, each being analyzed five times, while the five samples analyzed by the control laboratory were produced from a single sampling bottle. The mean concentration measured by the standard laboratory was 42,900 mg/L compared to 38,400 mg/L for the control laboratory.

Considering the significant difference between the mean concentrations measured by the two laboratories, a second analysis was conducted. Samples of the five bottles analyzed by the standard laboratory were sent to the control laboratory for analysis. From these five bottles, 25 aliquots were created and analyzed. The new results obtained by the control laboratory produced a mean concentration of 44,000 mg/L, and confirmed that the mean concentration initially measured was too low.

Using the lithium concentrations obtained during the second analysis, the test statistic computed using the two-population test (Appendix D-1) gave a value slightly outside the acceptance limits considering a level of significance of 0.05 (Table 5-4). However, the mean concentration validation test gives for the validation variable -0.026, a value within the validation limits.

Table 5-4. Validation Chart for Test C3

Sample	Hypothesis Test (mg/L)			Mean Test (mg/L)			Validation Result
	Lower Limit	Test Statistic	Upper Limit	Lower Limit	Value	Upper Limit	
Concentrated Analysis 1	-2.05	4.55	2.05	-0.04	0.11	0.04	Rejected
Concentrated Analysis 2	-2.01	-2.35	2.01	-0.04	-0.026	0.04	Accepted
Blank	-12.71	-0.62	12.71	Mean -0.015	-0.007 0.015	Mean 0.015 SD 0.05	Accepted
Diluted	-2.37	3.23	2.37	Mean -0.06	0.04 0.035	Mean 0.06 SD 0.05	Accepted

Both laboratories analyzed two blank samples. For both samples, the standard laboratory measured a lithium concentration greater than 0.01 mg/L. For Test C0, it was possible to validate the concentration of the blank samples using a hypothesis test on paired sample data. However, the reliability of the test was limited due to the very small number of samples analyzed. For the two, paired samples the degree of freedom of the test was one, which implied a large validation range for the null hypothesis. Nevertheless, the test statistic was small (-0.62), which indicated that the mean concentration of the paired samples is close to zero.

The validity of the blank samples measured by the standard laboratory was also confirmed by the evaluating whether the mean difference concentration was within the mean value validation limits. For the blank samples, the mean concentration is –0.007 mg/L, which was inside the ±0.015 mg/L validation limits. Therefore, considering the results obtained with the two validation tests, the blank concentrations measured by the standard laboratory are accepted, which means they were accurate enough to validate the reference flow meter.

For the diluted samples, nine pairs were collected for the validation analysis of the concentration measured by the standard laboratory. The first results provided by the control laboratory showed a mix-up of three sample concentrations, probably due to a handling deviation during the sample labeling. To ensure that the unexpected results were caused by a handling deviation, the standard laboratory reanalyzed the three samples, and the samples were sent to the control laboratory for another analysis. The results from the second analysis matched.

Results show that the paired samples do not stand up to the hypothesis that the paired sample data have a zero mean assuming a significance level of five percent. However, the test on the mean value and standard deviation of the paired samples indicates that the concentrations measured by the two laboratories are within the margin of accuracy. The mean concentration of the paired samples was equal to 0.04 mg/L with a standard deviation of 0.042 mg/L. Therefore, the diluted concentrations measured by the standard laboratory were considered accurate enough to be used to validate the reference flow meter.

5.2.5 Conclusion

In order to use a lithium dilution test to validate the reference flow meter, all three sources of data (i.e. concentrated, blank and diluted) must be accepted according to the validation tests described above. If one is not accepted, it is assumed that the flow rates computed using the lithium concentrations measured by the standard laboratory did not have the level of accuracy necessary to validate the reference flow meter.

In this application, all three sources of concentrations were accepted for Tests C0 and C3. Therefore, all flow rates computed using the lithium concentrations measured by the standard laboratory could be used to validate the reference flow meter.

