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Performing Quality Flow Measurements at Mine Sites

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Performing Quality Flow Measurements at Mine Sites

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Cincinnati, Ohio 45268

National Risk Management Research Laboratory
Office of Research and Development
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Cincinnati, OH 45268

NOTICE

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FOREWORD

The U.S. Environmental Protection Agency 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 is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threatens 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.

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E. Timothy Oppelt, Director
National Risk Management Research Laboratory

ABSTRACT

Accurate flow measurement data is vital to research, monitoring, and remediation efforts at mining sites. This guidebook has been prepared to provide a summary of information relating to the performance of flow measurements, and how this information can be applied at mining sites. Information presented in this guidebook includes the theory, methods, selection criteria for these methods, and quality assurance/quality control (QA/QC) guidance for performing flow measurements at mining sites.

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LIST OF ACRONYMS

ADCPs	Acoustic Doppler Current Profilers
ADVs	Acoustic Doppler Velocimeters
AVM	Acoustic Velocity Meter
BMPs	Best Management Practices
BOR	Bureau of Reclamation
CAA	Clean Air Act
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
cfs	Cubic Feet per Second
cms	Cubic Meters per Second
CWA	Clean Water Act
EGL	Energy Grade Line
EPA	U.S. Environmental Protection Agency
FSs	Feasibility Studies
ft/s	Feet per Second
ft^2	Square Feet
gpm	Gallons per minute
HGL	Hydraulic Grade Line
l/s	Liters per Second
LDVs	Laser Doppler Velocimeters
LiBr	lithium bromide
MDLs	Method Detection Limits
MWTP	Mine Waste Technology Program
NaBr	Sodium Bromide
NaCl	Sodium Chloride
NEPA	National Environmental Policy Act
NPDES	National Pollutant Discharge Elimination System
NRCS	U.S. Natural Resource Conservation Service
NRMRL	National Risk Management Research Laboratory
QA	Quality assurance
QA/QC	Quality Assurance/Quality Control
QAPP	Quality Assurance Project Plan
QC	Quality Control

LIST OF ACRONYMS (continued)

RI/FS	Remedial Investigations/Feasibility Studies
RIs	Remedial Investigations
RPD	Relative Percent Difference
RSD	Relative Standard Deviation
SCS	Soil Conservation Service
SME	Society of Mining Metallurgy and Exploration
TMDL	Total Maximum Daily Loads
USGS	United States Geological Survey

1.0 INTRODUCTION

Mining projects have historically impacted the quantity, velocity, and timing of surface water flow by altering natural drainage patterns and the infiltration/runoff relationships in a watershed. Mine structures, such as waste rock dumps, tailings impoundments, leach facilities, and process facilities potentially impact natural stream systems through discharges of storm water and wastewater, impounding water, changing the character of gaining and losing stream reaches through mine dewatering, mining through stream channels and flood plains, and by diverting, re-routing, and channelizing streams. Waste dumps, tailings impoundments, mine pits and other facilities often become permanent features of the post-mining landscape that can cause fundamental changes in the physical characteristics and behavior of a watershed (O'Hearn, 1997). Measurement of mine facility discharges, therefore, are critical to understanding environmental impacts created by post-mining operations.

1.1 PURPOSE AND NEED OF GUIDEBOOK

The U.S. Environmental Protection Agency (EPA) is responsible for ensuring that mining operations do not adversely impact the environment during construction, operation, or following mine closure. EPA's authority is granted under provisions of the National Environmental Policy Act (NEPA), the Clean Water Act (CWA), and the Clean Air Act (CAA). The EPA National Risk Management Research Laboratory (NRMRL), Sustainable Technology Division, houses the Mine Waste Technology Program (MWTP). As a part of this program, both basic and applied research projects are conducted relating to the treatment of wastes associated with or generated by mines. Environmental monitoring programs, as well as research projects, require accurate measurements of discharges from mine facilities and of stream flows both above and below mine sites. Accurate flow measurements provide the foundation for successful environmental monitoring programs and research designed to minimize, reduce or prevent pollutant loading from mine facilities. Accurate flow measurements are critical to analyze potential short- and long-term impacts to site hydrology, water quality, aquatic biota and ecosystems.

The purpose of this guidebook is to outline and provide comparative information of different methods used to measure stream flow or mine facility discharges. This guidebook presents tools appropriate for selecting measurement methods appropriate for the needed application. The guidebook is designed for personnel and engineers responsible for developing plans of operation, conducting site characterization studies and research of hydrologic and water quality systems, designing hydrologic control structures, designing Best Management Practices (BMPs), or developing environmental monitoring programs at mine sites.

1.2 ORGANIZATION OF GUIDEBOOK

The guidebook is divided into five separate sections. Section 2.0 of this guidebook describes basic concepts related to flowing water and measurement. This section has been provided because a general understanding of these concepts is extremely important in choosing an appropriate method to obtain flow measurements, determining appropriate sites for measurement, and in implementing the method in the field. Section 3.0 provides descriptions of accepted methods used to measure flow, describes siting criteria for measurements, and provides useful information for understanding when to use and or not to use a particular measurement. Section 4.0 provides a comparison of methods, including selection criteria, thereby summarizing some of the information in Section 3.0 in order to assist with selection of the appropriate measurement method. Section 4.3 provides a discussion of some typical scenarios at mine sites where flow measurements are required and recommends methods which could be used. A discussion of Quality Assurance/Quality Control (QA/QC), specific to mine flow measurements, is provided in Section 5.0. Appendix A provides background information describing types of mine facilities, potential impacts to site hydrology, water quality, and aquatic resources, and the importance of flow measurements to other EPA programs and site characterization studies. This appendix has been included because background knowledge of typical mine features, waste facilities and dumps, and process operations is important when outlining objectives for flow and water quality studies and in choosing flow measurement methods.

2.0 BASIC CONCEPTS OF OPEN CHANNEL FLOW MEASUREMENT

Open channel flow is defined as flow in any channel where the liquid flows with a free surface. Open channel flow is not under pressure; gravity is the only force that can cause flow in open channels and a progressive decline in water surface elevation always occurs as the flow moves downstream (BOR, 1997). Examples of open channel flow at mine sites include: rivers, streams, creeks, discharges from tailings ponds, and other uncovered conduits. Closed channels, such as adits, tunnels, and ventilation shafts, can be treated as open channels when flowing partially full and not under pressure.

The purpose of Section 2.0 is to briefly introduce the reader to basic terminology and concepts related to open channel flow to allow for a simpler and more accurate presentation of the flow measurement techniques and methods in Section 3.0. A working knowledge of these concepts and relationships is extremely important in selecting the appropriate measurement tool as well as siting, calibrating, and collecting data from the chosen measurement device. This section is included as a supplement to this document and offers background information that some readers may already understand. It is not meant as a complete discussion of each concept but more as a summary discussion. Cited references offer more in depth explanations if desired.

2.1 BASIC WATER MEASUREMENT CONCEPTS

Most open channel water measuring devices or methods calculate stream discharge from a combination of head, stage, and velocity measurements with respect to a common reference point. These terms are described below:

2.1.1 Gage Datum

Gage datum is a common elevation selected as a reference point for subsequent measurements and calculations pertaining to gage installation, calibration, and operation. The datum may be a recognized datum (e.g., mean sea level) or an arbitrary datum chosen for the convenience of measuring gage heights in relatively low numbers. When using an arbitrary datum, the datum selected for gage operations should be below the zero flow, or no flow elevation to eliminate the possibility of negative gage heights (Buchanan and Somers, 1982).

A permanent datum should be maintained to ensure that the gage-height record uses the same datum for the life of a gage. The permanent datum can be maintained by establishing two or three reference marks that are independent of the gage. The reference marks are periodically checked to make sure the datum is fixed in the same location. Establishing reference marks independent of the gage allows the datum to be reestablished if the gage is damaged or destroyed (Buchanan and Somers, 1982).

2.1.2 HEAD

Head is an engineering term frequently used in water measurement equations and practice. Under open channel flow conditions, head is the difference in elevation, relative to a specific datum, between the water surface elevation at locations upstream and downstream of the water measurement location. The resulting pressure on the fluid at the downstream point is expressible as the elevational difference, or head. Head can also be expressed in terms of differences in pressure.

2.1.3 STAGE

Stage is the height of the water surface above an established datum plane. Stage measurements are often used or incorporated into calculations to determine stream discharge within a particular channel reach. Stage is typically measured with a staff gage, a fixed scale measuring device installed in a primary measuring device (Section 3.0) or in an open channel reach where the channel configuration and channel geometry is well-defined. Staff gages are often mounted vertically; however, greater accuracy can be obtained by inclining the staff so that the graduations are larger for a given change in water surface elevation (Grant and Dawson, 1997). The water surface elevation (i.e., stage) read from the staff gage is commonly called the gage-height.

2.1.4 VELOCITY

The Manning equation relates velocity to total bed resistance or friction to calculate flow velocity (*V*). The equation balances the gravitational acceleration of water in an inclined, open channel against surface area and bed roughness. The Manning equation is intuitively appealing because of its simple form:

$$V = \frac{1.49}{n} R^{\frac{2}{3}} S^{\frac{1}{2}}$$

where:

V = flow velocity, feet per second
n = Manning roughness coefficient
R = hydraulic radius, feet
S = longitudinal slope, feet per foot

Manning's n is a dimensionless number that defines the flow resistance of a unit of bed surface. Resistance is a function of particle size, bed shape, and constructional bed forms (e.g., ripples).

Manning's n incorporates many physical factors including the channel roughness, irregularity of the channel cross section, channel alignment and bends, vegetation, sedimentation, scouring, and channel obstructions (Barfield et al., 1981). Table 2-1 presents a list of commonly used values for Manning's n.

Table 2-1. Typical Values for Manning's n

Type and Description of Conduits	**Min.**	**Design**	
Earth bottom, rubble sides	0.028	0.032	0.035
Drainage ditches, large, no vegetation			
<2.5 hydraulic radius	0.040		0.045
2.5 - 4.0 hydraulic radius	0.035		0.040
4.0 - 5.0 hydraulic radius	0.030		0.035
>5.0 hydraulic radius	0.025		0.030
Small drainage ditches	0.035	0.040	0.040
Stony bed, weeds on bank	0.025	0.035	0.040
Straight and uniform	0.017	0.0225	0.025
Winding, sluggish	0.0225	0.025	0.030
(A) Clean, straight bank, full stage, no rifts or deep pools	0.025		0.033
(B) Same as (A) but some weeds and stones	0.030		0.040
(C) Winding, some pools and shoals, clean	0.035		0.050
(D) Same as (C), lower stages, more ineffective slopes and sections	0.040		0.055
(E) Same as (C), some weeds and stones	0.033		0.045
(F) Same as (D), stony sections	0.045		0.060
(G) Sluggish river reaches, rather weedy or with very deep pools	0.050		0.080
(H) Very weedy reaches	0.075		0.150

SOURCE: Barfield et al. (1981)

Hydraulic radius (*R*) can be approximated for parabolic channels where the water surface width is >> than the depth of the water as:

$$R = \frac{2}{3} d$$

where *d* is the average depth. For channel geometries that approximate trapezoidal or rectangular cross sections and where the bottom width is >> than the average depth, R is approximately equal to average depth (*d*). The hydraulic radius of a stream with a triangular cross section can be approximated as 0.5*d* (Barfield et al, 1981). Uncertainties associated with the Manning equation can be minimized by basing the variables on accurately measured data. Specifically, the channel cross section should be surveyed to obtain accurate measurements of width, depth, and hydraulic radius.

The actual distribution of flow velocity is generally quite complex. Open channel flow is often laminar or near-laminar, with the different layers moving at different velocities. Flow velocity at the contact point with the channel boundary is low (Barfield et al., 1981). Typically, the highest velocity flow is located in the center of the flow channel and slightly below the water surface. Figures 2-1 and 2-2 present typical velocity profile and a typical vertical velocity distributions under open channel flow conditions. A general knowledge of velocity distributions is extremely important in evaluating and selecting a method of flow measurement. Sites with irregular or complicated channel geometries, such as meanders or riffle areas, can cause a decrease in measurement accuracy when using methods that rely on velocity measurements to calculate discharge. These methods and factors associated with the proper siting for measurements are described in Section 3.0.

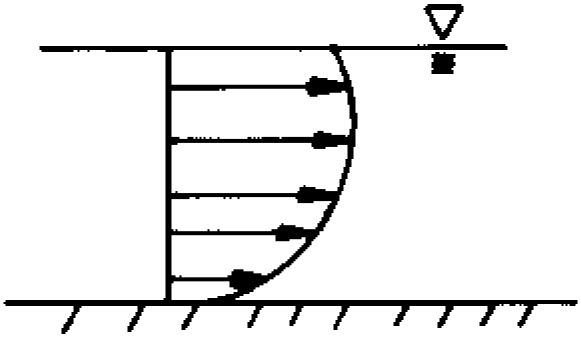


Figure 2-1. Typical Open Channel Velocity Profile (Barfield et al., 1981)

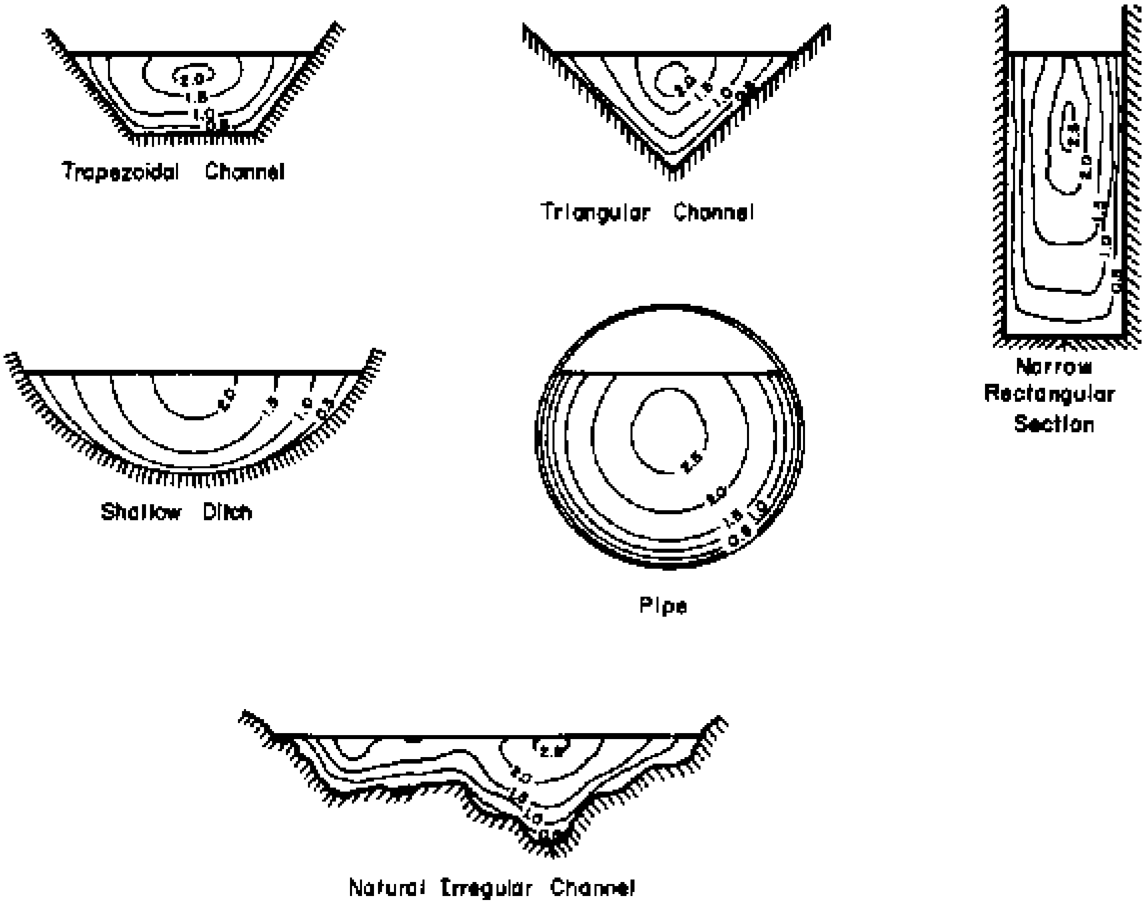


Figure 2-2. Typical Velocity Distributions for Several Channel Profiles (Barfield et al., 1981)

2.1.5 Discharge

Discharge is the volume of water per unit time flowing past a set point or station. Open channel discharge is commonly reported in cubic feet per second (cfs) or cubic meters per second (cms). Gallons per minute (gpm) is the common unit of measure used in studies to evaluate and predict mine site water balances. Gpm is also the common measurement unit for reporting industrial and wastewater treatment plant discharges. Many discharge measurements made at mine sites and from mine facilities, therefore, are converted to gpm in order to evaluate their association with the water balance for the mine.

A series of discharge measurements made at a gaging station is often used to define a discharge rating curve for a site. A discharge rating curve may be a simple relationship between stage and discharge, or a more complicated relationship that includes stage, slope, rate of stage change, and other factors (Carter and Davidian, 1968). Most methods and devices for measuring flow are designed to calculate stream discharge.

Discharge (Q) is generally expressed in cfs and is calculated from:

$$Q = VA$$

where V is the average flow velocity at a cross section, in feet per second (ft/s), and A is the area of that cross section, in square feet (ft^2) (Barfield et al., 1981). The Manning equation (Section 2.1.4) can be used to estimate average flow velocity (*V*). To obtain discharge (*Q*) in units besides cfs, the constant of 1.49 in the Manning equation can be changed to 669 if discharge (*Q*) will be reported in gpm, or 1.00 for liters per second (l/s) (Grant and Dawson, 1997). The primary measuring devices presented in Section 3.0, however, provide more accurate estimates of discharge than can be obtained using the above equation combined with estimates of average velocity obtained by the Manning equation.

2.2 OPEN CHANNEL FLOW RELATIONSHIPS

Open channel flow occurs under one of three possible flow conditions: sub-critical; critical; or super-critical. Three basic relationships govern open channel flow: the continuity equation, the momentum equation, and the energy equation. Each of the relationships is briefly described in the following sub-sections. The reader is encouraged to consult some of the hydrology and hydraulic engineering texts listed in the reference section for more information.

2.2.1 Continuity Equation

The continuity equation is a simple mass balance and can be written as:

$$Inflow - Outflow = \Delta Storage$$

where inflow represents the volume or rate of flow across an upstream cross-section during time t and outflow is the volume or rate of flow across a downstream cross section during time t. The change in storage (Δstorage) is the rate or volume at which water is accumulating or diminishing within the section.