5.3 Validation of the Reference Flow Meter

This section presents the methods used and the results obtained to verify and validate the reference flow meter data. Two methods were used to verify the accuracy of the reference flow meter and to validate the reference flow data: the tracer dilution and the flow under the gate.

5.3.1 Validation Methods

To demonstrate that the reference flow meter was accurate and that it exhibited no bias, the reference flow data was compared to that obtained with the tracer dilution and the flow under the upstream gate for replicas C0 and C3, and compared with flow under the downstream gate for Tests B and D.

5.3.1.1 Qualitative Analysis

To assess qualitatively the validity of the reference flow data, two types of figures were produced:

1. *Reference meter verification: flow rate measurements*: These figures present, in the case of replicas C0 and C3, the flow rate output by the reference flow meter, the flow rate calculated from the tracer dilution and the flow rate estimated from the equation of the flow under the upstream gate (energy balance equation). For replicas C0 and C3, the flow rate from the gate equation is actually the sum of the flow under the upstream gate and the flow from the Craig Collector (which is measured at its downstream end), delayed by 15 minutes to account for travel time between the gate (and Craig Collector) and the reference testing site. Therefore, this flow rate is given as a rough approximation only. In the case of the three replicas of Tests B and D, there is no tracer dilution data and the flow rate is calculated from the gate equation for the downstream gate without any modification.

2. *Reference flow rate comparison: reference meter versus dilution*: These figures present the flow rate output by the reference flow meter as a function of the flow rate calculated from the tracer dilution (replicas C0 and C3). The y = x (or 1:1) line is drawn as an indication of a perfect fit between the two data sets. The correlation coefficient r (between the flow data and the y = x line) is also presented. A perfect fit would generate an r of 1.

5.3.1.2 Statistical Analysis

A hypothesis test on paired sample data (replicas C0 and C3) was performed to assess the validity of the reference flow meter. In the paired sample hypothesis test, a new data set was calculated, consisting of the differences between the flow rates measured by the reference flow meter and those computed from tracer dilution. The hypothesis test was then performed as a one-population test on the differences. This test validated whether the new population made of paired data has a zero mean. The idea consists in validating whether the mean of the paired samples was significantly different from zero, with a given level of significance, assuming that the paired data population has a zero mean (the null hypothesis).

5.3.1.3 Reference Flow Deviation Distribution Analysis

This test consisted in drawing the bar chart of the flow deviation distribution for which the deviation is defined as follows:

$$\Delta Q = \frac{Q_{dilution} - Q_{reference}}{\left(Q_{reference} + Q_{dilution}\right)/2} \tag{5-4}$$

The reference flow deviation distribution test is the only test described in the protocol for which a quantitative assessment is done. In order to validate the measurements produced by the reference flow meter, 95 percent of the flow deviation data (ΔQ) must be included within the acceptance range. According to the protocol, the acceptance limits are ±0.095 during dry weather flow and ±0.087 during wet weather flow. These acceptance margins were re-evaluated during the course of the project to better account for uncertainties related to the concentrations measured by the laboratories. Using the concentration accuracy margins obtained experimentally, the lowest acceptance margins were –0.1066 and –0.1288 for dry and wet weather flows, respectively. Upper acceptance limits were 0.1074 for dry weather flow and 0.1355 for wet weather flow (Appendix D-7). The wet-weather flow of 2.57 MGD (112.5 L/sec) was defined as 1.5 times the maximum dry-weather flow of 1.71 MGD (75 L/sec).

The test also included two qualitative assessments. To accept the flow rates measured by the reference flow meter, the frequency distribution of ΔQ must resemble a bell-shaped curve and the mean deviation must be close to zero.

The frequency distribution plots are presented with two-percent increments and additional information on each figure, including the:

- Margin of deviation (±*X* percent) that contains 95 percent of all measurements (i.e. standard deviation ±2σ);
- Percentage of measurements within a margin of deviation of ±8.7 percent (wet weather tracer dilution deviation);
- Percentage of measurements within the re-evaluated margin of deviation of ±13.55 percent (wet weather tracer dilution deviation);
- Mean deviation of all measurements; and
- Median deviation (provides an indication of the spread).