2.2.2 Energy Equation

The energy equation, also known as Bernoulli’s theorem or equation, is given by:

$$\frac{V_1^2}{2g}+y_1+z_1+\frac{p_1}{\gamma}=\frac{V_2^2}{2g}+y_2+z_2+\frac{p_2}{\gamma}+h_{L,1-2}$$

where:

V = average flow velocity, feet per second
g = gravitational constant, 32.2 feet per second squared
y = depth of flow, feet
z = elevation of the channel bottom above some datum point, feet
p = pressure, pounds per square foot
γ = unit weight of water, 62.4 pounds per cubic foot
$h_{L,1-2}$ = represents the energy loss between section 1 and 2, feet

Bernoulli’s equation, which represents an energy balance between two points along a channel, is graphically depicted in Figure 2-3.

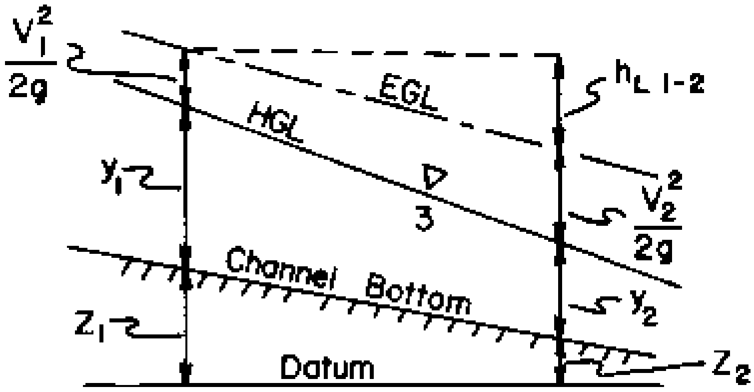


Figure 2-3. Graphical Representation of the Terms in Bernoulli’s Equation for an Open Channel (Barfield et al., 1981)

Each complete term in the equation has the units of length and each term is associated with a "head." The term $V^2/2g$ is the velocity head, $y + z$ is the elevation head, and p/γ is the pressure head (Barfield et al., 1981). Total energy is the sum of the velocity head, pressure head, and elevation head and is represented by the energy grade line (EGL) in Figure 2-3. The hydraulic grade line (HGL) is the sum of the elevation head and the pressure head. In open channel flow, the free water surface is exposed to the atmosphere so the pressure head is equal to zero. The water surface is represented by the HGL under open channel flow conditions.

Bernoulli's equation can be used to derive the Froude number (Fr) for a given stream reach. The Froude number is a dimensionless number defining the type or degree of water turbulence in a reach. The Froude number, the ratio of the inertia force to the force of gravity, can be used to distinguish between sub-critical, critical and super-critical flows. Critical flow occurs when the Froude number is unity (i.e., 1), inertial forces are equal to gravitational forces. Critical flow is unstable, tending towards one of the other two conditions. A Froude number less than unity (i.e., inertial forces are less than gravitational forces) indicates sub-critical flow. Sub-critical flow is laminar with each element of fluid moving in approximate parallel paths with uniform velocity. A Froude number greater than unity (i.e., inertial forces are greater than gravitational forces) indicates super-critical flow. Super-critical flow is turbulent, characterized by breaking surface waves and increased resistance to flow. The Froude number associated with a given reach has important implications for flow measurement, and sediment loading, transport, and erosion. Flow measurements are typically taken in reaches with sub-critical or critical flow. Very few methods can accurately measure stream discharge in stream reaches with super-critical flow. The Froude number (Fr) can be calculated from:

$$Fr = \frac{V}{\sqrt{gh_m}}$$

where V is velocity (fps), g is the gravitational constant, and h_m is hydraulic mean depth (ft). Open channel flow measurement generally requires Fr of the approach flow to be less than 0.5. Sub-critical approach flows avoid wave action that could hinder or prevent accurate flow readings (BOR, 1997).

Experience and knowledge regarding sub-critical, critical, and super-critical flow are extremely important in determining a method for measuring discharge and in siting a location for measurement. For example, water measurement flumes function best when flow is forced through the flume at a depth where flow is critical. At critical depth, discharge can be measured using one upstream head measurement station. Moreover, calibration of weirs and flumes is simplified because these measurement devices have one unique head value for each discharge (BOR, 1997).

2.2.3 Momentum Equation

The momentum principle states that the sum of forces in a given direction is equal to the change in momentum in that direction. M is a constant that represents the specific force plus momentum. In a short reach where frictional resistance is insignificant and the channel slope is small (i.e., the sine of the channel slope approaches zero), M can be derived from (Barfield et al., 1981):

$$\frac{y_1^2}{2}+\frac{qV_1}{g}=\frac{y_2^2}{2}+\frac{qV_2}{g}=M$$

where:

M = specific force plus momentum constant
y = depth of flow, feet
V = average flow velocity, feet per second
g = gravitational constant, 32.2 feet per second squared
q = flow rate per unit of width, ft^2/sec or cfs/ft

Figure 2-4 is a graphical representation of a plot of depth (y) versus M for a constant q. Every M has two possible depths and a definite minimum. At the minimum M (y_c on Figure 2-4), specific energy is minimum and only a single flow depth occurs. This condition is referred to as critical flow ($_{y.}$).

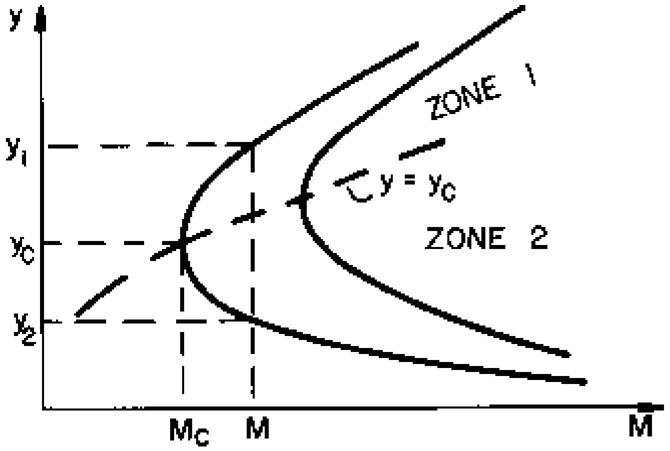


Figure 2-4. Typical Specific Force plus Momentum Curve (Barfield et al. , 1981)

Super-critical flow (y_2) occurs when depth is less than critical and velocity is greater than the critical condition. When depth is greater than critical and velocity is less than critical the flow is termed sub-critical (y_1) (Roberson et al., 1988). As previously noted, experience and knowledge regarding sub-critical, critical, and super-critical flow are extremely important in determining a method for measuring stream discharge.

3.0 MEASUREMENT METHODS

The stage (i.e., height) of water in a stream can be readily measured at some point along a stream reach with a staff gage or water level recorder. Conversion of stage to a discharge rate, or quantity of flow per unit time, can then be accomplished by stream gaging or the use of precalibrated flow measurement devices. Section 3.1 presents the use of gages for measuring and recording stage in relation to calculating discharge. Sections 3.2 and 3.3 describe the use of pre-calibrated weirs and flumes, including the appropriate use for each measurement method, and describes how the measurements are made. The remaining sections describe non-structural flow measurement devices, such as current meters, acoustic flow meters, and the application of tracers and dye dilution methods. Each section, in addition to a description of the measurement devices, discusses siting criteria for the particular devices, the importance of site selection for obtaining accurate measurements, and the applicability of the method.

3.1 GAGES

The gage is the part of the water measurement structure (e.g., weir, flume) that measures stage height, or stage height and velocity, for input into the equation to calculate discharge. Gages can also exist separate from a physical structure. A staff gage, for example, could be attached to a bridge piling and use the channel itself as the measuring structure.

Gages are either non-recording or recording types. Recording gages keep track of stage levels at preset intervals and non-recording gages require an observer to read stage height from the gage. Non-recording gages have the advantage of low initial costs and relatively simple installation. However, non-recording gages require an field observer to take regular measurements. Over time, accuracy and precision may be enhanced with a recording gage. Recording gages eliminate the need for regular field observation and allow collection of reliable, long-term stage records. Non-recording gages are discussed in Section 3.1.2 and recording gages in Section 3.1.3.

3.1.1 General Criteria for Selecting Sites to Establish Gages

Water measurement sites are typically selected after a thorough reconnaissance of the area; including examination of geologic, topographic, and other maps of the area. Tentative sites are marked on maps and the stream characteristics are examined in the field. Carter and Davidian (1968) outline basic factors to be considered when choosing a site for measuring flow. These basic factors are general siting considerations that are applicable to all measurement approaches discussed in this guidebook.

- Channel characteristics should be such that a fixed and permanent relationship can be established between stage and discharge. Good measurement sites are often located in reaches with critical or sub-critical flow (e.g., immediately upstream of riffles or falls).

- Sites that experience backwater conditions should be avoided. Poor measurement conditions occur when backwater submerges measurement structures. Backwater conditions can result from downstream tributaries, lakes, channel constrictions, tailings ponds, storm water ponds or other sources.

- The channel cross section should be known or measurable by survey, and geomorphologically stable to ensure quantification of an accurate stage-discharge relationship.

- Flow should not bypass the site in ground water (i.e., intermittent conditions), or side channels. Measurement errors can also occur in reaches where significant flow occurs through alluvial gravels in the substrate. This is often a problem at mine sites because mines are often located in remote mountainous areas where channel substrates often are composed of large cobbles and gravels. Under these conditions, accurate flow measurements can be obtained using dye-dilution or tracers methods (see Section 3.6).
- The site should be accessible under reasonably foreseeable flow and weather conditions.

3.1.2 Non-Recording Gages

A reliable record of stage can be obtained through systematic observation of a non-recording gage by a trained observer. Factors to consider when making the choice to rely on a non-recording gage include:

- Site accessibility.
- Weather.
- Length of data collection.
- Regularity of data collection.
- Hydrologic variability.

Generally, a recording gage should be selected for use at mine sites, with a non-recording back-up, unless the site is easily accessed under all weather conditions. Non-recording gages could be used if only periodic measurements are necessary or cost is a driving factor. Site access to remote gages at mine sites is often difficult. Non-recording gages will tend to miss storm driven, peak flow, or other unique events unless the observer happens to be taking readings when the event occurs. It is often impractical in remote mine areas to travel to important sites to obtain flow measurements during storm events.

Common types of non-recording gages are staff, wire-weight, float-tape, and electric-tape. These gages are described in detail below.

Staff Gage

A staff gage is used to read stage height and is a common component of most gaging stations or measurement programs. The United States Geological Survey (USGS) vertical staff gage is considered the standard. The USGS staff gage is made from one or more porcelain enameled iron sections. Each section is 4 inches wide and 3.4 feet long with measurements every 0.02 feet.

Staff gages are installed in either a vertical or inclined alignment. Vertical staff gages are commonly used as reference gages in stilling wells or as a backup gage situated in the channel outside the stilling well. Vertical staff gages can be installed on bridge pilings or other permanent, fixed structures in the river channel, providing that channel geometry is understood. Knowledge of the channel cross-section allows stage height, as measured on the staff gage, to be converted to discharge using either Manning's equation, or using a specific stage-discharge relationship if one has been developed. Inclined staff gages are constructed from heavy timber and securely attached to some permanent foundation. Inclined staff gages are less susceptible to damage by floods and floating debris because they are flush against the streambank (Buchanan and Somers, 1982).

Wire-Weight Gage

The standard type A wire-weight gage consists of a drum wound with a single layer of cable, a bronze weight attached to the end of the cable, a graduated disc, and a Veeder counter. The disc is graduated in tenths and hundredths of a foot and is permanently connected to the Veeder counter. The bronze weight is lowered until it touches the water surface. Stage is measured as a combined reading of the counter and the graduated disc (Buchanan and Somers, 1982).

Float-Tape Gage

The float-tape gage consists of a float, a graduated steel tape, a counterweight, and a pulley. The float is attached to one end of the graduated steel tape and the counterweight is attached to the other. The float is typically a 10-inch diameter copper float that rests on the water surface and is kept in place by the counterweight. Float-tape gages are commonly found inside stilling wells (Buchanan and Somers, 1982).

Electric-Tape Gage

Electric-tape gages consist of a graduated steel tape fastened to a weight, a reel for the tape, a battery, and a voltmeter or buzzer. The tape is lowered until it contacts the water surface. Contact with the water surface completes the electronic circuit and produces a signal to the voltmeter or buzzer. Electric-tape gages are typically used for measuring stage height in stilling wells or shallow ground water wells. These gages are occasionally used outside and can be particularly useful if oil is floating on the water surface. The electric-tape gage can be used to measure the oil/water interface due to the fact that oil is a dielectric (Buchanan and Somers, 1982).

3.1.3 Recording Gages

Recording gages automatically track changes in the water surface with respect to time, eliminating the need for regular site visits to read the gage. Recording gages can also be relied upon to capture more variability in the range of discharges, including extreme events, because water level is being continuously recorded or recorded at regular intervals. The two common types of water stage recorders are analogue or graphic, and digital. The analogue recorder has been used extensively since the early part of the twentieth century; however, digital recorders are becoming increasingly common. While the digital recorder is replacing the analogue, neither system is foolproof. Both systems should be installed, with the analogue as a back-up, at particularly important or sensitive sites (British Columbia, 1998).

Water stage recorders can either be connected to a float located in a stilling well or to a bubbler or submersible pressure sensor. The stilling well is fastened to the channel bottom or water measurement device; intake pipes ensure that the water level in the stilling well is equal to the water level in the channel or measuring device. Stilling wells are used, instead of measuring stage directly off the water surface, to protect the stage recorder and minimize fluctuations in the water surface caused by wind and waves. The bottom of the stilling well must be lower than the minimum anticipated stage and the top above the maximum expected stage. Intakes should be properly sized to prevent lag during rapid stage changes and prevent velocity-head effects in the stilling well. Bubbler or submersible pressure sensors do not require the use of a stilling well. These devices are not affected by small fluctuations in water surface elevation caused by wind or waves because they rely on pressure (i.e., head) measurements taken inside the water column. Accuracy of these devices, however, can be affected by changes in barometric pressure.

Digital Recorder

Digital recorders use electronic sensors and data loggers to record and store water level information in database ready digital format. Data can be downloaded from the data logger to a personal computer for easier, faster, and more accurate compilation of recorded values. Digital recorder technology has progressed to the point where data on water quality and meteorology, in addition to water level, can be collected with a single recorder (British Columbia, 1998). Digital recorders can also be set up for remote access via telephone or the internet. Several varieties of digital recorders are available, including ultrasonic level sensors, submersible pressure sensors, and pressure measurement sensors or bubbler gages.

Ultrasonic sensors send out a series of sound waves through the air, the sound waves strike the water surface and bounce back to the sensor. Total transit time from the sensor to the water surface and back is related to the distance traveled and water stage. Ultrasonic sensors are non-invasive, requiring no physical contact with the channel being measured (British Columbia, 1998). This can be advantageous in situations where periodic flooding might carry away a conventional gage station or water quality concerns (e.g., pH extremes or metals) might affect the longevity or reliability of the recording device. Accuracy can be affected if environmental conditions (i.e., temperature, pressure, humidity) change the travel speed of the sound wave.

Submersible pressure sensors measure water stage with a pressure transducer mounted at a fixed depth in the water column. The sensor transmits an analogue or digital signal to the data logger through underwater conductors. A submersible pressure sensor also, generally, has a vent tube that allows the sensor to equilibrate itself to changes in barometric pressure. Submersible pressure sensors are relatively inexpensive, easy to install, and accurate. Analogue sensors can have an accuracy as good as 0.1 percent and digital sensors can be as accurate as 0.02 percent or better. Submersible pressure sensors typically have to be replaced if leaks develop; generally the electronics will be damaged beyond repair (British Columbia, 1998). Submersible pressure sensors are not affected by wind, turbulence, floating foam, or debris.

Pressure measurement, or bubbler, sensors are highly accurate digital sensors which measure the gas pressure required to generate a bubble at the end of a submerged orifice line. The pressure required to create the bubble is proportional to the water head above the orifice. Bubbler sensors cost less than submersible digital sensors and the only component in the water is the low cost orifice line. The sensor and the pressure source, nitrogen tank or battery compressor, are located in a shelter outside the channel. The bulky pressure tank is the main disadvantage to bubbler sensors; accuracy is similar to submersible digital sensors (British Columbia, 1998). Bubbler sensors are also not affected by wind, turbulence, floating foam, or debris.

Graphic Recorder

Graphic recorders chart a continuous trace of water stage with respect to time. Stage is recorded on a strip-chart or drum recorder with a pen or pencil attached to the gage-height element.

Most graphic recorders can record an unlimited range by a stylus reversing device or by unlimited rotation of the drum. Strip-chart recorders can be operated for several months between servicing. These types of recorders are extremely practical and cost effective at mine sites that often require monitoring of stream flow at remote locations in upper portions of a watershed or on important tributaries entering a site. Drum recorders need to be serviced weekly (Buchanan and Somers, 1982).

3.2 WEIRS

Weirs are the simplest, least expensive, and probably the most common type of device for measuring open channel flow. A weir is simply an obstruction or dam built across an open channel. The weir basin is formed by partial impoundment of water behind the weir face. The impoundment is only partial because water will continue to flow over the weir crest, the top edge of the weir plate. Typically water flows over the weir crest through a notch cut in the center of the weir crest. The notch can be V-shaped, rectangular, or trapezoidal (Grant and Dawson, 1997). Weirs are named for either the shape of the weir notch, as in 'sharp-crested weirs', or for the shape of the flow control section, as in 'broad-crested weirs'. Both types are discussed in subsequent sections.

Weirs can be temporary or permanent measurement fixtures. Portable sharp-crested weirs may be used to measure small flows in earthen channels or lined tunnels. A simple weir for measuring flows in small earthen channels can be constructed from a stiff piece of metal cut in the shape of, but somewhat larger than, the channel cross section. A carefully cut weir notch is located along the top edge of the metal sheet. The metal sheet is forced into the channel bottom and sides, perpendicular to the direction of flow. The crest is adjusted until level. Portable long-throated flumes can be used at sites where insufficient head exists for sharp-crested weirs (see Section 3.3). In larger channels, weir plates are installed in bulkheads that have been sealed and sandbagged into place to prevent shifting as water pressure builds up behind the weir plate.

The stream of water leaving the weir crest is called the nappe. Proper measurement conditions occur when the nappe flows 'free' over the weir crest. Free flow, or critical flow, occurs when the nappe is thrown clear of the weir face and air flows freely under the nappe, and between the nappe and the weir face. Weirs provide accurate discharge measurements only within flow ranges specified by the size and geometry of the weir notch or crest. When the downstream water level rises to a point where air no longer flows freely beneath the nappe, the nappe is not ventilated and accuracy of the discharge measurement suffers because of low pressure beneath the nappe. Weir measurements are not usable when the downstream water level submerges the weir crest (Grant and Dawson, 1997).

The actual measuring point is located upstream of the weir plate in the weir basin. A staff gage is commonly used to measure the head (height of water above the crest) at a point in the weir basin upstream from the point where drawdown begins. Drawdown, or surface contraction, is the slight lowering of the water surface as the water approaches the weir. Drawdown typically begins at a distance of about twice the elevation head on the crest upstream of the weir. The gage should be situated a distance upstream of the weir equal to four times the maximum head expected over the weir (Grant and Barnes, 1997). Measurement accuracy can be enhanced by using a recording gage situated in a stilling well, instead of a staff gage in the weir basin (BOR, 1997).

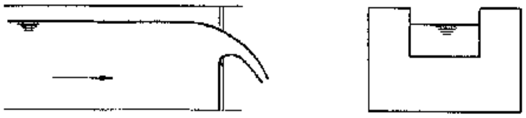
3.2.1 Siting Criteria for Weirs

Weirs should be sited in a straight reach of the channel, normal to the line(s) and direction of flow. The weir crest must be level and the bulkhead plumb. Adequate cut-off walls are tamped in place to prevent water from undermining the weir structure. The stream reach or channel selected must allow positioning of the weir so that all stream flow is channeled over the weir crest. Flow undermining the weir structure can cause relatively severe errors in the discharge measurement, especially during low flow conditions. The average width of the approach channel should approximate the width of the weir box for a distance of 10 to 20 feet upstream for small weirs and greater than 50 feet for the larger structures. This insures that flow entering the weir structure is uniform.

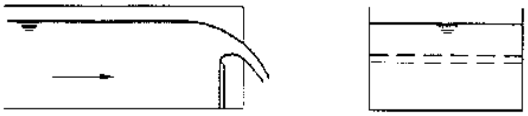
Weirs are relatively easy to construct and maintain, and measurements are accurate as long as the proper flow conditions and channel dimensions are maintained. Weirs are not suitable for flat sloped channels that will not generate enough head loss for a free flowing nappe. Weirs are also not suitable for water carrying significant loads of silt or other suspended solids, unless the weir is designed such that solids can be periodically flushed out through the bottom of the weir. Otherwise, deposition of suspended solids in the weir basin will alter flow conditions and a loss in measurement accuracy will be realized. (Grant and Dawson, 1997). Other specific limitations are discussed under the specific weir types.

3.2.2 Sharp-Crested Weirs

A sharp-crested weir has a blade with a sharp upstream edge (Brooks et al., 1994). Passing water only touches the thin upstream edge of the blade; the nappe clears the remainder of the crest (Brooks et al., 1994). The traditional sharp-crested weirs used for measuring discharge are: rectangular weirs, V-notch weirs, and Cipolletti weirs (Figure 3-1) (BOR, 1997).

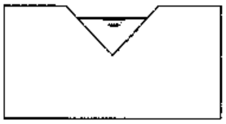


Contracted Rectangular



Suppressed Rectangular

Cipoletti Contracted



Contracted Triangular or V-Notch

Figure 3-1. Sharp-crested Weirs (BOR, 1997)

Sharp-crested weirs are designed such that the minimum distance of the sides of the weir from the channel banks is at least twice the expected head. The crest of the weir should be at least twice the expected head above the bottom of the weir basin (Grant and Dawson, 1997). The downstream water surface should always remain at least 0.2 feet below the V-notch or crest. Discharge readings should be discarded if the contraction is not springing underneath for the entire length of the nappe (Roberson et al., 1988).

BOR (1997) identifies 12 necessary conditions for accurate flow measurement using sharp-crested weirs.

- The upstream face of the weir plates and bulkhead must be plumb, smooth, and perpendicular to channel flow.

- The weir crest needs to be level for rectangular and trapezoidal shapes. The bisector of V-notch angles must be plumb.

- The edges of the weir opening must be located in one plane. The corners of the weir opening must have proper specified angles.

- The top thickness of the crest and side plates should measure between 0.03 and 0.08 inch.

- All weir plates need to have the same thickness over the entire overflow crest boundary. Plates thicker than 0.08 inch should be beveled to an angle of at least 45 degrees on the downstream edge of the crest and sides. The downstream edge of V-notches should have a 60 degree angle to prevent water from clinging to the downstream face of the weir.

- Upstream edges must be straight and sharp. Burrs and scratches should be removed by machining or perpendicular filing; abrasive cloth or paper should not be used.

- The bottom edge plates and upstream fastener projection should be located at least the distance of two measuring heads from the crest. All upstream faces must be free of oil and grease.

- The overflow sheet or nappe touches only the upstream faces of the crest and side plates.

- The weir head measurement is the difference in elevation between the crest and the water surface at a point located upstream. The upstream point is a distance equal to four times the maximum expected head on the weir.

- The weir head measurement should be at least 0.2 feet to prevent the overflow sheet from clinging to the downstream weir face.

- The weir approach should be kept clear of sediment deposits and other debris.

The following sections describe common sharp-crested weirs and include an equation for calculating discharge from each. A range of measurable flow is presented for the smallest recommended design for each of the sharp-crested weirs, as well as a maximum flow for the largest structure of each type. The minimum range is presented under the assumption that discharges from mine sites are typically small and diffuse. The reader is referred to Grant and Dawson (1997) for more specific design factors, measurement ranges and values for the discharge equation constants for the three types of sharp-crested weirs presented.

Rectangular Weirs

Rectangular weirs have vertical sides and a horizontal crest (Brooks et al., 1994). A crest length of one foot is the minimum recommended for a rectangular weir since V-notch weirs can more accurately measure the same flow rates as rectangular weirs smaller than one foot. The minimum recommended crest length of one foot generally corresponds to a minimum flow of 0.286 cfs (128 gpm), assuming an elevation head of 0.2 feet, and a maximum flow of 1.06 cfs (476 gpm) with a head of 0.5 feet. Rectangular weirs can be designed to measure flows up to 335 cfs (150,000 gpm), assuming full end contractions, a crest length of 10 feet and head of 5.0 feet (Grant and Dawson, 1997).

The equation commonly used for obtaining actual discharge is (Grant and Dawson, 1997):

$$Q = K(L - 0.2H)H^{1.5}$$

where:

Q = flow rate
K = constant depending on units
L = crest length of weir
H = head on the weir

V-Notch Weirs

Sharp-crested V-notch or triangular weirs are used in situations where precise measurements of low flows are required. V-notch weirs are effective for low flow measurement because this type of weir has no crest length and requires less elevation head for the nappe to spring free of the crest. The minimum elevation head on a weir of this type is 0.2 feet with a maximum of 2.0 feet. A small V-notch weir with a notch angle of 22 ½ degrees can measure flows ranging from 0.009 cfs (3.99 gpm) at a head of 0.2 feet, up to 2.81 cfs (1,260 gpm) at a head of 2.0 feet. A notch angle of 120 degrees can measure flows up to 24.5 cfs (11,000 gpm) at a head of 2.0 feet (Grant and Dawson, 1997).

The discharge for a free flowing V-notch weir is given by (Grant and Dawson, 1997):

$$Q = KH^{2.5}$$

where:

Q = flow rate
K = a constant defined by the angle of the notch and units of measurement
H = head on the weir

Compound Weirs

Compound weirs are often used in situations where a V-notch weir could handle the normal range of flow but measurement of occasional larger flows would require a rectangular weir. The two profiles, rectangular and V-notch, can be combined to form a compound weir. Compound weirs accurately measure flow whether the weir is functioning as a V-notch or a rectangular weir. The problem, however, with compound weirs is accurate measurement in the transition between V-notch and rectangular weir behavior. Thin sheets of water will begin to flow over the rectangular weir crest in an unpredictable manner when discharge begins to exceed the capacity of the V-notch. This problem can be minimized if the sizes of the V-notch and rectangular sections are selected such that discharge measurements in the transition zone are of minimal importance. Discharge over a compound weir is calculated by applying the standard discharge equation for each segment of the weir to the head on that segment of the weir (Grant and Dawson, 1997). Compound weirs can be useful at mine sites simply because they accommodate a wide range of flows; the V-notch portion can accurately measure fall and winter low flows while the rectangular portion, plus the V-notch, provides accurate measurement of spring peak flows.

Trapezoidal (Cipolletti) Weirs

Trapezoidal weirs are similar to rectangular weirs except that the sides incline outwardly, not vertically. When the sides have an outward inclination of 1 horizontal to 4 vertical, the weir is known as a Cipolletti weir. Compared to a rectangular weir, the discharge equation is simpler because no correction factor is included for the crest width; discharge occurs as if the end contractions are suppressed. Trapezoidal weirs have a slightly greater measurement range, although measurement accuracy is less than would be obtained from a V-notch or rectangular weir. The accuracy of the Cipolletti equation is reported by BOR (1997) to be within ±5 percent of actual discharge. The smallest recommended trapezoidal weirs with a crest length of one foot has a measurement range between 0.301 cfs (135 gpm) at a head of 0.2 feet and 1.19 cfs (534 gpm) at a maximum head of 0.5 feet. A large trapezoidal weir with a crest length of 10 feet can measure flows up to 376 cfs (169,000 gpm) at a maximum head of 5.0 feet (Grant and Dawson, 1997).

The equation for calculating discharge using a free flowing Cipolletti weir takes the form of (Grant and Dawson, 1997):

$$Q = KLH^{1.5}$$

where:

Q = flow rate
K = constant depending on units
L = length of the weir crest
H = head on the weir

3.2.3 Broad-Crested Weirs

A broad-crested weir has a flat or broad surface over which the stream discharge flows. Broad-crested weirs are used much less frequently than sharp-crested weirs and are often pre-existing structures: dams, levees, and diversion structures. Broad-crested weirs are commonly used when sensitivity to low flows is not critical and where sharp crests could be dulled or damaged by sediment or flowing debris (Brooks et al., 1994). Flumes, however, are generally preferable for measuring debris and sediment-laden flows because broad-crested weir accuracy will be diminished by sediment accumulation upstream of the weir face.

True broad-crested weir flow occurs when the upstream vertical head above the crest is between the limits of one-twentieth to one-half of the crest length in the direction of flow (BOR, 1997). Sharp-crested weirs are preferable to broad-crested weirs for low flow measurement; however, under moderate to high discharges, the accuracy of a broad-crested weir approaches that of a sharp-crested weir, while maintaining several advantages (BOR, 1997):

- Broad-crested weirs can be computer calibrated.

- Broad-crested weirs should be considered when rust, abrasion, or impact might cause maintenance problems for sharp-crested weirs.

- Specially shaped broad-crested weirs can be designed to fit complicated channel cross-sections.

- Broad-crested weirs pass sediment and debris better than sharp-crested weirs, but can accumulate sediment upstream of the weir face.

- Broad-crested weirs can be submerged between 80 and 90 percent without affecting the measurement, depending on the shape of the downstream transition in the channel.

Broad-crested weirs are hydraulically similar to long-throated flumes. Computer calibrations of broad-crested weirs use the same principles and theories developed for long-throated flumes (*see* Section 3.3).

3.3 FLUMES

A flume is an artificial open channel constructed to contain flow within a designed cross section and length (Brooks et al., 1994). Flumes do not impound water like weirs, rather they restrict the channel area or change the channel slope to increase flow velocity and change the level of water flowing through the flume (Grant and Dawson, 1997). Flumes are typically constructed in streams with channel characteristics such that the natural stage-discharge relationship is subject to changing channel morphology, or is insensitive (Kilpatrick and Schneider, 1983). Flumes are well-suited to small flashy streams where current-meter discharge measurements are impractical due to rapid changes in stage. Flumes are also used in situations where existing channel head loss is too small to permit use of a weir or when significant quantities of sediment or solids must pass through the measurement device. The high velocity of flow passing through the flume keeps solids in suspension and functions as a self-cleaning mechanism (Grant and Dawson, 1997).

Flumes are commonly designed with a contraction in channel width and/or a drop or steepening of bed slope to produce critical or super-critical flow in the throat of the flume (Figures 3-2 through 3-4). The throat of the flume is the region where contraction occurs. The increase in slope, narrowing of the channel, or a combination of the two increases flow velocity to a value greater than the critical velocity for the discharge(s) of interest. To satisfy the continuity equation, depth of flow must decrease when a given quantity of water is discharged at a higher velocity. Critical flow and depth can only occur in a previous sub-critical channel by introduction of external processes (i.e., steepening of slope or constriction) that force the flow to pass through the critical region (Grant and Dawson, 1997). A hydraulic jump will typically occur at the point where flow passes from critical back into the sub-critical region and is visually observed as a wave preceding a return to sub-critical depth and velocity. The hydraulic jump may occur at the end of the constriction or at the point when channel slope becomes shallower. The hydraulic jump is the release of specific energy generated by inducing critical and super-critical flow.

The relation between the depth of water measured at a point upstream of the water surface drawdown and discharge is a function only of the configuration of the flume (Kilpatrick and Schneider, 1983), and this relation can be determined prior to installation. In situations where critical depth cannot be achieved, head must be measured in both the approach section and in the throat in order to determine the discharge rate (Grant and Dawson, 1997).

3.3.1 Siting Criteria for Flumes

Once the decision has been made that a flume is the appropriate measuring device for a site, the decision must be made as to whether to use a critical flow flume or a super-critical flow flume. Either type of flume will transport debris of considerable size without deposition in the structure. Excessively large rocks may become deposited at, or upstream from, the critical depth section of either critical or super-critical flow flumes. If this occurs in a critical flow flume, the discharge rating will change since head is measured upstream of the critical flow section and a large, solid object in the flow path may affect the depth of water. Super-critical flow flumes, such as the San Dimas flume, should be selected for sites where this is likely to happen. This type of flume measures head downstream of the critical depth section and less likely to be affected by flow disruptions above the critical depth section.

A critical-flow flume should be selected if the flume can pass the transported sediment load. The discharge rating for a critical-flow flume is more sensitive than the discharge rating for a super-critical-flow flume. The HS, H, and HL flumes have the smallest capacities of the critical flow flumes and have relatively high precision of measurement. These flumes are used extensively in small watershed research studies. The Parshall flume is generally selected for all other situations where the use of a critical-flow flume is desired. These flume types will be described later.

When the flume type and size are selected for the expected flow conditions, the flume must be fitted for optimum compatibility with the natural channel. Four factors must be considered in the precise fitting and placement of flumes:

- Channel characteristics.
- Range of discharge to be gaged.
- Desired precision of measurement.
- Maximum allowable backwater.

Flumes should not be installed too close to reaches with turbulent, surging or unbalanced flow, or in a stream reach with a poorly distributed velocity pattern (i.e., unequal and non-parallel lines of flow). Any of these flow conditions in the reach upstream of the flume may cause large errors in discharge measurements. Flumes should be placed in reaches with tranquil flow, defined as reaches with fully developed flow in long straight, mildly sloped channels that are free of curves, projections, and waves

(BOR, 1997). As a general rule, the approach channel should be a distance equal to 40 times the hydraulic radius, or 10 times the channel width at the water surface (BOR, 1997). Hydraulic radius is the cross-sectional flow area divided by the wetted perimeter.

The velocity of the approach channel should exceed 1 foot per second to discourage aquatic pests, insects, and sediment deposition (BOR, 1997). Approach channel flow with a Froude number less than or equal to 0.5 (sub-critical flow) over the entire range of expected discharges will prevent waves from forming and interfering with head measurement (BOR, 1997). Additionally, the channel reach selected for flume placement should have a stable and consistent bottom elevation.

A common failing in siting a flume is incorrect vertical placement. Excessive downstream channel scour and erosion can occur if the flume is placed too high in the channel. Furthermore, if the flume is placed too low, excessive backwater may cause submergence at higher flows. If the user is unsure about the proper size flume for a particular channel, it is generally better to select a flume that may be too big rather than one that is too small. An undersized flume can result in excessive backwater with frequent overtopping and possible scour around the edge of the flume. However, all flumes represent a compromise between measurement sensitivity (i.e., precision) and accuracy over the entire flow range.

3.3.2 Long-Throated Flumes

Long-throated flumes are common water measuring devices because they are easily fitted into a wide variety of channel shapes, ranging from simple to complex. Long-throated flumes have numerous advantages over other measuring devices, including long-term accuracy, technical performance, design, and calibration.

Long-throated flumes constrict the channel to cause critical flow; channel steepening is not necessary. A simple type of long-throated flume consists of a flat raised sill or crest across a trapezoidal channel. The approach ramp transitions from the approach channel invert. The crest drops vertically back to the downstream channel invert. Figure 3-2 is an illustration of a flat-crested, long-throated flume.

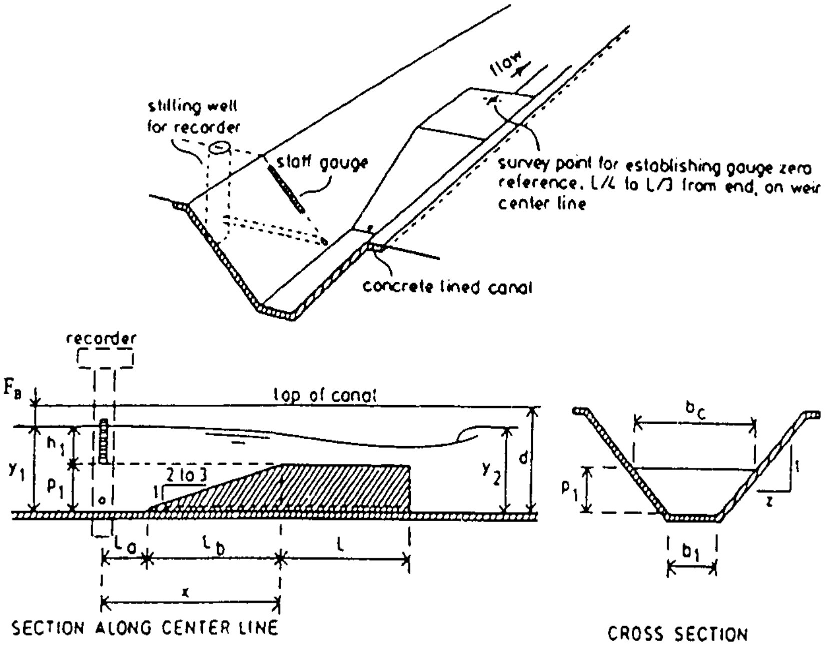


Figure 3-2. Flat-crested, Long-throated Flume (BOR, 1997)

BOR (1997) reports several advantages to using long-throated flumes for discharge measurements:

C Rating tables can be calculated with less than ±2 percent error, if critical flow occurs in the throat.

C Calculations can be made for any combination of prismatic throat and arbitrarily shaped approach channel.

C Long-throated flumes can be shaped to a wide range of channel shapes. The cross section of the flume's throat can also be shaped to accurately measure a complete range of discharge, from low to high flows.

C Long-throated flumes can be portable and can fit conveniently into open channels.

C Long-throated flumes tend to pass floating debris and sediment.

C Specific rating tables can be developed using post-construction dimensions of the long-throated flume, assuming that the throat is horizontal in the direction of flow.

- Long-throated flumes tend to be more economical than other measurement devices.
- Long-throated flumes can be designed and calibrated using computer applications.