5.3.2 Test C0 Results

5.3.2.1 Qualitative Analysis

Figure H-142 presents flow rates output by the reference flow meter, flow rates calculated from the tracer dilution and, as an indication, flow rates estimated from the equation of the flow under the gate for the upstream gate (with modifications for the Craig Collector and travel time). Tracer dilution data points are presented with two markers: the dark circles are data taken during transition periods (rising and ebbing water profiles) and the hollow circles are data taken during stable flow conditions. This segregation is used for later analysis. The reference meter and tracer dilution data points were very close, with some minor differences at higher flows of 17.1 and 29.7 MGD (750 and 1,300 L/sec). The estimation of the flow under the gate also followed the reference flow meter curve very closely.

Figure H-120 presents flow rates output by the reference flow meter as a function of flow rates calculated from the tracer dilution. Again, two markers were used to segregate data points taken during transition and stable periods. The larger deviations from the y = x (or 1:1) line were the data points during transition periods and during higher flows. The correlation coefficients (r) calculated from all data points and from stable conditions only were very close to 1.

Qualitatively, these two figures show that the flow rates output by the reference flow meter were very close to those calculated from tracer dilution (and from those estimated from the flow under the gate). There were no indications that the reference meter was poorly calibrated or malfunctioning.

5.3.2.2 Statistical Analysis

The hypothesis test on paired samples validates whether the new population made of paired flow data has a zero mean (null hypothesis test). Since the value of the test statistic (-0.528) is within the lower and upper limits (±1.990) of the validation range for the given level of significance (5 percent), the null hypothesis is accepted. This result indicates a strong probability for the paired flow data to belong to a zero mean population.

5.3.2.3 Reference Flow Deviation Distribution

Figure H-127 presents the reference flow deviation distribution for replica C0. Two of three conditions for the test to be satisfied are met: the frequency distribution approaches a normal curve and the mean deviation is close to 0 (0.3 percent). The median deviation (-0.1 percent) provides an indication of the spread of the data set. The condition that was not met is the fraction of deviation data included in the acceptance margins. Since most of Test C0 is conducted under wet weather conditions, the acceptable margin of deviation for 95 percent of measurements is ±8.7 percent according to the protocol. Only 87.8 percent of measurements are within the ±8.7 percent margin of deviation. However, as indicated in Figure H-127, 97.6 percent of measurements are within the reevaluated ±13.5 percent margin of deviation.

The largest positive deviation was 19.7 percent (at 14:30), and occurred during the transition from 8.56 to 1.71 MGD (375 to 75 L/sec). The largest negative deviation was –13.4 percent (at 15:25) and is observed at the very end of the test during maximum dry weather flow (1.71 MGD; 75 L/sec). All negative deviations larger (in absolute value) than –10.0 percent occurred during maximum dry weather flow while all positive deviations larger than +10.0 percent occurred during transition periods.

Figure H-128 presents the reference flow deviation distribution for all data points during stable conditions and those during stable conditions but without maximal dry weather flow. In both cases, the frequency distribution approaches a normal curve and the mean deviation is close to zero (-0.6 percent and -0.1 percent, respectively). The acceptable margin of deviation of ±8.7 percent for 95 percent of the measurements is met for data points during stable conditions without maximal dry weather flow (with 100 percent of measurements within this margin) and barely missed for all data points during stable conditions (with 94.4 percent of measurements within this margin).

5.3.3 Test C3 Results

5.3.3.1 Qualitative Analysis

Figure H-143 presents flow rates output by the reference flow meter, flow rates calculated from the tracer dilution and, as an indication, flow rates estimated from the equation of the flow under the gate for the upstream gate (with modifications for the Craig Collector and travel time). Tracer dilution data points are presented with two markers: the dark circles are data taken during transition periods (rising and ebbing water profiles) and the hollow circles are data taken during stable flow conditions. This segregation is used for later analysis. The reference meter and tracer dilution data points are very close at maximum dry weather flow of 1.71 MGD (75 L/sec) while the reference flow rates are always larger for the two intermediate flow rates of 8.56 and 17.1 MGD (375 and 750 L/sec), and always smaller for the highest flow rate of 29.7 MGD (1,300 L/sec).