3.3.3 Short-Throated Flumes

Short-throated flumes are considered “short” because the flume is designed to control flow in a region that produces curvilinear flow. The overall specified length of the flume structure may be relatively long, however, the area of critical flow depth (i.e., the throat) is short. Accurate calibration of these types of flumes is difficult because calibration changes by site and level of discharge. For this reason, rating curves for short-throated flumes are usually determined empirically by comparing water depth at the measuring point with other more precise and accurate methods of determining discharge (e.g., current meters or other means of direct measurement). Parshall and Venturi flumes are two common examples of short-throated flumes.

Parshall Flume

The Parshall flume is a variation of the Venturi flume. A Parshall flume is characterized by a contracting inlet, a parallel-sided throat, and an expanding outlet, all with vertical walls (Brooks et al., 1994). Parshall flumes have a sharp drop in the slope of the floor through the throat in the flume. The break in floor slope causes the critical depth and location for measurement of vertical head to occur at the entrance to the throat. This feature creates a control that commonly requires that water depth (head) only be measured at a single point located near the approach to the throat. (Kilpatrick and Schneider, 1983). Parshall flumes have been developed and calibrated with throat widths ranging from 1 inch to 50 feet (Kilpatrick and Schneider, 1983). Figure 3-3 presents a plan and side view of a typical Parshall flume.

Parshall flumes can measure flows under submerged conditions, an advantage over the Venturi flume (Brooks et al., 1994). Submerged conditions occur when the water surface downstream of the flume is high enough to reduce the discharge. Parshall flumes typically contain two water-level recorders to measure discharge under submerged conditions, one located in the sidewall of the contracting inlet and one located slightly upstream from the lowest point of flow in the throat (Brooks et al., 1994). Both water-level recorders are used to determine the difference in vertical head between the two measuring points. This difference is then applied when calculating discharge under submerged conditions. Only the upper measuring point is used when calculating discharge under non-submerged conditions (Brooks et al., 1994).

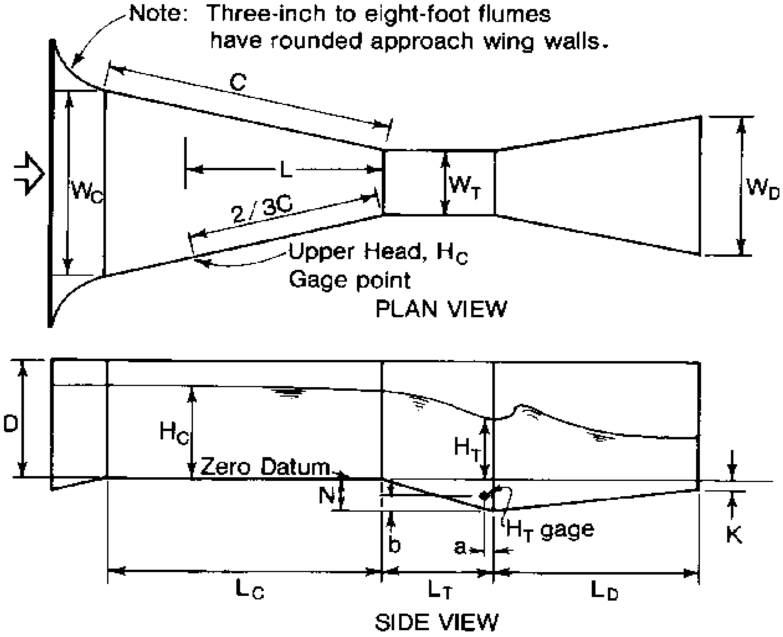


Figure 3-3. Configuration and Proportions for Parshall Flumes (Kilpatrick and Schneider, 1983)

The Parshall flume was developed primarily for use in irrigation canals, stream diversions or small routing channels. Recently, these flumes have been successfully used as gaging-station controls in natural streams. An advantage of the Parshall flume is that it will pass small- to medium-sized sediment without affecting the discharge rating curve and the accuracy of the measurement. The discharge rating will be affected by installing the flume with poor channel alignment and when there is an uneven distribution of stream flow entering the approach. The rectangular cross section makes the Parshall flume insensitive to low flows (Kilpatrick and Schneider, 1983). Under low-flow conditions, temporary V-notch weirs can be installed at the entrance to the flume throat to more accurately measure discharge (Kilpatrick and Schneider, 1983).

Parshall flumes have been constructed with throats ranging in width from 1-inch to 50-feet. Very small Parshall flumes have throat widths of 1, 2, or 3 inches and have minimum - maximum flow rates of 0.010 - 0.194 cfs (4.28 - 87.3 gpm), 0.019 - 0.478 cfs (8.55 - 215 gpm), and 0.028 - 1.15 cfs (12.6 - 516 gpm), respectively. Small Parshall flumes have throat widths of 6-inches through 8-feet, and large Parshall flumes have throat widths greater than 10-feet (Grant and Dawson, 1997).

Venturi Flume

A Venturi flume is any rectangular, trapezoidal, triangular, or other regular shape with a gradually contracting section that leads to a constricted throat (Brooks et al., 1994). The flume expands immediately downstream of the throat (Brooks et al., 1994). The floor of a Venturi flume is the same grade as the channel (Brooks et al., 1994). Stilling wells are located at the entrance and at the throat to measure head. The difference in head between the two wells is related to stream discharge.

Trapezoidal flumes are increasingly used to measure flows associated with hardrock mine discharges. The trapezoidal flume is designed to measure super-critical flows. The trapezoidal shape conforms to the natural shape of a channel, minimizing the required length of the transition section, as compared with a rectangular flume. Trapezoidal flumes require flow to transition between the trapezoidal channel cross-section and the rectangular flume cross-section. The walls of a trapezoidal flume slope outward to provide increased sensitivity to low flows while maintaining measurement of higher flows. Thus, trapezoidal flumes can measure a larger range of discharges than other types of flumes. Trapezoidal flumes also have a flat bottom. The flat bottom allows the flume to be placed directly on the channel bottom and permits the flume to pass sediment and other debris (Grant and Dawson, 1997).

Special Short-Throated Flumes

Many flumes have been designed to meet specific organizational needs and for special use situations, and are often termed *Special Flumes*. These flumes are commonly referred to as short-form or short-throated flumes. Two special flumes are discussed below, the H-type flumes, and the San Dimas flume. These flumes are extremely difficult to calibrate because of the sharp connection of the convergence and divergence of flows.

H, HS, and HL Flumes

The U.S. Natural Resource Conservation Service (NRCS), formerly Soil Conservation Service (SCS); developed HS, H, and HL flumes, or generally H-type flumes, for measuring intermittent run-off from small watersheds (Kilpatrick and Schneider, 1983). H-type flumes are commonly used to measure run-off from feedlots, infiltration areas, and low flows of streams in pollution abatement projects. H-type flumes can measure a wide range of flows with reasonably good accuracy and are simple to construct and install. The wide measurement range makes these flumes particularly useful for measuring drainage water.

H, HS, and HL type flumes have converging vertical sidewalls cut back on a slope at the outlet to provide a trapezoidal projection. These sidewalls promote self-cleaning of the flume floor. The flumes have a level floor that becomes extremely narrow at the downstream end. This narrow area was designed to increase the sensitivity of the discharge rating curve, and thus, increasing the precision of the discharge measurement (Kilpatrick and Schneider, 1983). A free fall is used to establish critical flow at the downstream end of the flume. While the flume is designed for use under free fall conditions, submergences of up to 50 percent do not significantly affect the head versus discharge relationship (Kilpatrick and Schneider, 1983). Vertical head is measured upstream from the end of the flume in the converging approach section (Kilpatrick and Schneider, 1983).

The three flumes are similar in general configuration but have different proportional dimensions. The HL flume has the greatest capacity, where the letter L is an indication of a large capacity. Conversely, the HS flume has the smallest capacity, where the letter S is an indication of small capacity (Kilpatrick and Schneider, 1983). HS flumes were designed to measure small discharges with maximum flow rates between 0.085 and 0.821 cfs (38.1 to 368 gpm). H flumes were designed to measure medium discharges with maximum flow rates between 0.347 and 84.5 cfs (156 to 37,900 gpm). HL flumes were designed to measure larger flows, up to 117 cfs (52,600 gpm) (Grant and Dawson, 1997). Typical HS, H, and HL flumes are presented in Figure 3-4.

San Dimas Flume

A San Dimas flume has the same function as a broad-crested weir with the exception that flow is constricted from the side, rather than the bottom (Brooks et al., 1994). This flume has a converging approach reach with a flat floor. A hump is located at the downstream end of the approach reach; this is the critical depth cross section. The super-critical reach, downstream from the hump, has a rectangular cross section with a 3 percent slope. Head is measured in the super-critical-flow reach of the flume, three feet downstream from the critical depth cross section. San Dimas flumes are very insensitive to low flow conditions and exhibit very poor accuracy. This is because of the rectangular shape and because the measurements are made from a section of the flume with super-critical flow. San Dimas flumes can be operated in conjunction with sharp-crested weirs to measure low flow conditions. Provisions, however, must be made to bypass high flows around the sharp-crested weir because sediment loads can damage the crest blade.

Small San Dimas flumes can be designed to measure flows with a minimum head of around 0.1 feet and minimum discharges of 0.16 cfs (71.8 gpm). Large San Dimas flumes can be designed to measure flows up to 300 cfs (134,625 gpm) (Kilpatrick and Schneider, 1983). The San Dimas flume is best used to measure debris-laden flows in mountain streams under relatively high stream flow regimes. The side constriction prevents sediment deposition and relative high flow velocities keep the flume clean of debris (Brooks et al., 1994).

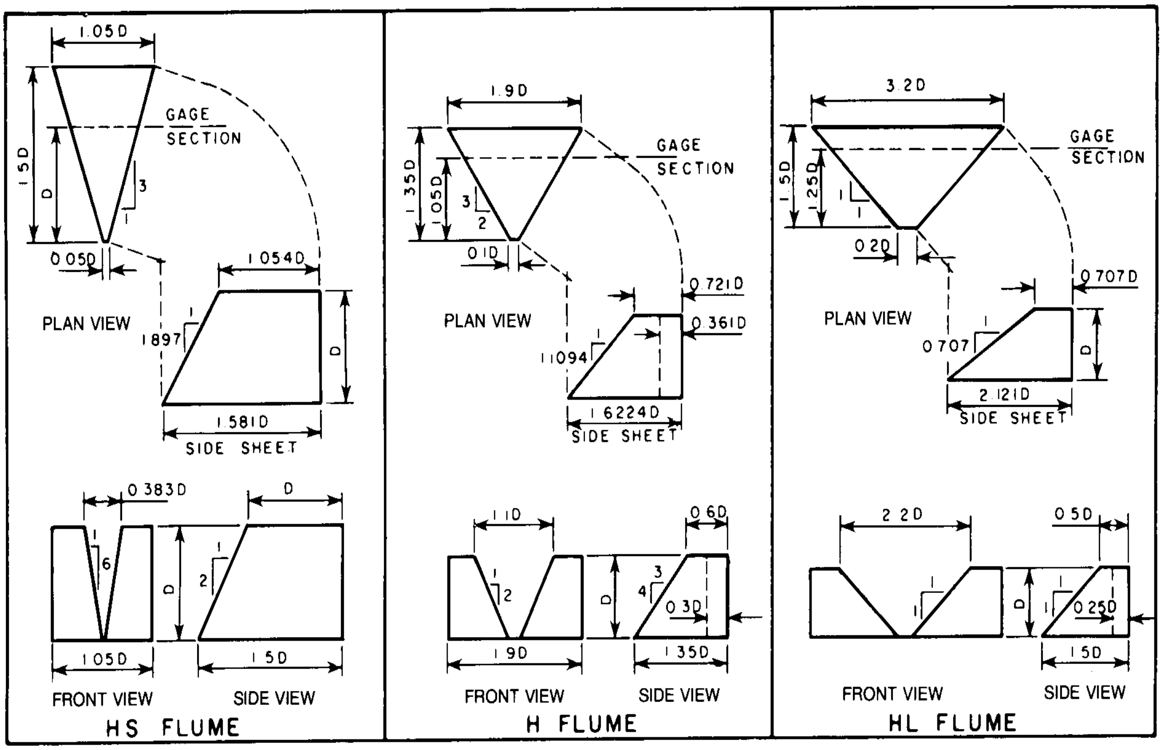


Figure 3-4. Configuration and Proportions of Type Hs, H, and Hl Flumes (BOR, 1997)

Cutthroat Flumes

The cutthroat flume gets its name from the absence of a parallel-wall throat section. This flume is a simple, flat-bottom device that can be placed directly on an existing channel without further excavation. Cutthroat flumes work well in flat-gradient channels where measurement conditions occur under both free and submerged flow conditions. Free flow conditions are preferable as only one head measurement needs to be taken, upstream of the constriction. Submerged flow requires measurements of both upstream and downstream head. The cutthroat flume is dimensionally defined by a characteristic length and throat width. All other flume dimensions can be derived from length and width (Grant and Dawson, 1997). Grant and Dawson (1997) present common sizes of cutthroat flumes; other sizes can be interpolated from these.

Cutthroat flumes have the advantage of ease of design, construction, calibration, and installation. However, the rectangular cross-section negatively affects measurement accuracy when trying to measure flows lower than those for which the flume was designed.

3.4 CURRENT METERS

Current meters measure flow velocity at specific horizontal and vertical points within a cross section of a channel or stream and therefore are less accurate than flume or weir measurement methods when measuring uneven flow channels. Each measured velocity point is assigned to a small portion of the cross-sectional flow area, where the computed discharge for a given point is the measured velocity multiplied by the cross-sectional area represented by that point measurement. This method results in several partial discharges being computed across a single cross section of the channel being measured. The total discharge for the cross section is the sum of the partial discharges. Velocity data is typically collected over the expected range of total discharges.

3.4.1 Siting Criteria for Current Meters

Current meter gaging stations should be situated in straight, uniform channel reaches with smooth banks and stable beds. The gaging station should be sited as far as possible from areas of disturbance in the flow pattern. Flow disturbance diminishes the reliability of the relationship between gage height and discharge. If current meters are used to develop a stage-discharge relationship, this rating curve should be frequently recalculated for channels with unstable beds, changing bed and bank conditions, or with large amounts of aquatic vegetation. These factors all change the relationship between the stage height of water and the cross sectional area of the channel.

3.4.2 Types of Current Meters

Several different types of current meters are used in water measurement: anemometer and propeller velocity meters; electromagnetic velocity meters; Doppler velocity meters; and optical strobe velocity meters. These meters are described in the following sections. The anemometer and propeller type meters are the most commonly used devices and are the most readily available.

Anemometer and Propeller Velocity Meters

Anemometer and propeller velocity meters measure velocity with anemometer cup wheels or propellers. The Price current meter and the smaller pygmy meter modification are the most common examples of this type of meter. These meters provide a small electronic pulse that is transmitted to a small head-set worn by the user. The meter can be set to produce a countable pulse for each complete revolution or for every 10 complete revolutions, depending on the range of velocity of the flow being measured. These types of velocity meters do not measure the direction of velocity, restricting their use to sites with relatively laminar, and critical or sub-critical flow regimes (BOR, 1997).

Electromagnetic Velocity Meters

Electromagnetic current meters produce and log voltage that is proportional to the velocity of the flow. In this manner, the meter provides a direct reading of velocity. The user is not required to count revolutions of the meter, as is required with anemometer and propeller type velocity meters. Electromagnetic velocity meters are able to measure cross sectional and directional flows (BOR, 1997). These meters cannot be used near metallic objects.

Doppler Type Velocity Meters

This type of current meter determines velocity from measurements of changing source light or sound frequency from the frequency of reflections from moving particles (e.g., sediment, or air bubbles). Lasers are used as the source light with laser Doppler velocimeters (LDVs); acoustic Doppler velocimeters (ADVs) use sound. Vertical current profiles can be measured using acoustic Doppler current profilers (ADCPs). ADCPs measure average velocities of selected size cells in a vertical series. ADCPs are typically used to measure deep flow and currents in reservoirs, oceans, and large rivers (BOR, 1997). Doppler type velocity meters can measure velocity components from multiple directions.

Optical Strobe Velocity Meters

Optical strobe velocity meters are comprised of mirrors mounted around a polygon drum. The drum can be rotated at precisely controlled speeds. Light from the water surface is reflected into the meter’s lens system by the mirrors. The rate of drum rotation is controlled by the user who is looking at the reflected images through an eyepiece. The images become steady and the water surface appears to be still when the drum is rotated at the proper speed. Surface velocity is calculated from the rotational speed of the drum and the distance from the mirrors to the water surface. Velocity is translated into discharge by applying a coefficient and multiplying by the cross-sectional area of that particular reach (BOR, 1997).

The optical strobe velocity meter can be used to measure flood flows, high velocity flows, and debris laden flows since the gage does not require any parts to be immersed in the current. The accuracy of this meter is affected by the proper selection of the coefficient, available from standard tables, because the meter only measures the velocity of the water surface (BOR, 1997).

3.4.3 Methods to Determine Flow Velocity

Several different methods can be used to measure mean velocities with a current meter. The methods differ in the specific depths and number of depths that velocity measurements are taken at a measuring point along a channel cross section. The choice of the method used is dependent on the objectives of the measurement, the relative depth of water in the cross section, and the type of channel being measured. These methods are summarized below:

Two-point method -- The two-point method relies on velocity measurements taken at 0.2 and 0.8 of the total depth from water surface. Flow velocity for the measurement point is taken as the average of the two measurements. The use of this approach is encouraged because it increases the accuracy of the results and is based on known hydraulic properties that typically exist in open channels. This method should not be used at sites with water depths less than two feet (BOR, 1997).

Six-tenths-depth method -- The six-tenths-depth method is generally used when flow depth is less than two feet. This method provides satisfactory results by measuring velocity at 0.6 of the total depth from the water surface (BOR, 1997).

Vertical velocity-curve method -- The velocity profile is defined by taking velocity measurements along a vertical profile. The accuracy of the computed mean velocity is determined by the number of velocity measurements obtained. This approach is highly accurate, but time consuming and expensive (BOR, 1997).

Subsurface method -- The subsurface method requires that velocity be measured near the water surface. The measurement is multiplied by a coefficient ranging between 0.85 and 0.95, depending on factors such as water depth, velocity range, and streambed characteristics. The accuracy of this method depends upon the selection of the proper coefficient (BOR, 1997).

Depth integration method -- The depth or traveling integration method measures velocity at various points along a vertical line. Measurements are taken as the meter is slowly and uniformly raised and lowered two to three times throughout the range of water depth. Flow velocity is the average of all observations. The depth integration method is not accurate and should only be used for comparisons or screening-level estimates (BOR, 1997).

3.4.4 Computing Stream Discharge

Discharge is calculated from current meter data using the velocity-area principle, "total discharge is the summation of all computed partial discharges". A partial discharge is defined by:

$$q_n = \overline{V_n} a_n$$

and total discharge is expressed as:

$$Q = \sum_{1}^{n} (\overline{V_n} a_n)$$

where:

q = discharge for a partial cross-sectional area in cubic feet per second
Q = total discharge, cubic feet per second
V_n = the mean velocity of the partial cross-sectional area, feet per second
a_n = area of the partial cross section, feet squared

Partial discharge can also be calculated using the simple average method, midsection average method, or Simpson's parabolic rule. These approaches are discussed extensively by BOR (1997), and other hydrology texts.