The higher the flow rate, the lower the lithium concentration. At 29.7 MGD (1,300 L/sec), the lithium concentration is roughly 0.273 mg/L. A small deviation on the blank samples would result in a large deviation in flow rate estimation for the higher flows. Since blank samples were taken every 30 minutes, the in-between concentrations were interpolated from the two known values. This might explain the mismatch between the reference and dilution data sets. The curve of the flow under the gate is in the same vicinity as the reference flow meter curve.

Figure H-121 presents flow rates output by the reference flow meter as a function of flow rates calculated from the tracer dilution. Again, two markers are used to segregate data points taken during transition and stable periods. The larger deviations from the y = x (or 1:1) line are the data points during transition periods and during higher flows. The correlation coefficients (r) calculated from all data points and from stable conditions data points only are very close to one.

Qualitatively, these two figures show that the flow rates output by the reference flow meter are close to those calculated from tracer dilution (and from the ones estimated from the flow under the gate). There are no indications that the reference meter is poorly calibrated or malfunctioning.

5.3.3.2 Statistical Analysis

The hypothesis test on paired samples validates whether the new population made of paired flow data has a zero mean (null hypothesis of the test). Since the value of the test statistic (0.700) is within the lower and upper limits (±1.990) of the validation range for the given level of significance (5 percent), the null hypothesis is accepted. This result indicates that there exists a strong probability for the paired flow data belongs to a zero mean population.

5.3.3.3 Reference Flow Deviation Distribution

Figure H-128 presents the reference flow deviation distribution for replica C3. None of the three conditions for the test to be satisfied are met. The frequency distribution does not resemble a normal curve (two peaks), the mean deviation is decentered negatively (-2.0 percent) and only 80.5 percent of measurements are within a margin of deviation of ±8.7 percent (as indicated in the protocol for wet weather). The median deviation (-3.8 percent) is even more negatively decentered. However, as indicated on Figure H-128, 95 percent of measurements are within the reevaluated ±13.5 percent margin of deviation.

The largest positive deviation is 20.5 percent (at 7:45) and the largest negative deviation is -45.8 percent (at 8:30). Both occurred at the very beginning of the test during the maximum dry weather flow of 1.71 MGD (75 L/sec). All negative and positive deviations larger than ±10.0 percent (in absolute value) occurred during maximum dry weather flow. Negative deviations are mostly due to the intermediate flows of 8.56 and 17.1 MGD (375 and 750 L/sec) and positive deviations to the highest flow of 29.7 MGD (1,300 L/sec). Since there are more data points at intermediate flows, the curve is decentered negatively.

Figure H-131 presents the reference flow deviation distribution for all data points during stable conditions and those during stable conditions but without maximum dry weather flow for replica C3. In both cases, as for Figure H-128, none of the three conditions for the test to be satisfied are met. Only data under stable conditions without maximal dry weather flow meet the recalculated criteria of 95 percent of measurements within a margin of deviation of ±13.5 percent.

5.3.4 Test B and D Results

Figures H-138 through H-140 present flow rates from the reference flow meter and from the flow under the downstream gate equation for the three replicas of Test B, while Figures H-143 through H-145 present the same information for the three replicas of Test D. The flow under the downstream gate comes from a standard hydraulic equation. At low flows (Test B and beginning and end of Test D), the reference flow meter and gate equation curves are nearly superimposed. As the flow rate increases (Test D), the gap between the two curves also increases, with the gate equation curve always being higher. This is true for all three replicas of Test D. Therefore, the reference flow meter reacted in the same fashion each time (not a punctual malfunction).

5.3.5 Conclusion

Except for Test C3, the qualitative validation analyses show that the reference flow meter provides results representative of the flows computed using tracer dilution tests and an energy balance equation in the vicinity of sluice gates. The figures show the flow rates output by the reference flow meter, the tracer dilution, and the energy balance equation show a good match between the three time series data sets. The general behavior can be summarized as follows:

- For the highest flow rates, the measured reference flows follow closely the flows computed by the energy balance equation, but are slightly below the flows computed using tracer dilution. This observation is particularly visible for Test C3. This phenomenon could be due to an overestimation of the blank concentrations caused by contamination of the sampling bottles.

- For dry weather flows and low wet weather flows, the reference flow curve is slightly above the tracer dilution flow curve. This observation is particularly apparent for Test C3 and can be explained by the fact that the diluted concentrations of the standard laboratory were barely accepted. The diluted concentrations measured by the standard laboratory are systematically greater by 6 percent than the concentrations measured by the control laboratory. This constant offset can be the reason why the flow rates measured by the reference flow meter are systematically above the flow rates computed using tracer dilution.

For Test C3, the reference flow meter does not pass the qualitative and the quantitative validation tests for the reference flow deviation distribution. However, it appears that the validation test is strongly affected by potential problems related to the measurement of the blank and diluted concentrations. Nevertheless, using the acceptable margin of deviation determined using the updated accuracy values for lithium concentration measurements, 95 percent of the reference flow measurements are within ±13.5 percent.

5.4 Validation of the Reference Depth Meter (Bubbler)

This section presents the methods used and results obtained to validate the reference water-depth data. Two methods were used to verify the accuracy of the reference depth meter (bubbler) and to validate the reference water-depth data: manual readings and an ultrasonic depth meter.

5.4.1 Validation Methods

To demonstrate that the reference depth meter (bubbler) was accurate and exhibited no bias, the reference water depth data was compared qualitatively and quantitatively to that obtained with manual readings for Tests B, C, and D, and for all these tests combined. A frequency distribution analysis was performed with the reference depth meter for Tests B, C, and D combined.

5.4.1.1 Qualitative Analysis

To assess qualitatively the validity of the reference water depth data, two types of figures were produced:

1. *Reference meters verification: depth measurements*: These figures present water depths from the reference depth meter (bubbler), from manual readings, and from the ultrasonic depth meter for the three replicas of Test B, four replicas of Test C, and three replicas of Test D.

2. *Reference depth comparison: reference meter versus manual measurement*: These figures present water depths output by the reference depth meter as a function of the manual measurements for Tests B, C, and D, and for all these tests combined. The y = x (or 1:1) line is drawn as an indication of a perfect fit between the two data sets. The correlation coefficient (r) between the reference data and the y = x line is also presented. A perfect fit would generate an r of one.

5.4.1.2 Statistical Analysis

A statistical test (a hypothesis test on paired sample depth data) was performed to assess the validity of the reference depth data. In this test, a new data set was calculated, consisting of the differences between the depths measured by the reference depth meter and those measured manually. The hypothesis test was then performed as a one-population test on the differences. This test validates whether the new population made of paired data has a zero mean, and whether the mean of the paired samples was significantly different from zero, with a given level of significance assuming that the paired data population has a zero mean (the null hypothesis).

5.4.1.3 Reference Depth Deviation Distribution

This test consists of drawing the bar chart of the water-depth deviation distribution for which the deviation is defined as:

$$\Delta D = D_{manual} - D_{reference} \quad or \quad D_{ultrasonic} - D_{reference} \qquad (5\text{-}5)$$

The reference depth deviation distribution test is the only test described in the protocol for which a quantitative assessment is done. In order to validate the measurements produced by the reference depth meter, 95 percent of the depth deviation data (ΔD) must be included in an acceptance range. According to the protocol, the acceptance limits are ±1.25 in. (31.7 mm) or two percent full-scale. The test also includes two qualitative assessments. To accept the water depths measured by the reference depth meter, the frequency distribution of ΔD must resemble a bell-shaped curve and the mean deviation must be close to zero.