3.5 ACOUSTIC VELOCITY METERS

An acoustic velocity meter (AVM) measures the velocity of flowing water by means of a sonic signal. AVMs work on the principle that a high frequency acoustic signal sent upstream travels slower than a signal sent downstream. Average path velocity is calculated by accurately measuring the transit times of signals sent in both directions along a diagonal path (BOR, 1997). Average axial velocity is calculated from information on the angle of the acoustic path relative to the direction of flow (BOR, 1997). Meters of this type are useful for measuring discharge at streamflow sites where the relation between discharge and stream stage varies with time (e.g., variable backwater conditions) and when stream gradients are too flat to permit accurate measurements for slope computations.

The AVM is a non-mechanical, non-intrusive device capable of measuring lower velocities than a current meter. AVMs provide a continuous and reliable record of water velocities over a wide range of conditions, subject to four constraints.

1. Accuracy is reduced and performance degraded if the acoustic path is not a continuous straight line. The path can be bent by reflection if it passes too close to a stream boundary

or by refraction if the path passes through density gradients resulting from changes in salinity or temperature.

2. Signal strength is attenuated by particles or bubbles that absorb, spread, or scatter sound.

3. Changes in streamline orientation can affect system accuracy if the variability is random.

4. Errors relating to signal resolution are much larger for a single threshold detection scheme than for multiple threshold schemes.

AVM systems range from a simple velocity meter to complex computerized systems that collect and transmit real-time discharges. Site factors determine whether a single path is adequate or whether multiple paths are required.

3.5.1 Siting Criteria for Acoustic Velocity Meters

AVM systems can be used over a wide range of flows from low flow situations to sections where velocity is extremely fast. BOR (1997) describes a good AVM site as:

C A reach with a uniform velocity distribution and confined channel.

C The channel should be straight for 5 to 10 channel widths upstream and 1 to 2 channel widths downstream.

C The channel bottom should be relatively stable.

C The cross-sectional area and profile should be relatively consistent through the gaged reach.

Other site selection criteria include considerations of the limiting acoustic criteria, equipment requirements, and potential installation problems.

Data must be collected on stream cross section, water temperature, and salinity profiles. Other conditions that may affect AVM performance include: air entrainment; algae; moss; weed growth; and suspended sediment (Laenen, 1985). These data may need to be collected over time so that maximum temperature, salinity differentials, maximum suspended sediment concentrations and particle-size distribution; and maximum and minimum stages can be reliably estimated (Laenen, 1985). Temperature and salinity gradients are minor in many streamflow situations and data collection will be unnecessary.

Gradients would be expected in streams with slow moving or ponded water, downstream from tributary inflows, downstream from thermal discharges, and tidal reaches (Laenen, 1985).

AVMs cannot be used to compute velocity where large eddies persist in the stream, nor can they be used in reaches with extreme turbulence or other poor hydraulic measuring conditions (e.g., air and gas entrainment) (Laenen, 1985). Sources of air and gas entrainment include dam spillways, natural stream riffles, and decaying vegetation (Laenen, 1985).

3.5.2 Types of Acoustic Velocity Meters

Single-Path Acoustic Velocity Meters

Single-path AVMs function as flowmeters by calibrating the acoustic path velocity against mean channel velocity, estimated using standard stream gaging techniques (BOR, 1997). The angle between the acoustic path and the average direction of streamflow is normally between 30 and 60 degrees. The discharge rating procedure involves collecting data on stage-area relationships, acoustic path velocities, and mean discharge velocities for the expected range of flows and stages. The velocity rating is derived using a linear regression with instantaneous mean channel velocity as the dependent variable and acoustic path velocity as the independent variable (BOR, 1997). Discharge is estimated by multiplying the predicted mean channel velocity by the cross-sectional area at the gage site. Flow measurement accuracy is limited by the quality of data collected for the calibration ratings. Single-path AVMs can attain accuracies within ±3 percent of the actual discharge (Laenen, 1985).

Multipath Flowmeter

Multipath flowmeters use several acoustic paths which are mounted at various elevations throughout the measurement section. The velocity profile is established from the average axial velocity for each acoustic path. The velocity profile is numerically integrated over the channel's cross-sectional area to determine the volumetric flow rate. The accuracy of a multipath flowmeter is relatively independent of the velocity profile (BOR, 1997). Integration errors often occur because velocities near the channel bottom and water surface cannot be measured because of acoustic interference. However, if properly used, multipath flowmeters can attain accuracies within 1 percent of actual discharge (Laenen, 1985).

3.6 TRACERS AND DYE DILUTION METHODS

Tracers injected into a stream behave in a similar manner as water particles traveling with the flow. The measurement of the movement of a tracer is essentially the same as measuring the movement of an element of fluid in the stream, taking into account the dispersion characteristics of the fluid. Most tracers used for measurement of stream flow are very conservative with respect to water (i.e., they flow and behave similarly to water molecules under conditions of flow, and do not have significant attenuation properties). After injection of a tracer to a stream, dispersion and mixing occurs as the tracer moves downstream (Kilpatrick and Cobb, 1985). Mixing and dispersion occur in three dimensions, vertical, lateral, longitudinal. Under most open channel flow conditions, an equal mixing of a conservative tracer is usually achieved first in the vertical direction, followed by equal mixing in the lateral (cross-stream direction) at a point further downstream. Longitudinal mixing in the downstream direction continues indefinitely because no boundaries are encountered in this dimension.

Figure 3-5 shows the typical response to the injection of a tracer into a flowing channel with downstream distance. After injection of a tracer, either as a slug or at a continuous rate, a response curve can be plotted at any downstream point by plotting tracer concentration against time. These response curves form the basis for determining stream characteristics including time-of-travel, dispersion, and discharge.

3.6.1 Siting Criteria and Sources of Error

The accuracy of open channel discharge measurements using tracers can be affected by the choice of the reach where measurements are taken. Specifically, backflow eddies can delay the dye and impede mixing. An ideal reach for tracer measurement will not contain large backflow eddies or stagnant pools. As with other methods, measurements should be taken in stream reaches that have steady uniform flow, no large eddies or deep pools, and measurable cross sections.

Accuracy is also sensitive to how well the tracer cloud's center of mass is determined with respect to time. The first and last observations of a cloud may be difficult to detect, and the center of mass may not be located in the time center of the cloud. Discharge measurement accuracy with tracers can approach ±1 percent with the use of expensive equipment such as multiport pop valves, turbulators, complex electrodes, and fluorometers (BOR, 1997). Discharge estimates can also be obtained with tracer methods. The least accurate tracer method would be to break a bottle of dye at an upstream station and estimate how long the center mass takes to pass by the downstream measuring station.

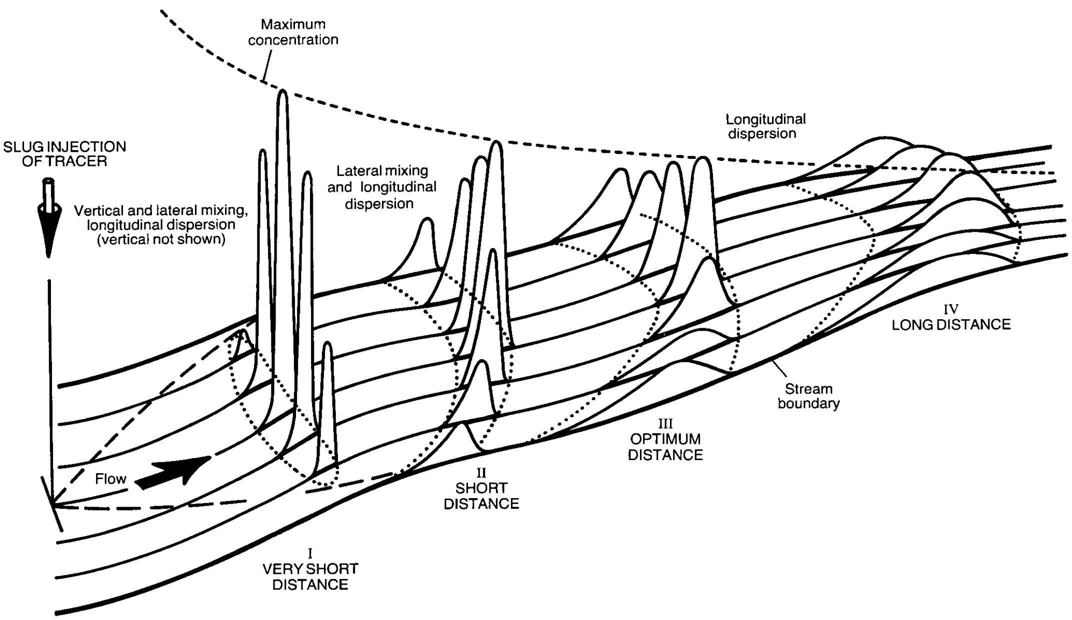


Figure 3-5. Lateral Mixing and Longitudinal Dispersion Patterns and Changes in Concentration Distributions from a Single, Slug Injection of a Tracer (Kilpatrick and Wilson, 1989)

3.6.2 Types of Tracers

A tracer is anything that mixes with water or travels with the flow of water. As previously indicated, an ideal tracer moves conservatively with respect to the water and exhibits no significant properties of attenuation or retardation with respect to flow. A tracer has to be detectable and measurable at downstream points. Tracers used in hydrologic studies include:

- Dyes of various colors.
- Chemicals such as fertilizer, salt, or gases.
- Radioisotopes.
- Heat.
- Traveling turbulent eddy pressure sequences.
- Neutrally buoyant beads.
- Floats.

Dyes and salts are the most convenient tracers for measuring discharge at mine sites. Salt tracer concentrations are determined by measuring the evaporated dry weight, through chemical titration, or by electrical conductivity. When salt solutions are used as tracers, chemical or conductivity methods are used for detection and concentration measurements. The salt-dilution method works well in small to medium sized turbulent streams. Large streams require excessive quantities of salt to significantly change electrical conductivity above background values.

Dye tracing involves introduction of dye into a water body followed by collection of water samples over time and space to measure the response. Response is a function of the dye concentration in the samples, as measured using a fluorometer (Wilson et al. 1986). Fluorometric procedures for dye tracing can be used to measure time-of-travel, dispersion, reaeration, and stream discharge. Dyes used as tracers include Fluorescein, Rhodamine B, Rhodamine WT, and Pontacyl Pink B. These dyes are all easily visible and/or detectable using fluorimetry in dilute concentrations. The Rhodamine dyes are considered nontoxic by the U.S. Food and Drug Administration. Rhodamine and Pontacyl Pink B are considered relatively stable and are resistant to fading and changes in their fluorimetric properties. They are also resistant to chemical changes by other waterborne constituents, and resist deposition onto flow surfaces, weeds, and sediments (BOR, 1997). Prior to using any dye for flow measurement, however, it is recommended that the selected dye(s) be tested with water and earth embankment samples for adsorption, chemical reactions, and fading before conducting the discharge measurement program (BOR, 1997). For example, these dyes can be affected under strongly acidic conditions caused by acid generating ores or waste rock. In addition, the precipitation of iron oxyhydroxides in streams that had been dissolved as a result of acid mine drainage can also affect fluorimeter readings. Under these conditions, the use of salt tracers would be recommended.

Dye tracing has two characteristics that make this technique favorable for measuring stream discharge. First, dye tracing has low detection and measurement limits. Fluorometers can measure dye concentrations down to one part per million (ppm) and detect dye down to one part per billion (ppb) (BOR, 1997). Second, measuring dye tracer concentrations is simple, relatively easy to apply in the field, and accurate with fluorometric techniques.

Kilpatrick and Cobb (1985) suggest that tracer methods can be particularly useful under the following flow conditions:

- Where it is difficult or impossible to use a current meter due to high velocities, turbulence, or debris.

- Where, for physical reasons, the flow is inaccessible to a current meter or other measuring device.

- Where, for some conditions, the rate of change of flow is such that the time to make a current-meter measurement is excessive.

- Where, the cross-sectional area cannot be accurately measured as part of the discharge measurement or is changing during the measurement.

3.6.3 Methods to Determine Stream Discharge

Two approaches can be used to measure discharge using dye or salt tracers (BOR, 1997; Kilpatrick and Cobb, 1985). The velocity-area method uses the time required for a tracer to travel down a known channel distance and then uses the average cross-sectional area for the reach to determine stream discharge. The dilution method measures stream discharge using the measured downstream concentration of a fully mixed tracer that is being added upstream at a constant rate (BOR, 1997).

Velocity-Area Method

Stream discharge is calculated using the velocity-area method as follows:

$$Q = \frac{AL}{T}$$

where:

Q = stream discharge, in cubic feet per second
A = average cross-sectional area of the reach length, in square feet
L = the length of the stream reach between detection stations, in feet
T = tracer travel time between the detection stations, in seconds.

Both salts and dyes can be measured using the velocity-area method; however, each requires different detection equipment. Dyes have the advantage of being visible, allowing for simpler measurements when fluorometers are not used.

Salt-Velocity-Area Method

The salt-velocity-area method is based on the fact that salt in solution increases the electrical conductivity of water (Kilpatrick and Cobb, 1985). This approach has the potential for higher accuracy and precision and has been successfully used in open channels and conduits. Sodium chloride

(NaCl) is typically the salt used in the tracer injection solution. Other halide compounds, such as lithium bromide (LiBr) or sodium bromide (NaBr), have been used in situations where high background concentrations of chloride in stream waters interfere with the conductivity measurement (Kimball, 1999). The salt concentration in the tracer solution must be high enough to significantly increase the electrical conductivity of the receiving water.

The method is employed by injecting the tracer solution into the receiving water upstream from the measurement reach. The measurement reach should be located a sufficient distance downstream from the injection point to allow for complete mixing of the tracer in the receiving water. This reach should be selected such that it is uniform and the channel-flow geometry can be defined exactly. A pair of electrodes is installed near the sides of the channel at both the upstream and downstream ends of the measurement reach. The two pairs of electrodes should be sited far enough apart, upstream and downstream, to allow accurate measurement of travel time between them. A central instrument records and graphs electrical conductivity at the electrode sites with respect to time. Electrical conductivity increases as the tracer cloud passes through the electrodes. Data are recorded and graphed by the central instrument. The time of travel is equal to the length of time required for the peak mass of the tracer cloud to pass through both sets of electrodes.

The salt-velocity-area method is highly accurate; however, special equipment (i.e., an electrode system) and experienced personnel are required to apply the method. Accuracy can be enhanced by selecting reaches where cross sections and reach length can be measured with relative ease.

Dye-Velocity-Area Method

Maximum accuracy from dye tracer solutions can be achieved using a fluorometer. The procedures are similar to the salt-velocity-area method except that a fluorometer, instead of the electrode system, is used to measure dye concentrations at a downstream cross-section. The American Society of Mechanical Engineers *Performance Test Codes* (1992) can be followed to achieve very accurate discharge measurements.

Dilution Method

Measurement of stream discharge by dilution methods depends on the determination of the degree of dilution of an added tracer solution by the flowing water. Stream discharge is calculated using the dilution method as follows:

$$QC_o + qC_1 = (Q+q)(C_2)$$

and stream discharge (Q) is solved using the following equation:

$$Q = q\frac{C_1 - C_2}{C_2 - C_0}$$

where:

C_0 = background concentration of the tracer in the stream
C_1 = concentration of the strong injected tracer solution
C_2 = the concentration of tracer at the sampling station, after full mixing
q = discharge of the strong solution injected into the flow

When using salt tracers, dry weight can be substituted for concentration values and the weight of water per second can be substituted for discharges (BOR, 1997). The dilution method is appealing because it does not require measurements of stream cross sections; however, possible tracer (salt or dye) losses may be a problem. Dye losses can generally occur when excessively long stream reaches are used, and when there is relatively high concentrations of suspended clays or organic particles that can absorb the dye (Kilpatrick and Cobb, 1985). Losses can also occur when significant concentrations of chemicals like chlorine are present that oxidize or quench the dye (Kilpatrick and Cobb, 1985).

The dilution method does require a sufficiently long flow length to ensure that there is complete mixing prior above the chosen sampling location. The length of stream required to provide complete mixing can be reduced by setting up a system to simultaneous inject the tracer at several points laterally across the stream or channel.

4.0 COMPARISON OF METHODS AND SELECTION CRITERIA

As discussed in Section 1.0, EPA's responsibilities include National Pollutant Discharge Elimination System (NPDES) permitting and monitoring of discharges at mine sites under jurisdiction of the CWA, evaluation of environmental impacts associated with NEPA analyses, conducting remedial investigations/feasibility studies (RI/FS) studies under CERCLA, or conducting baseline research. Measurements of stream or facility discharges at mine sites are typically associated with these types of studies or are often incorporated as part of a larger study designed to characterize surface and ground water hydrology, characterize water quality, or identify loading sources of contamination. The choice of an appropriate or applicable method to measure discharges at mine sites, therefore, is highly dependent on the objectives of the study being conducted. This section outlines and discusses a range of specific factors which should be considered before choosing a method to conduct discharge measurements at mine sites.

4.1 METHOD SELECTION GUIDELINES AND ACCURACY

Selection of the proper measurement technique to measure stream discharge at a mine site is dependent on a variety of factors. Site-specific factors, the type of mine facility or waste facility from which discharges are occurring, and the intended use of the data must be considered and weighed by the user. As presented by BOR (1997), the main factors to be considered when choosing a discharge measuring device or a measurement method are:

- accuracy requirements;
- cost;
- legal constraints;
- range of expected flow rates;
- head loss;
- adaptability to site conditions;
- adaptability to variable operating conditions;
- type of measurements and records needed;
- operating requirements;
- ability to pass sediment and debris;
- life expectancy of measuring device;
- maintenance requirements;
- construction and installation requirements;
- device standardization and calibration;
- field verification, troubleshooting, and repair;
- user acceptance of new methods;
- vandalism potential; and

- environmental impact of the method.

These factors are discussed in detail below:

Accuracy

The target accuracy, or a desired accuracy required for a discharge measurement, is perhaps the most important consideration. Most methods or measurement devices can produce accuracies within ±5 percent of actual discharge. Some specific devices, such as current meters, can attain higher accuracies under laboratory conditions, but maintaining these accuracies in the field is often not possible or requires increased effort and expense. It is important to note that the accuracy which can actually be achieved in a discharge measurement will often be lower (i.e., greater than ±10 percent error) if a method is selected that is not appropriate for the specific site conditions (BOR, 1997).

Expected accuracy is commonly reported for most measuring devices, such as current meters, acoustic velocity meters, weirs, or flumes. Most of the methods outlined in Section 3.0 also rely upon some secondary measurement device. It should be noted that any error associated with the secondary device will reduce the accuracy reported for the primary measurement method.

Cost

The total cost of the measurement method includes the cost of the device or devices used for the measurement or monitoring, installation, operation and maintenance, and any associated equipment. Cost estimates should include the potential cost of manual measurements using non-recording devices, versus the use of automatic recording type methods. A discharge measurement device or method should be selected based on lowest expected cost over the serviceable life of the device, and the appropriate accuracy for the study or monitoring program being conducted at the mine.

Legal Constraints

Governmental or administrative water board requirements may dictate which types of water measurement devices can be used on particular streams or geographic areas. In addition, EPA or another agency may require the use of a particular device or measurement methods; based on conditions of NPDES permits, consent decrees, or other requirements of a particular permit.

Flow Range

Many measurement devices and methods only function within a limited range of flows. Large errors occur when stream discharge is outside of the prescribed range of the measurement device. For example, sharp-crested weirs do not yield good measurements under high flow conditions, and broad-crested weirs are inaccurate for low flow conditions. The project objectives and the characteristics of the stream or discharge outfall will determine what types of flows and range of flows will need to be measured. Mine sites are particularly challenging with respect to the potential range of flow regimes that can occur at a discharge point. This primarily occurs because mine sites often contain a variety of storm water containment devices, channel diversions, or discharge structures which are designed to only discharge under low-frequency design flows (i.e., such as for a 10- or 100-year storm event).

Head loss

Some water measurement devices require a minimum drop in vertical elevational head (i.e., depth of the water) between two measurement points in order to operate properly. This is the case with flumes and weirs. The appropriate, minimum difference in elevational head may not be available on some sites, particularly in areas with flat topography. Furthermore, a trade-off can exist between head loss and measurement cost. Sharp-crested weirs, for example, are relatively inexpensive but require a large head loss. Acoustic velocity meters are more expensive but require relatively little head loss.

Adaptability to Site Conditions

The selection of a measuring device hinges on the actual site of the proposed measurement. The shape of the flow section will favor some devices over others and the chosen device should not interfere, or impede with site hydraulic conditions and normal flow regimes.

Adaptability to Variable Operating Conditions

Streamflow varies over spatial and temporal dimensions; the selected measuring device should accommodate the expected range of flows as well as variations in operating conditions. Changes in upstream or downstream head would be examples of variable operating conditions. Weirs, for example, should be avoided if downstream flows can submerge the measuring device. Most importantly, the measuring device should be useful to the water measurer. In some cases, devices and methods that are easily applied are more likely to be used, and used properly, than complicated measuring devices.

Type of Measurements and Records Needed

The user needs to decide if water must be measured on a continuous basis, occasionally, or episodically. The device chosen will vary depending upon the type of data collected. Continual measurements require construction of a permanent structure with a recording gage. Periodic measurements can be accomplished with flow meters, tracers, or other non-structural measurement devices.

Operating Requirements

Operating requirements include labor, and operation and maintenance expenses. The monitoring project should determine available personnel before selecting a device. A remote site might call for a flume or weir with a digital gage recorder. A set-up of this type has few moving or electronic parts and can be checked every couple of months. At other sites it may be convenient to have measurements taken manually, foregoing the expense of a recording gage.

Ability to Pass Sediment and Debris

Sediment is deposited anywhere stream velocity is reduced, such as near flow measurement devices. Rating curves often have to be continuously recalibrated since sediment deposition changes the cross-sectional area of flow. This affects the calculation of discharge. The measurement site should be analyzed to determine the level of sediment expected, and whether it will be possible to clean out the measuring device. San Dimas flumes were designed for small, turbulent mountain streams with a high debris load. Discharge is measured upstream from the deposition area and, theoretically, measurements are not affected by debris.

Device Environment

Measurement devices should be compatible with the site environment. Proper operation and longevity are a cost consideration, and any device with moving parts and sensors is susceptible to environmental damage. For example, devices can be harmed by rapid temperature changes, sediment, ice, acidity or alkalinity in water, biological growths, mineral encrustation, and other environmental influences. Failure to take these site factors into consideration may lead to premature failure or loss of measurement accuracy.

Maintenance Requirements

Measuring devices have unique maintenance schedules. Current meters, for example, require periodic maintenance and the site must be maintained to ensure no change in the cross-sectional flow area. Regular maintenance programs are recommended for all measurement devices; lack of care will reduce accuracy and shorten the life of the equipment.

Construction and Installation Requirements

Installation costs include the difficulty of installing a particular measuring device at the site and any channel work that may be required to ensure accurate measurements. The configuration of the site, as well as other site conditions, will often dictate the appropriate measurement device.

Device Standardization and Calibration

A standard water measurement device implies a documented history of performance based on theory, controlled calibration, and use. A standard device should be fully described, accurately calibrated, constructed correctly, installed properly, and adequately maintained according to the original specifications and flow limitations. Many standard devices will have discharge equations and tables for calibrating the device. Small deviations from the specified dimensions can occur when measuring devices are fabricated on-site or incorrectly installed. These deviations may affect the calibration and accuracy of discharge measurements. The use of pre-fabricated measuring devices avoids the calibration problems that may occur with custom devices.

Acceptance of New Methods

Water measurement devices should build on and integrate previously proven measurement methods at the site, as much as possible. Proposed changes that add to the established practice are often easier to implement and more likely to be accepted.

Vandalism Potential

Measuring devices located near public access are prime candidates for vandalism. If vandalism is a possibility, one should choose measuring devices or methods with minimal instrumentation or instrumentation that is easily protected. Measuring devices are often located in sheds or placed in buried vaults to discourage vandals.

Impact to the Environment

Consideration should be given to potential environmental impacts associated with the various measuring devices. These devices vary greatly in the amount of disruption to existing conditions needed for installation, operation, and maintenance. Weirs and flumes, for example, constrict the channel, slow upstream flow, and then accelerate flow through the measurement device. These hydraulic changes can change local sedimentation patterns, affect aquatic habitat, and impede fish movement.

4.2 COMPARISON OF METHODS

The objectives of conducting flow measurements and the specific site conditions, usually restrict or narrow the possible choices for water measurement devices and methods. This document has presented the various water measurement devices appropriate for natural or man-made open channels. Tables 4-1, 4-2, and 4-3 provide a comparison of methods and devices for the major selection criteria discussed above. Table 4-1 provides general guidelines for all discussed measurement methods. Tables 4-2 and 4-3 do not provide non-structural approaches (e.g., dye tracing) because these methods are portable and do not require regular site maintenance or concern about debris flows. Table 4-2 presents minimum and maximum ranges for head and discharge for commonly used flumes and weirs. The minimum values correspond to the smallest measurement device of that type commonly available and the maximum values are for the largest size of that measurement device commonly available. The ranges are not for a single flume or weir. The symbols used in Table 4-3 provide a relative ranking of devices and methods. The “+” symbol indicates that the device has positive attributes, “0" equates to neutral, and a “-” suggests that the device may have negative attributes with respect to that criteria.

Each water measurement situation is unique and, as such, no universal selection method exists. However, Tables 4-1, 4-2, and 4-3 outline the strengths and weaknesses of the various flow measurement methods and devices discussed in this guidebook. Personnel responsible for conducting flow measurements at mine sites should weight the various criteria to select the optimal device or method for the specific objectives to be met.

Table 4-1. Water Measurement Device Selection Guidelines*

Measurement Device	Advantages	
Gages (non-recording)	5. Low cost. 6. Good for sites where only periodic measurements are required. 7. Can be used to back-up a recording gage. 8. Can be used without a primary measurement device (i.e., weir, flume) if channel geometry is understood and stable.	1. Site must be easily accessible for regular observation and data collection. 2. May miss storm driven peak flows or other unique events. 3. Requires a stable, known cross-section, that has been surveyed.
Gages (recording)	1. Recording gages automatically record stage at user defined intervals. 2. With digital recorders, the data log can be downloaded to a personal computer. 3. Digital recorders can be accessed remotely. 4. Bubblers and pressure transducers are not affected by wind, turbulence, or debris. 5. Ultrasonic sensors are good for sites that periodically flood or where water quality concerns might damage other types of gages. 6. Pressure transducers and bubblers are highly accurate.	1. Bubble gages require periodic maintenance when used in streams with high concentrations of grease, suspended solids, or silt. 2. Recording gages are more expensive than non-recording gages. 3. Bubbler and pressure transducer accuracy can be affected by changes in barometric pressure. 4. Pressure transducers generally must be replaced if damaged. 5. Requires a stable, known cross-section, that has been surveyed.

Table 4-1. Water Measurement Device Selection Guidelines* (continued)

Measurement Device	Advantages	
Sharp-Crested Weirs	1. Low cost. 2. Ease of installation. 3. V-notch weirs are used for precise measurement of low flows. 4. Compound weirs can accurately measure a wide range of flows. 5. Trapezoidal weirs have a greater measurement range and a simpler discharge equation than V-notch or compound weirs.	1. Require a head loss of at least 0.2 feet. 2. The approach channel must be kept clear of sediment and debris. 3. Cannot measure super-critical flow. 4. Cannot measure flow when submerged. 5. Trapezoidal weirs are less accurate than V-notch and compound weirs.
Broad-Crested Weirs	1. Useful at sites where a sharp-crested weir could be damaged by sediment or debris. 2. Can be computer calibrated. 3. Can be designed to fit complicated channel cross-sections. 4. Can be submerged up to 90% without affecting measurement accuracy.	1. Require a head loss of at least 0.2 feet. 2. Not sensitive enough for low flow measurements. 3. Accuracy can be diminished by sediment accumulation upstream of the weir face. 4. Not as accurate as sharp-crested weirs. 5. Cannot measure super-critical flow.

Table 4-1. Water Measurement Device Selection Guidelines* (continued)

Measurement Device	Advantages	
Long-Throated Flumes	1. Good for small, flashy streams. 2. Require less head loss than weirs. 3. Self cleaning. 4. Easily fitted to a variety of channel shapes. 5. Accurate to ±2% of actual discharge. 6. Can be computer calibrated. 7. Long throated flumes can be portable.	1. Flumes should not be installed in reaches with turbulent, surging, or unbalanced flow, nor reaches with poorly distributed velocity patterns. 2. Typically costs more to install, compared to a weir. 3. Sites with high upstream velocity are generally not suitable for long-throated flumes. 4. Upstream banks should be high enough to contain the increased depth caused by flume installation.
Short-Throated Flumes	1. Self cleaning. 2. Require less head loss than weirs. 3. Accuracy less affected by approach velocity. 4. Well suited to small, flashy streams. 5. Parshall flumes can measure discharge under submerged conditions. 6. Trapezoidal flumes can measure super-critical flow. 7. Trapezoidal flumes measure a wider range of flow than other flume types. 8. H-type flumes are simple to construct, install, and operate. 9. San Dimas flumes are good for measuring debris laden streams with high flows.	1. Short-throated flumes can be difficult to calibrate, particularly H-type and San Dimas flumes. 2. Short-throated flumes can be expensive and difficult to install. 3. Flumes should not be installed in reaches with turbulent, surging, or unbalanced flow, nor reaches with poorly distributed velocity patterns. 4. Parshall flumes are insensitive to low flows. 5. San Dimas flumes are insensitive to low flows and not very accurate. 6. Upstream banks should be high enough to contain the increased depth caused by flume installation.

Table 4-1. Water Measurement Device Selection Guidelines* (continued)

Measurement Device	Advantages	
Current meter	1. Can be used at high discharge rates, > 150 cfs. 2. Do not require much head loss. 3. Good for calibrating recording gages.	1. High cost and requires manual operation. 2. Not accurate for measuring flows less than 10 cfs. 3. Accurate measurements require uniform flow, smooth banks, and stable beds.
Acoustic Velocity Meter	1. Multipath AVMs can attain accuracies within 1% of actual discharge, ±3% for single path acoustic flowmeters; under proper conditions and careful calibration. 2. Able to measure bidirectional flow and backwater conditions. 3. AVMs can take continuous measurements over a long period of time. 4. Good for flat gradient streams. 5. Often used when section rating and stream gaging costs are high.	1. AVMs cannot be used in reaches with eddies or a high degree of turbulence. 2. Entrained gases and/or suspended sediment affect the acoustic signal strength and measurement accuracy. 3. AVMs are generally only practical when channel widths are large. 4. High initial cost. 5. Accuracy is highly dependent on the quality of data collected for calibration.

Table 4-1. Water Measurement Device Selection Guidelines* (continued)

Measurement Device	Advantages	
Tracer and dye dilution methods	1. Salt-dilution method works well in small to medium sized, turbulent streams. 2. The dye-dilution method has low detection and measurement limits. 3. Measuring dye tracer concentrations is simple, relatively easy to apply in the field, and accurate with fluorometric techniques. 4. Measurement accuracy can be ±1% of actual discharge. 5. Often used when flow is inaccessible or conditions are unsuitable for other measuring devices. For example, channels where a significant amount of the discharge occurs through the stream substrate and gravels. 6. Suitable for measuring flow where the channel cross-section cannot be accurately measured or changes. 7. Salt-velocity-area method is highly accurate.	1. Measurement accuracy can be as low as 30% of actual discharge if the technique is not properly applied. 2. Closed conduit measurements are typically more accurate than open channel measurements. 3. Complete mixing can be a problem at low velocities. 4. Dyes can be affected by strongly acidic conditions. 5. Dissolved iron oxyhydroxides can affect fluorometer readings. 6. Tracer methods require special equipment and experienced personnel.

Table 4-2. Water Measurement Device Selection Criteria

Device	Head Loss (feet)		Design Flow Range (cfs)		Other Considerations
	Minimum	Maximum	Minimum	Maximum	
Rectangular Weir	0.2	5.0	0.286	335	Able to measure higher flows than V-notch weirs in channels suitable for weirs (i.e., appropriate head loss).
V-Notch Weir	0.2	2.0	0.009	24.5	Accurate device particularly suited to low flow measurement. Best weir profile for discharges less than 1 cfs or up to 10 cfs.
Trapezoidal Weir	0.2	5.0	0.301	376	Similar to a rectangular weir except that the inclined edges simplify the discharge equation. Less accurate than both the V-notch and rectangular weir.
Compound Weir	0.2	5.0	0.009	335	The compound weir is a rectangular weir with a V-notch cut into the crest. Compound weirs lose accuracy in the transition between when the weir is functioning as a V-notch and a rectangular.
Parshall Flume	0.10	3.50	0.010	347	Most widely used flume for permanent installations. Installation is fairly difficult.
Trapezoidal Flume	0.03	1.29	0.0001	7.08	Can measure super-critical flows, the trapezoidal cross-section permits a wider measurement range than other flumes, and the flat bottom passes sediment and other debris.
H-Type Flume	0.02	4.0	0.0002	117	The principal advantage to H-type flumes is the wide range of measurable flows with reasonable accuracy. Flume construction and installation are relatively simple.
Cutthroat Flume	varies	varies	varies	varies	Passes solids better than a Parshall due to flat bottom. Functions well with a high degree of submergence.

* Grant and Dawson, 1997

Table 4-3. Water Measurement Device Selection; Ranking of Factors

Device	Measurements		Sediment/Debris		Longevity		Maintenance	Construction	Field[1] Verify	Standard-ization[2]
	Discharge	Volume	Sediment Pass	Debris Pass	Moving Parts	Electricity Needed				
Sharp-crested weirs	+	-	-	-	+	+	0	-	0	+
Broad-crested weirs	+	-	0	+	+	+	+	+	+	0
Long-throated flumes	+	-	0	+	+	+	+	0	+	0
Short-throated flumes	+	-	0	+	+	+	+	-	-	+
Current metering	+	-	+	+	0	0	0	+	0	+
Acoustic velocity meters	+	0	+	+	0	-	-	+	-	-

SOURCE: BOR (1997)

** Symbols (+, 0, -) are relative indicators for comparing devices to the stated criteria; (+) is a positive attribute, (0) is a neutral attribute, and (-) is a negative attribute.

1. Field Verify - After construction or installation, some verification of the calibration is generally recommended. Verification simply serves as a check against gross errors in construction or calibration.
2. Standardization - Device standardization and periodic calibration may be required.

4.3 COMMON METHODS USED AT MINE SITES

As previously discussed, the choice of an appropriate or applicable method to measure discharges at mine sites is extremely dependent on the objectives of the study being conducted. Selection of the proper measurement technique to measure stream discharge at a mine site is dependent on a variety of factors which include, type of waste facility or mine feature, existing site conditions, the need for recording or non-recording methods, site availability, and desired precision and accuracy. With most methods of flow measurement, some experience is required to both determine the best specific measurement method for a given purpose and site, and to accurately install the measurement device or conduct the measurement.

There are several common features associated with many mine sites that offer unique difficulties in obtaining flow measurements. Common situations that occur at mine sites which often make it difficult to measure flow or choose a measurement method are:

- Measuring groundwater discharge from abandoned adits or ventilation shafts.
- Measuring discharge from tailings ponds and below tailings dams.
- Measuring stream flows in high mountain streams with unstable channel conditions and turbulent flows.

Methods which are commonly employed for these mining situations are discussed below.

4.3.1 Measuring Discharge From Adits

Abandoned adits commonly discharge groundwater, either ephemerally during periods of high runoff and groundwater elevation, or perennially when the adit is located below the elevation of the normal groundwater table. Discharge from adits is often highly acidic (i.e., acid mine drainage) containing high concentrations of dissolved metals and sulfate. Accurately measuring discharge from adits can be difficult because they are often perched on hillsides. Flow often occurs down hillsides via unstable channels or gullies that continuously change direction, size and geometry. This prevents the use of any recording or non-recording measurement method that relies on the development of a stage discharge relationship or a stable channel to develop a cross-sectional profile.

Flumes are often utilized to measure discharge from adits where conditions directly below the adit outfall provide a relatively level surface for flume installation and sufficient room to have an adequate approach channel (see Section 3.3.3). H or HS Flumes can be particularly useful for measuring flow from adits because their design promotes self-cleaning of debris and sediment in the flume floor.

Installation must be accomplished to insure that all flow is routed through the flume. Specific advantages to using an H, HS, or other type of critical flow flume are:

- Use in unstable or irregular channels.
- Low maintenance and self cleaning (i.e., passes sediments and debris).
- Accurate measurements under low-flow regimes such as those that occur from adits.
- Precision and consistency over time.
- Low-cost.

Disadvantages may include:

- Difficult to install, depending on specific site conditions and experience of user.
- The method is usually non-recording.

In general, weirs are not conducive to making flow measurements from adits because of unstable channel conditions. Small V-Notch weirs could be constructed to measure adit discharge, if the discharge occurs to a relatively stable channel that is straight with parallel lines of flow for at least 10 to 20 feet upstream. In addition, the width of the stream must also be approximately the width of the weir box for this distance. These conditions do not generally occur near adits. A further disadvantage of weirs is that they are not suited to measuring flows containing high amounts of sediment. Adit discharge is often high in suspended solids and precipitated iron oxyhydroxides that result in acid mine drainage. High suspended solids can damage the weir blade, causing inaccurate measurements. Likewise, the use of current meters also require that a stable channel and stable flow conditions exist. Flow meters require velocity measurements at several locations along a channel cross section at appropriate depths. Flows from adits are often less than the minimum depth required to use the meter, and channel cross sections can not be properly segregated to obtain measurements of cross sectional area (A).