The frequency distribution plots are presented with 0.25-in. increments and additional information on each figure, including the:

- Margin of deviation (±*X* percent) that contains 95 percent of all measurements (i.e., standard deviation ±2σ);
- Percentage of measurements within a margin of deviation of ±1.25 in. (31.7 mm) or two percent full scale;
- Mean deviation of all measurements; and
- Median deviation (provides an indication of the spread).

Qualitative and statistical analyses are presented for Test B, C, and D and for these three tests combined.

5.4.2 Test B Results

5.4.2.1 Qualitative Analysis

Figures H-146 through H-148 present water depths from the reference depth meter (bubbler), manual readings, and reference ultrasonic depth meter for the three replicas of Test B, respectively. Generally, all three curves are superimposed except at the very beginning of replicas B1 and B2 (at 9:00) and during two purges of the bubbler (at 9:10 and 13:10 during replica B2).

Figure H-122 presents water depths output by the reference depth meter as a function of manual measurements. The larger deviations from the y = x (or 1:1) line are the data points during the transition period from the 18-in. back flow to the 36-in. back flow. During this transition and under the 36-in. back flow, the reference depth meter seems to slightly underestimate the water depths compared to the manual readings, although the correlation coefficient (r) is very close to one.

Qualitatively, these four figures show that the water depths output by the reference depth meter are very close to the manual readings and those from the ultrasonic depth meter. There are no indications that the reference depth meter was poorly calibrated or malfunctioning.

5.4.2.2 Statistical Analysis

The hypothesis test on paired samples validates whether the new population made of paired data has a zero mean (null hypothesis of the test). Since the value of the test statistic (16.39) is outside the lower and upper limits (±1.972) of the validation range for the given level of significance (five percent), the null hypothesis is rejected. This result indicates that there is a strong probability that the paired depth data do not belong to a zero mean population. The two sets of data come from populations having very small standard deviations. Therefore, even though the depth measurements are almost the same, the intersection covered by the distributions of the two populations is small, independent of the values measured. The statistical test reveals a measurement bias between the bubbler and the manual readings.

5.4.2.3 Reference Depth Deviation Distribution Analysis

Figure H-132 presents the reference depth deviation distribution for Test B (bubbler versus manual measurements). All conditions for the test to be satisfied are met. The frequency distribution approaches a normal curve, the mean deviation is close to the median deviation, which is also close to zero (mean deviation 0.39 in.; 9.9 mm); and more than 95 percent of measurements are within the acceptable margin of deviation according to the protocol (2 percent full-scale: 1.25 in.; 31.7 mm).

5.4.3 Test C Results

5.4.3.1 Qualitative Analysis

Figures H-149 through H-152 present water depths from the reference depth meter (bubbler), manual readings, and reference ultrasonic depth meter for the four replicas of Test C. Water depths from the three instruments vary more than for Test B, principally due to the presence of stationary waves during these tests. Replicas C0, C1, and C3 present the same pattern: reference depth measurements are lower than manual readings but higher that the ultrasonic readings during the 17.1 MGD (750-L/sec) stable period, while the opposite is found at the 29.7 MGD (1,300-L/sec). During the two 8.56 MGD (375-L/sec) stable periods, manual readings were usually closer to the ultrasonic data points. Both manual readings and ultrasonic depths were affected by stationary waves (may be at the crest or trough), whereas the bubbler buffers the information over a larger volume of water. It should be noted that the manual readings were taken close to the bubbler site.

Figure H-123 presents water depths output by the reference depth meter as a function of manual measurements. At lower depths, data points are generally on the perfect-fit line and then, as the depth gets higher, they oscillate on each side of the line. Despite this fact, the correlation coefficient (r) is relatively close to one (0.984).