In many cases, adits are located on very steep slopes and are not conducive to direct measurement of discharge. Study objectives for measuring flows from adits, however, are usually tied to determining impacts to water quality in receiving streams or watersheds. In these cases, it is often possible to indirectly measure impacts to water quality and quantify loading from a particular adit or other mine feature. If there is a receiving stream below a particular adit, the loading contribution and affect to water quality from this source can be quantified by taking synoptic samples of stream discharge and water quality at locations above and directly below the adit. In conducting this type of study, appropriate measurement methods must be chosen and sites must be located both above and below the influence of the adit or mine feature. Measurements for stream discharge, and corresponding water quality samples must be taken at approximately the same time (i.e., as close together as possible) without influence from recent rainfall-runoff events. Calculations to determine relative loading and contributions from sources are discussed in detail in Appendix A. Instantaneous load at each location is calculated by multiplying stream discharge by constituent concentration. Loading is commonly expressed in pounds per day or kilograms per day for each constituent of concern. The change in instantaneous load between the two locations can be used to quantify the effect to water quality from the source (EPA, 1996).

4.3.2 Measuring Discharge From Tailings Ponds

Most mines dispose of tailings in engineered impoundments that cover areas ranging from a few acres to more than a thousand acres. These facilities can discharge tailings water either directly from the impounded pool or as seepage of pore fluids. Seepage discharge typically occurs from one or more points from raised embankments to stream channels or designed diversion channels. The (typically engineered) foundation slope determines the location and number of seepage discharge points.

A variety of methods to measure rates of seepage and/or storm water discharge from tailings impoundments can often be employed, depending on specific site and channel conditions, below the discharge point. Discharge usually occurs into natural or designed drainage channels with relatively stable channel conditions. For this reason, channel geometry and channel cross-sections can be measured or are known. Current meters, flumes and weirs could all be applicable to measure discharge from tailings impoundments under these conditions. However, rectangular or V-Notch weirs are commonly employed at these sites because they offer the following advantages:

C Precise measurement of low flows. Small V-Notch weirs can be designed to measure discharges ranging between 0.01 cfs (3.99 gpm) and 24.5 cfs (11,000 gpm). These relatively low flows often occur from tailings discharges especially during drier seasons. Rectangular weirs can be designed to measure flows up to 335 cfs (150,000 gpm).

C Weirs can be used to establish permanent measuring points with a high degree of precision between sampling dates.

C Weirs offer easily obtainable and consistent sampling locations for concurrent water quality samples.

C Automatic recording can be employed with some weir systems by measuring stage in the weir basin with a pressure transducer or float mechanism.

4.3.3 Measuring Discharge in Remote Areas with Unstable Channel Conditions

Flow measurements are extremely important for studies evaluating changes in water quality, pollutant loading, and surface and ground water interactions. The identification of influent and effluent stream reaches, and study of the impacts that specific mine facilities and features have on hydrology and water quality within a watershed is dependent on accurate stream flow measurements taken synoptically (e.g., samples collected at approximately the same time) at key locations within a stream. Unfortunately, many mine facilities and many mine features occur in remote locations within a watershed that are not conducive to many methods used to measure stream discharge. Optimum locations immediately below specific mine features or mine discharges commonly do not have conducive stream channel and flow conditions to measure stream discharge. This can occur because of the remoteness of the site, the existence of steep channels with turbulent flow conditions, or at sites where a significant proportion of stream flow occurs within alluvial gravels and cobbles in the streambed. Under these conditions, the use of dye or salt tracers offers several advantages and is often the only method available to determine stream discharge at several locations within a remote watershed. Carefully applied, tracer techniques combined with sampling at multiple locations can be used to:

- Determine the relative pollutant load occurring from specific mine features, waste dumps, tailings facilities, and adits to watersheds.

- Identify losing and gaining stream reaches and quantify the exchange of streamwater and groundwater.

- Evaluate loadings of metals and other constituents in gaining stream reaches caused by influent ground water.

- Evaluate precipitation and dissolution reactions of metals in specific stream reaches or below tributaries of sub-watersheds.

- Determine natural geochemistry and background water quality conditions in upper watersheds above the influence of mining.

5.0 QUALITY ASSURANCE/QUALITY CONTROL FOR FLOW MEASUREMENTS

5.1 OVERVIEW OF THE QA/QC PROCESS AND DEVELOPING A QUALITY ASSURANCE PROJECT PLAN

Quality assurance (QA) is a system of defined activities, the purpose of which is to provide confidence that specified standards of quality are achieved. A QA/QC program, as defined by a Quality Assurance Project Plan (QAPP), should be included as a part of each project as a means of integrating the quality planning, quality assessment, quality control (QC), and quality improvement efforts needed in order to meet user requirements. These QA/QC components include management; QA Objectives; measurement and data acquisition; assessment and oversight; and data validation, usability, and reporting. Included are "guidelines" for QA/QC specifications as defined for mine flow measurement projects. Specific measurements required to achieve project objectives are also discussed.

A QAPP is developed to define project specific QA/QC requirements. Specific QA activities, including QC checks, are noted in the project QAPP. The purpose of specified quality assurance activities is to reduce measurement errors to agreed upon limits and to produce results of acceptable and known quality. Therefore, specific project requirements are documented as a part of the QAPP. This will help to ensure that the measurement system is in control and that it provides the detailed information necessary for assessment of the collected data.

QA/QC guidelines should be incorporated by project personnel in conjunction with project requirements. Precision, accuracy, representiveness, comparability, completeness, and sensitivity are defined in the QAPP and are different for different projects; however, guidance is provided in this document as to specific measurement objectives that can be achieved. Along with this guidance, additional QA/QC considerations are included to provide elements needed for the development of an appropriate QAPP. This section therefore, includes a general discussion of appropriate QA/QC elements as would be required for flow measurements at mining sites.

5.2 QA/QC COMPONENTS

5.2.1 QA Management

QA oversight is needed for all projects to provide an independent assessment of quality assurance activities. It is important that QAPPs for all projects (including mine flow measurements) be independently reviewed to determine if project objectives can be achieved per the QA/QC requirements specified in the subject QAPP. In addition, periodic assessments of QAPP implementation is recommended. These assessments should be performed by QA personnel who are independent of management activities. QA oversight is needed in order to provide initial QAPP review and periodic project assessment. The amount of QA oversight required will vary depending upon project scope and the intended use of project results.

5.2.2 Quality Assurance Objectives

Precision is the ability of a measurement system to generate reproducible data. For most parameters, precision is determined from the results of duplicate determinations, and is reported as relative percent difference (RPD). Relative standard deviation (RSD) is used when triplicate or additional like measurements are made.

$$\text{RPD} = \frac{(D_1 - D_2)}{(D_1 + D_2)/2} \times 100$$

where: D_1 and D_2 are the two observed values, and D_1 is > D_2.

$$\text{RSD} = \frac{\text{standard deviation}}{\text{mean}} \times 100$$

The frequency and acceptance criteria for replicate sample measurements are based upon the objectives of the project, and are specified in the QAPP. Precision estimates are best obtained by comparison of duplicate calibration determinations (e.g., pressure transducer check using staff gage) or duplicate field measurements, if applicable (e.g., reading of staff gage).

Duplicate flow measurements are best obtained by field observation. Because flow measurements are dependent upon reading or siting of specific instrumentation, variability of two or more measurements are not expected to differ greatly when these measurements are taken within approximately the same time period. Siting of a gage for example, used to measure stage height for input into the equation to calculate discharge from a weir or flume, may vary only slightly due to surface water disturbance. This measurement variability could be calculated and a precision estimate determined by making two or more consecutive measurements. Current meters or acoustic flow meters may also experience slight variability when measurements are taken in close time proximity, one to another. When taking two or more replicate measurements for flow meters, it is important to remember:

- Time between measurements should be minimal to determine instrument precision without adding variation in flow.

- If overall flow measurement and instrument precision are desired in order to obtain average flow over a period of time, several measurements could be made during a specified time period and precision calculated using several measurements.

- Precision estimates are used to determine variability and not bias, therefore efforts to eliminate measurement bias (e.g., two separate observers) should be used when possible.

Precision estimates for most flow measurement instrumentation should probably not vary by more than 2 to 5 %.

Accuracy is defined as the nearness of the reported result to the "true" value. Accuracy is assessed by comparison of flow results to engineering calculations or to manufacturer specifications.

Accuracy is dependent upon instrument siting criteria, alignment of the measurement device in the stream (i.e., flumes), number of different measurements obtained within a stream (i.e., current meters), overall construction and placement of the instrument. In this sense, accuracy and representativeness are related. Each of the previous sections in this document has discussed criteria required to obtain more accurate results and the expected accuracy of particular instrumentation has been provided (e.g., 2 - 5%). Accuracy of a particular instrument, however, is dependent upon manufacturer specifications and is not included for all measurement devices due to varying specifications. Flow measurements, however, have no “true” results for comparison. Some instrumentation (e.g., weirs or flumes) may be inherently more accurate than others (e.g., current meters). Choice of instrumentation will determine the accuracy of the final result. Because stream variation and type of flow measurement are interdependent, engineering judgment is required to determine the most accurate instrument for the measurement being made. If very accurate measurements were required, two different instruments could be used for comparison. This comparison should most likely be used only as comparative numbers and assumptions as to which device is most accurate would be an engineering judgment.

As noted, in most cases a particular measurement device may have no “true” or calculated value for comparison. Manufacturer specifications may be used or in special situations it may be best to express an accuracy determination by repeat measurements of the result until the “true” value (e.g., average value) has been determined. This would require enough determinations to represent a statistical population. For example, three separate measurements of the same flow could be made using the same device. A percent RSD could be calculated and then a “t” table used to produce a confidence interval. The width of the confidence interval could than be used to express the expected accuracy of the particular device. Narrower confidence intervals could be determined by more replicate measurements. (Note that this is useful methodology for an accuracy determination when no independent measurement can be made.) The average result, which is expressed as a confidence interval, could be used as a standard or "true" value by which subsequent measurements could be compared. Accuracy for flow measurements could then be expressed as a percent bias. This is the difference between the measured value and the calculated or "true" value as noted above. The equation below expresses accuracy as a percent bias.

%Bias = (measured value-true value)/true value x 100

Examples are provided in Table 5-1 which provides issues or considerations associated with accuracy and precision for several types of mine flow measurements. While only a summary, more complete information can be found in Section 3.0 which describes each of these measurements. This table is not intended to provide comprehensive information but to stimulate additional thought when considering "measurement quality objectives" required to satisfy project objectives.

Accuracy of measurement devices can be within +/- 5% or better depending upon conditions noted above. In some cases, it is possible to check the accuracy and/or precision of a measurement by using another measurement. For example, it may be possible to make occasional checks of discharge using a graduated cylinder and stopwatch, provided the total discharge can be collected in such a manner (e.g. discharge at a pipe). This requires small enough flows such as may occur from mine adits. In many cases, the accuracy or precision of the measurement will only be able to be determined based upon criteria and conditions required for set-up and then relying upon the theoretical calculations noted for the different measurements. Physical inspection on a periodic basis is critical to maintaining accurate and precise measurements. Table 5-1 also provides more comprehensive guidelines critical to achieving accurate and precise measurements.

Data <u>completeness</u> is a measure of the extent to which the data base resulting from a measurement effort fulfills the objective for the amount of data required. Completeness is defined as the percentage of valid data obtained compared to the number of tests required to achieve a statistical level of confidence in the results.

Table 5-1. Accuracy and Precision Considerations for Mine Flow Measurement Methods

Measurement Method	**Accuracy Considerations**	
Gages (non-recording)	1. ability to read gage height (viewing obstructions) 2. ability to record unusual events (changes which occur between measurement periods)	variation of different observers
Gages (recording)	1. ability to measure small fluctuations 2. inaccuracy caused by corrosive conditions such as weathering	
Weirs	1. free flow of water over the weir crest 2. water carrying significant loads of sediment or debris 3. construction, shape, placement, etc. (See criteria noted in section 3.2.2 for sharp crested weirs)	occasional check of measurement device in field (visual observation and collection of duplicate measurements)
Flumes	1. siting criteria, requirements of straight channels above and below flume 2. decision as to flow measured being critical or super-critical 3. channel characteristics 4. approach velocity	occasional check of measurement device in field (visual observation and collection of duplicate measurements)
Current Meters	1. channel conditions, siting criteria, streamline orientation 2. laminar, critical or sub-critical flow 3. methods used to determine flow velocity	comparison of different methods used for determining flow velocity (Section 3.4.3)
Tracers or dye	• mixing conditions including time of travel, dispersion, and discharge • backflow and eddies • calibration of measuring device	precision check of measurement device

Representativeness is ensured by a well-defined sampling strategy designed to collect measurements which exhibit average properties of the site at that stage of the technology. Examples of how to collect appropriate samples have been previously noted in this document. Representativeness is enured by collecting sufficient samples to characterize the site or collecting measurements that appropriately define the problem. Means of collection and standard methods used to collect flow measurements are defined in the body of this document. It should be remembered that representative data are defined by the method of collection and the manner in which the method is implemented. Collecting representative data is therefore dependent upon individual or site specific factors including the instrument chosen for measuring a particular flow, survey methods used for instrument placement, determining if flow is turbulent or laminar, placement of the flow instrument in the output stream, etc.

Comparability is generally achieved by the use of standard methods. This makes collected data comparable to other sites or projects that have similarly defined situations. Standardizing methods for collection of flow data is one of the objectives of this document. Reporting the data in standard units of measure and adhering to the specified calibration and set-up procedures all contribute to comparability of the data.

Unlike chemical analyses, however, flow measurements have no specifically recommended procedures that are universal for similar situations. The choosing of a flow measurement method is dependent upon many variables (e.g., expected flow rate, changes in seasonal flow, stream debris, etc.) and is not specifically defined for every situation. Therefore comparability of data from two separate sites may be less tangible than comparison of analytical data from two different areas. When data from two different sites are compared the engineer must factor these previously mentioned variables into their evaluation to determine if the collected data can be compared. In this manner comparability refers to comparability of measurements from two different sites or perhaps comparability of data collected by two separate measurement methods.

Method detection limits (MDLs) or Sensitivity are determined based on instrument detection limits. Resolution of the particular instrument will determine the MDL. A particular instrument or device can only measure to an absolute lower limit. Some typical sensitivities are given in Table 5-2 and have been discussed in the previous sections. In the planning stage of a project, required detection limits need to be specified so that an appropriate measurement method can be selected.

Table 5-2. Sensitivity Limitations for Different Mine Flow Measurement Methods

Measurement Method	Typical Sensitivity (see appropriate section)
Rectangular weir	0.286 cfs
V-notch weir	0.009 cfs
Trapezoidal weir	0.301 cfs
Compound weir	0.009 cfs
Parshall flume	0.010 cfs
Trapezoidal flume	0.0001 cfs
H/HS flume	0.347/0.085 cfs
San Dimas flume	0.16 cfs

Each of the above detection limits is given as an example and is dependent upon assumptions as described in previous sections for each of these instrument measurement devices.

The following tables (Table 5-3 and 5-4) present typical objectives and QC checks that may be used in a QAPP for evaluation criteria required with specific measurement devices. These tables are only examples and are not intended to cover specific project objectives.

5.2.3 Measurement and Data Acquisition

Several types of mine flow measurements have been previously defined in this document (see Section 3.0). Specifically, mine flow measurements require considerations as to the type of mine, the amount of flow expected, and the site conditions. QA considerations (precision, accuracy, and sensitivity) associated with these measurements are summarized in previous sections and therefore are not repeated here. QA/QC requirements and activities to ensure quality measurements are specified in noted subsections.

Table 5-3. Example QC Objectives for Specific Measurements

Measurement	Instrument	Accuracy	Precision	Detection Limits	
discharge	weir	+/- 5%	5% (compared by duplicate height measurement)	0.009 cfs	90%
stage height	pressure transducer	+/- 5% (factory certification or compared to manual measurement)	5% (duplicate readings)	0.010 feet	90%

Table 5-4. Typical QC Objectives for Specific Measurement Device

Measurement Device	QC Check	Frequency	Criteria	Corrective Action
Weir	obstruction of nappe	weekly	determine if flow is obstructed	clean and consider alternate measurement
Flume	determine if there is debris accumulation	weekly	significant build-up such that flow is obstructed	clean and consider alternate measurement
Pressure Transducer used to measure stage height	calibration check with staff gauge	monthly	within 5%	replace transducer

5.2.4 Assessment and Oversight

Audits are an independent means of confirming the operation or capability of a measurement system, and of documenting the use of QC measures designed to generate valid data of known and acceptable quality. An audit is performed by a technically qualified person who is not directly involved with the measurement system being evaluated. A performance evaluation is generally an objective audit of a quantitative nature, and a systems audit is a qualitative evaluation of the capability of a measurement system to produce data of known and acceptable quality.

A systems audit (the type of audit anticipated for mine flow measurements) is a qualitative determination of the overall ability of a measurement system to produce data of known and acceptable quality, by an evaluation of all procedures, personnel, equipment, etc. utilized to generate the data. It is an evaluation of whether adequate QC measures, policies, protocols, safeguards, and instructions are inherent in the measurement system to enable valid data generation, and/or the immediate identification of outlier data and subsequent actions. It must be performed in the field and is performed by someone independent of measurement activities.

A systems audit should review the project organization and technical personnel involved. Field activities are evaluated, including: use of proper sampling equipment, procedures for equipment maintenance, acceptable sampling protocol, calibration procedures for field measurements, and adequate field documentation and record-keeping procedures. The purpose of the audit is to provide recommendations as to how field measurements may better meet project requirements. If procedures are being followed as specified in the QAPP then the audit will document that appropriate procedures are being followed. Due to the nature of the measurements being evaluated, this audit must be performed by appropriately qualified personnel.

An example of some checklist items are provided below:

- Are method specifications as provided in the QAPP being followed?
- Was instrument siting criteria appropriately recorded and were specifications noted in the field log?
- Are duplicate measurements obtained and how are they obtained? Does instrument precision appear to meet QAPP specifications?
- How was flume alignment within the stream determined and was this properly recorded?
- If current meters are used, what method is being performed to determine flow velocity?
- Are stream discharge data appropriately calculated?
- How often are stream flow measurement data collected and are they recorded appropriately in the field log?

- What engineering oversight was performed to ensure proper installation of the specified flow device?

- Have personnel who are making field measurements been appropriately trained?