Qualitatively, these five figures show that the water depths output by the reference depth meter were somewhat different from the manual readings and those from the reference ultrasonic depth meter test due to the presence of stationary waves at higher flow rates. As previously mentioned, manual readings and the ultrasonic depth meter data were strongly affected by waves (punctual measurement can be at the crest or trough of waves) whereas the bubbler was less affected.

5.4.3.2 Statistical Analysis

The hypothesis test on paired samples validates whether the new population made of paired data has a zero mean (null hypothesis of the test). Since the value of the test statistic (0.723) was within the lower and upper limits (± 1.967) of the validation range for the given level of significance (five percent) the null hypothesis was accepted. This indicates that there was a strong probability for the paired depth data to belong to a zero mean population.

5.4.3.3 Reference Depth Deviation Distribution Analysis

Figure H-133 presents the reference depth deviation distribution for Test C (bubbler versus manual measurements). Only one condition for the test to be satisfied was met. The mean deviation was very close to zero (0.05 in. (1.3 mm)). The frequency distribution only vaguely resembled a normal curve and less than 95 percent of the measurements (77.8 percent) were within the acceptable margin of deviation according to the protocol (two percent full-scale, or 1.25 in. (31.7 mm)). The deviations larger than ±1.25 in. were positive deviations collected during the 17.1 MGD (750-L/sec) flow period. Since during this period the reference depth meter did not measure the same depth (due to the distance between the two measurement devices and the presence of a non-negligible stationary wave), it was legitimate not to consider these data in the frequency distribution test. The resulting frequency distribution graph resembles a bell-shaped curve and the quantitative frequency distribution test was satisfied.

5.4.4 Test D Results

5.4.4.1 Qualitative Analysis

Figures H-153 through H-155 present water depths from the reference depth meter (bubbler), manual readings and reference ultrasonic depth meter for the three replicas of Test D, respectively. Generally, all three curves are superimposed except under back-flow conditions, when the ultrasonic becomes out of range (maximum reading of 40.2 in. [1,022 mm]).

Figure H-124 presents water depths output by the reference depth meter as a function of manual measurements. Most data points were very close to the y = x (or 1:1) line. The larger deviations were recorded during the transition period from back flow conditions to maximum dry weather flow without back flow. The correlation coefficient (r) is one.

Qualitatively, these four figures show that the water depths output by the reference depth meter are close to the manual readings and those from the reference ultrasonic depth meter. There are no indications that the reference depth meter was poorly calibrated or malfunctioning.

5.4.4.2 Statistical Analysis

The hypothesis test on paired samples validates whether the new population made of paired data has a zero mean (null hypothesis of the test). Since the value of the test statistic (1.22) was inside the lower and upper limits (±1.968) of the validation range for the given level of significance (five percent), the null hypothesis was accepted. This indicates that a strong probability for the paired depth data to belong to a zero mean population exists.

5.4.4.3 Reference Depth Deviation Distribution Analysis

Figure H-134 presents the reference depth deviation distribution for Test D (bubbler versus manual measurements). The three conditions for the test to be satisfied are met: the mean deviation was very close to zero (0.04 in.; 1.0 mm), the frequency distribution resembled a normal curve and more than 95 percent of the measurements were within the acceptable margin of deviation (two percent full-scale) noted in the protocol.

5.4.5 Tests B, C, and D Combined

5.4.5.1 Qualitative Analysis

Figure H-125 presents water depths output by the reference depth meter as a function of manual measurements. Most data points were very close to the y = x (or 1:1) line. The larger deviations were from Test C. The correlation coefficient (r) was very close to 1.

5.4.5.2 Reference Depth Deviation Distribution Analysis

Figure H-135 presents the reference depth deviation distribution for Tests B, C, and D (bubbler versus manual measurements). Two of the three conditions for the test to be satisfied were met. The frequency distribution resembled a normal curve and the mean deviation was very close to zero (0.13 in.; 3.3 mm). Less than 95 percent of the measurements (88.9 percent) were within the acceptable margin of deviation according to the protocol (two percent full-scale, or 1.25 in. [31.7 mm]). This last observation reflects the measurement differences observed for Test C during the presence of stationary waves.

Figure H-136 presents the reference depth deviation distribution for Tests B, C, and D (bubbler versus reference ultrasonic depth meter). Only one of the three conditions for the test to be satisfied was met. The mean deviation was very close to zero (-0.20 in.; -5.1 mm). The frequency distribution only vaguely resembled a normal curve and less than 95 percent of the measurements (79.7 percent) were within the acceptable margin of deviation (two percent full-scale) noted in the protocol.

5.4.6 Conclusion

Except for Test C, the qualitative validation analyses showed that the reference depth meter provides results that were representative of the manual readings and the depths measured by the ultrasonic depth meter. The figures showing the water depths output by the reference depth meter, the manual readings, and the ultrasonic depth meter showed a good match between the three time series. The general behavior observed can be summarized as:

- Under normal conditions, the measured reference depths closely followed the water depths obtained by manual readings and by the ultrasonic depth meter. However, during replicas B1, B2, and B3, a relatively constant measurement offset was observed and detected by the statistical test. This offset was small, however, and could probably be eliminated by a slight readjustment to the calibration of the measurement devices.

- In the presence of stationary waves (Test C), significant depth differences were observed for the three measurement devices. However, these differences were not related to bad calibration or malfunctioning of the reference depth meter. The distance existing between the different depth meters can explain these results.

From these observations and the qualitative and quantitative results obtained for the different validation tests, the reference depth meter appears to be a valuable measurement device that can be used to generate reference depth data.

Appendices

Glossary

Accuracy - a measure of the closeness of an individual measurement or the mean of a number of measurements to the true value and includes random error and systematic error.

Bias - the systematic or persistent distortion of a measurement process that causes errors in one direction.

Comparability – a qualitative term that expresses confidence that two data sets can contribute to a common analysis and interpolation.

Completeness – a qualitative term that expresses confidence that all necessary data have been included.

Precision - a measure of the agreement between replicate measurements of the same property made under similar conditions.

Protocol – a written document that clearly states the objectives, goals, scope, and procedures for the study. A protocol shall be used for reference during vendor participation in the verification testing program.

Quality Assurance Project Plan – a written document that describes the implementation of quality assurance and quality control activities during the life cycle of the project.

Representativeness - a measure of the degree to which data accurately and precisely represent a characteristic of a population parameter at a sampling point, a process condition, or environmental condition.

Wet Weather Flows Stakeholder Advisory Group - a group of individuals consisting of any or all of the following: buyers and users of flow monitoring technologies, developers and vendors, consulting engineers, the finance and export communities, and permit writers and regulators.

Standard Operating Procedure – a written document containing specific procedures and protocols to ensure that quality assurance requirements are maintained.

Technology Panel - a group of individuals with expertise and knowledge of flow monitoring technologies.

Testing Organization – an independent organization qualified by the Verification Organization to conduct studies and testing of flow monitoring technologies in accordance with protocols and Test Plans.

Vendor – a business that assembles or sells flow monitoring equipment.

Verification – to establish evidence on the performance of flow monitoring technologies under specific conditions, following a predetermined study protocol(s) and test plan(s).

Verification Organization – an organization qualified by EPA to verify environmental technologies and to issue verification statements and verification reports.

Verification Report – a written document containing all raw and analyzed data, all quality assurance/quality control (QA/QC) data sheets, descriptions of all collected data, a detailed description of all procedures and methods used in the verification testing, and all QA/QC results. The test plan(s) shall be included as part of this document.

Verification Statement – a document that summarizes the Verification Report reviewed and approved and signed by EPA and NSF.

Verification Test Plan – a written document prepared to describe the procedures for conducting a test or study according to the verification protocol requirements for the application of flow monitoring technology. At a minimum, the test plan shall include detailed instructions for sample and data collection, sample handling and preservation, precision, accuracy, goals, and QA/QC requirements relevant to the technology and application.