5.2.5 Data Validation, Usability, and Reporting

For analytical data to be scientifically valid, defensible, and comparable, the correct equations and procedures must be used to prepare the data. Measurement evaluation is a systematic process of reviewing a body of data to provide assurance that the data are adequate for their intended use. The process includes the following activities:

- Auditing measurement system calibration and calibration verification.
- Auditing QC activities.
- Screening data sets for outliers.
- Reviewing data for technical credibility vs. the sample site setting.
- Auditing field sample data records.
- Checking intermediate calculations.
- Certifying the above process.

Prior to data collection, determinations are made regarding the data to be gathered in the field and the methodology to be used. Once the data are obtained, they must be reviewed and assessed as to their adequacy. If it is determined that the initial data collection concept did not provide adequate data, the entire process may need to be repeated to identify and correct data inadequacies. The following sections describe the data reduction, validation, and reporting procedures that should be incorporated into the QA program.

Data Reduction

All measurement system outputs (e.g., flow data) must be reduced into units which are consistent with the methods and which meet the comparability objective. In general, all raw data are recorded in field notebooks or on worksheets in standardized format, by the technician performing the test. Each method contains detailed instructions and equations for calculating the respective flow measurements. Typical data outputs are in cfs or gpm as noted in previous sections.

Data Validation

Data validation is a systematic process of reviewing data against a set of criteria to identify outliers or errors and to delete suspect values or to flag them for the user. Data reviews starts with the field quality control procedures specified in the QAPP. The quality control data produced are reviewed throughout data generation using the criteria and procedures described in this section to validate data integrity during collection and reporting of field data. Validation requirements are described in the QAPP. Some guidance regarding validation is presented in the following discussion.

Review of field and quality control data should initially be performed by the responsible technician. The data are checked for errors in transcription and calculations, and for compliance with quality control requirements. Failure to meet method performance quality control criteria results in the re-collection of appropriate data. After the initial review is completed, the data should be collected from summary sheets, workbooks, or computer files and assembled into a data package.

The next level of data review is the responsibility of the project manager. The project manager may also responsible for development and implementation of data review checklists, as needed. The areas addressed in the checklists typically include the following:

- Data collected according to specified methods.
- Instrumentation calibrated according to specified methods.
- Calculations performed correctly and verified.
- Transcription of raw and final data done correctly.
- Detection limits determined correctly and within required limits.

Typically , field personnel will review 100% of the data generated, including any calibrations and calculations, and will sign and date all field notebook entries. The field manager often reviews at least 10% of the generated data and all of the data quality indicators (e.g., triplicate groundwater level measurements for precision criteria). Any suspect data should be investigated. All outliers are identified in the report narrative. Outlier data should only be rejected if they can be explained by some physical phenomenon.

Data Reporting

All original data should be recorded in a permanent manner, and be readily traceable through all steps of the data generation/reduction/ validation/review process. Field measurements should be recorded in appropriate field notebooks and results reported in tabulated summary form, or as otherwise specified in the QAPP. Some guidance in terms of data reporting is presented in the following discussion.

Field data is typically reported by the technician in an appropriate log book. The field report should include all associated raw data, non-conformance records, memos and communication records and any other documentation for the reported results. The reported data is then validated, as discussed previously, and approved for reporting.

The reporting requirements should include: measurement summary and cross-reference, narrative discussion of QC sample results, field measurement methods and detection limits, and calculated data (tabulated summary, duplicate summary, calibration summary, and all associated raw data).

The validated field data should be used to prepare reports that evaluate the technology or project and assess its potential applications. The exact format and detail of the report to be prepared is not included in this document and is project dependent. However, the report should include, at a minimum, the following information:

- A thorough discussion of the procedures used to collect the measurements and to define data quality and usability should be included. The discussion will focus on the data quality indicators such as precision, accuracy, completeness, comparability and representativeness.

- The results of any assessments performed during the course of the project should be documented, including corrective actions initiated as a result of these assessments and any possible impact on the associated data.

- All changes to the proposed procedures should be documented regardless of when they were made. The rationale for the changes will be discussed along with any consequences of these changes.

- The identification and resolution of significant QA/QC problems should be discussed. Where it was possible to take corrective action, the action taken and the result of that action will be documented. If it were not possible to take corrective action, this, too, should be documented.

Reliable measurements of flow data require continuous monitoring and evaluation of the processes involved, i.e., quality assurance. To ensure optimum valid data generation, a scientifically sound and strictly adhered to quality control program must be incorporated into the data or measurement collection program. Such a QC program employs a prescribed sequence of routine procedures to control and measure the quality of the data generated. These procedures should be documented for verification of the collected measurements and for purposes of repeating the program or project as necessary. A data report is the final output that verifies appropriate data collection.

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APPENDIX A

Description of Common Mine
Potential Impacts to Surface Water Hydrology and Water Quality,
and the
Importance of Flow Measurements

DESCRIPTIONS OF COMMON MINE FACILITIES

Mining operations produce a variety of solid and liquid wastes that often require permanent management. Many mining operations predate environmental consciousness or laws, and at many sites, waste management (to minimize environmental consequences) was not practiced. However, new mining operations are required by various state and federal laws to incorporate sound design and management of waste disposal facilities, as well as monitoring programs incorporating measurements of both discharge and water quality. Abandoned mine sites continue to impact watersheds through rerouting or impoundment of surface and ground water flow, and pollutant loading.

Large mining operations can generate over a billion tons of solid wastes that cover areas exceeding a thousand acres. Even smaller operations must handle and dispose of formidable quantities of materials that can affect large areas. In order to prevent or minimize environmental impacts, waste facilities must be designed and reclaimed in a manner that minimizes or prevents environmental impacts.

The mining method employed and the type of mineral extracted are large factors in determining the volume and types of solid waste facilities developed. The methods employed to beneficiate and process ore are also factors associated with the types of waste produced and the characteristics of waste streams. Flow measurements are often required to monitor direct discharges or storm water runoff from different types of mine facilities, such as waste rock dumps, tailings impoundments, leach pads and process facilities. The remainder of this section provides a summary discussion describing different types of mining and common waste facilities that may exist at mine sites. A more detailed discussion of mining and processing methods can be obtained from SME (1992) and Lacy (1999), and more detailed discussions of the design and management of waste facilities is provided by MEND (1995), SRK (1992), and Vick (1990).

Types of Mines

There two major classes of mining methods, surface and underground. Common surface mining methods include open pit mining, quarrying, glory holing, strip mining, and placer mining.

1. Open pit mining is a surface mining method in which nearly all of the deposit and ore is removed in terrace-like working areas on the side of a pit. Grade and tonnage of materials available determine the size and limits of the pit developed as well as the size and configuration of waste rock dumps. In this type of mining, it is often necessary to blend different ore types to maintain character and grade of the mill feed, or different types of ore (i.e., oxide verses sulfide and low-grade ore) may need to be managed and processed

differently (Lacy, 1999). Oxide and sulfide ores require different types of beneficiation and processing, and some low-grade oxide ores may be processed in a leach pad facility. Open pits are often closed or reclaimed by simply allowing the pit to develop into a pit lake and waste rock dumps are usually closed and reclaimed in place.

2. Quarrying is similar to open-pit mining, however, it is usually restricted to mining dimension stone or prismatic blocks of marble, granite, limestone, sandstone, etc.

3. Surface Glory Hole method is generally performed on hillsides and often used to define irregular deposits of the surface. The method has a mine opening at the surface and ore is removed by gravity through raises connected to adit haulage ways. Ore is transported to the surface or side-hill using tramways (Lacy, 1999). This method generally results in smaller volumes of waste rock removed and deposited in surface dumps.

4. Strip mining is surface mining where reclamation is contemporaneous with extraction. It is applicable to shallow, flat-lying deposits of coal, oil-shale, clay, sand, gravel, and some uranium, phosphate and placer deposits. As the overburden is removed from one portion of a mineral deposit, it is used to fill in the trench left by the previous removal. In this manner, the overburden is continuously refilled to the adjacent previously mined area and reclaimed.

5. Placer mining is a method for the recovery of heavy minerals using water to excavate, transport, and or concentrate the mineral being mined (Lacy, 1999). Placer methods vary greatly depending on the size and characteristics of the deposit being mined. However, placer mining in general, usually affects large areas because the ore bodies are in large alluvial deposits with low-grade, but a high volumes of mineral. The method can be highly visible and create large areas of disturbance. Many historic placer operations created serious impacts to stream channels, hydrologic systems and aquatic habitats.

6. Underground mining methods are generally similar. Ore is extracted from underground stopes, rooms, or panels located at depth. In comparison to surface mining little waste rock is produced and deposited at the surface in surface waste piles on tailings material dumps. Depending on the mineral being extracted, however, tailings and gangue may still be deposited above the surface. Without reclamation, abandoned adits and stopes from underground mining can become sources of acid mine drainage to surface waters which may require treatment and measurements of flow and water quality. This occurs when sulfide bearing minerals (usually pyrite) are exposed to air (oxygen) and ground water discharges to the surface.

Waste Rock Dumps

Waste rock is removed material from above or within the ore body and consists of non-mineralized and low-grade mineralized rock. Waste rock includes granular, broken rock and soils ranging in size from fine sand to large boulders, with the fines content dependent upon the nature of the geologic formation and methods employed during mining. Materials are designated as waste because they contain the target minerals in concentrations that are too low to process, because they contain additional minerals that interfere with processing and metals recovery, or because they contain the target metal in a form that cannot be processed with technology that existed at the time of mining. Waste rock may be acid generating and may contain metals that can be mobilized and transported into the environment. These materials generally require extensive geochemical testing to determine if they can create impacts to the environment over the short or long term. Special engineering designs, waste handling, or closure and reclamation plans may be required for those materials whose characteristics may pose significant risks.

In modern mining operations, waste rock and overburden that cannot be put to beneficial use or that contain compounds that may be detrimental to the environment, generally are placed in a location where they can be physically stabilized. Placement of waste rock is accomplished using a variety of techniques that may include end-, side-hill-, or random-dumping, and dozing. Historic operations generally did not engineer waste rock dumps to be either geotechnically or environmentally stable. Dump designs may vary markedly depending on the nature of the mining operation, the terrain in which materials are being placed, and the era in which mining took place. In steep, mountainous areas, dumps may have faces of a few hundred meters height. Dumps placed as valley-fill deposits often require the construction of rock underdrains to permit the flow of water through the drainage. Dump underdrains are often tied into the mine drainage or storm water drainage systems that convey seepage to treatment facilities and require measurements of flow and water quality. In newly planned mining operations, the materials used to construct these drains should be thoroughly tested to ensure that they will not contribute metals, acid, or other constituents to surface waters.

Dumps that would contain waste rock capable of releasing significant quantities of metals, acidity, or other constituents may require special design features or waste handling practices to minimize the potential for environmental impacts (SRK, 1992; Environment Australia, 1997). Dumps can be designed with features to control or reduce acid generation, control the migration of poor-quality drainage, or collect and treat poor-quality drainage (SRK et al., 1989).

Tailings Impoundments

Most mines dispose of tailings (sand- to silt-sized rock particles from which target minerals have been separated) in engineered impoundments that cover areas ranging from a few acres to more than a thousand acres. These facilities can discharge tailings water either directly from the impounded pool or as seepage of pore fluids. At many mines, clarified decant water, formed as solid particles settle out of suspension, is recycled to the process facility and reused. However, in wet environments, mines may find it necessary to release tailings water to surface streams through permitted discharge points. This is particularly true of impoundments that are used as emergency containment for excess storm runoff from other areas of the mine site. Because tailings may contain acid-generating minerals and a variety of metals, accurate knowledge of pool and seepage discharges under normal operations and during storm events is required to ensure that permit and environmental requirements are met.

Whether tailings impoundments are discharging facilities depends on the environmental and physical setting of the site, the site water balance, the type of embankment, impoundment design, and operational considerations. Tailings embankments can be designed as either water-retention dams and raised embankments (Vick, 1990). In modern impoundments, water-retention dams, which are intended to prohibit horizontal fluid flow, are constructed with impervious cores of earthen materials or concrete to their full height prior to tailings placement. In contrast, raised embankments begin with starter dikes designed to contain the amount of tailings expected during the first few years of production; the embankment is raised periodically as dictated by mine operations. Starter dikes typically permit horizontal flow because they are constructed using materials ranging from natural borrow soils to waste rock to tailings. Seepage discharge typically occurs from one or more points from raised embankments.

Important design features that affect surface discharge and seepage flow include the use of liner systems, seepage control and collection systems, and stream and surface run on diversions. Liner systems, intended to prevent vertical infiltration to ground water, may be installed at sites where mill effluent contains toxic or hazardous constituents. Depending on the permeability of the impoundment foundation, seepage may occur from unlined tailings facilities. The (typically engineered) foundation slope determines the location and number of seepage discharge points. Seepage control is used to protect the structures associated with a tailings facility and to provide barriers that partly or completely contain or direct the lateral subsurface flow of tailings water. Types of commonly used seepage barriers include cutoff trenches, grout curtains, and slurry walls (Vick, 1990). Seepage collection devices include collection wells, ditches, and ponds (Vick, 1990). Stream and run-on diversions may be incorporated into an impoundment if the embankment is constructed in the bottom of a valley having significant drainage from storm runoff or in a valley that produces substantial continual runoff. Diversions can be constructed either as conduits located below the impoundment or as ditches that skirt the perimeter of the impoundment.

Leach Facilities

Some primary ores, notably those of copper and gold, may be processed by heap or dump leaching techniques. Dump leaching is the process of applying a leaching agent (usually water, acid, or cyanide) to piles of ore directly on the ground. Valuable metal(s) are extracted by leaching over a period of months or years. Heap leaching is similar to dump leaching except the ore is placed on lined pads or impoundments in engineered lifts or piles. Ores may be coarsely crushed prior to leaching or may be leached as run-of-mine materials. Spent materials contain lower concentrations of the target mineral, and they may contain other metals, chemical complexes of the target metal, acid-generating minerals, and small quantities of the leach solution. After leaching, the spent ore may be treated by rinsing with fresh water or chemical additives that dilute, neutralize, or chemically decompose leach solutions and metal complexes.

Although the purpose of leach pads and dumps is to recover metals, these facilities cross into the realm of waste management upon closure (Hutchinson and Ellison, 1991). Process solutions have the ability to degrade surface and ground waters should they escape from leach pads and solution storage and conveyance systems. For most facilities, solution containment is achieved through the use of impermeable liners beneath leach pads, sumps, and pregnant and barren solution ponds, and dual-wall piping. Hutchinson and Ellison (1991) describe the types of natural and synthetic liners that are commonly used for these purposes. Regardless of the type of system that would be used, leach pads, solution storage ponds, and solution conveyance systems need to designed to accommodate the added volume of water that occurs during low probability storm events. This makes performing a rigorous analysis of the predicted water balance crucial to project design, and the monitoring of discharge or stream flow and water quality below these facilities critical.

Process Facilities

Mining conducted to extract and recover metals generally require beneficiation processes in which ore is cleaned, concentrated or otherwise processed prior to shipping to the consumer, refiner, smelter, or manufacturer who will extract or use the metal contained in the ore (EPA, 1994). Beneficiation is the separation of valuable minerals from less valuable rock called gangue. The processes and procedures for dressing and beneficiation of the mineral or metal ore are very similar for many metal extraction operations. Ore can be prepared by using operations such as crushing, grinding, washing, drying, sintering, briquetting, pelletizing, or leaching, and concentrated using gravity separation, magnetic separation, flotation or other means (EPA, 1994). A mill includes all ancillary operations and structures necessary for the cleaning and concentrating of the mineral or metal ore. Unless the mined ore is of very high grade, a mill will be located close to the mine to reduce costs of transporting the raw ore for beneficiation.

Leaching is commonly practiced to concentrate gold, copper or other metals. Leaching is the process of extracting a metallic compound from an ore by selectively dissolving the metal in a suitable solvent such as water, sulfuric hydrologic acid, or sodium cyanide solution. The desired metal is then removed from the leach solution by a chemical process, such as precipitation, or by an electrochemical process, such as electrowhinning and solvent extraction (EW/SX).

In modern mining operations, process solutions are not discharged directly from facilities to receiving waters without water treatment. Consequently, the list of chemicals used at a mine site can be extensive and may include flotation reagents, frothing and collection agents, scale inhibitors, flocculents, thickeners, leach solutions, and leachate neutralizing solutions.

Processing activities can release contaminants to surface waters in a variety of ways that include spills of reagent materials or processing fluids (e.g., pipeline ruptures), leaks at processing facilities (e.g., liner tears), storage pond overflows (e.g., during storm events), and facility failures (e.g., slope failure of a leach dump). Contaminant pathways can be direct (release directly to surface waters) or indirect. Examples of indirect contaminant pathways include infiltration to ground water that exchanges with surface water, seepage to soil or bedrock which discharges to surface water, and seepage through or below impoundment dams and berms.

POTENTIAL IMPACTS TO SURFACE WATER HYDROLOGY AND WATER QUALITY

Many surface water hydrological impacts are related to mine construction and the location of facilities. Road construction, logging, and clearing of areas for buildings, mills, and process facilities can reduce infiltration and increase the amount of surface runoff to streams and other surface water bodies. This can increase the peak flow and the total stream discharge associated with a given storm event. Unusually high peak flows can erode stream banks, widen primary flow channels, erode bed materials, deepen and straighten stream channels, and alter channel grade (slope). In turn, these changes in stream morphology can degrade aquatic habitats. Channelization (i.e., straightening) can increase flow velocities in a stream reach, potentially affecting fish passage to upstream reaches during moderate to high stream flows. Increased erosion upstream and the resulting sedimentation downstream can impact spawning gravels, egg survival and emergence of fry, as well as degrade benthic food sources.

Reduced stream flow, caused by withdrawals of surface or ground water for mine operations, can potentially affect aquatic habitats and requirements of aquatic resources. Fish have different flow requirements at different times of the year and these requirements vary for different species. Specific flows are required for spawning, maintenance of fish beds, fry emergence, juvenile rearing habitat, and adult passage. For these reasons, water withdrawals are often mitigated by establishing instream (minimum) flow requirements at critical times of the year. This requires adequate baseline characterization of hydrologic flow conditions throughout the year and characterization of the available habitat(s) associated with the fishery. Withdrawals of surface water can also reduce naturally occurring high flows that occur during high runoff periods. High flow events are often periodically required within a stream to entrain and transport sediments that were deposited during low flow periods when low peak velocities caused sediment deposition. These are known as channel maintenance flows. Channel maintenance flows are periodically required for a channel to maintain sediment transport capacity without aggrading, filling pools, and changing channel morphology, all of which can also affect aquatic habitat

Water quality issues associated with mine exploration, operation and abandonment activities involve the potential discharge of mine water and process solutions, increased loads of metals and other toxic pollutants, and the generation of acid generation from waste rock, spent ore, and mine workings. If these pollutants reach surface waters, toxic conditions could degrade water quality and affect important aquatic species. Potential analytes of concern for mining projects typically include pH, cyanide, and heavy metals. Stream flow effects caused by mining operations relate directly to potential impacts in water quality. It is common for many water quality constituents to correlate inversely with stream flow (i.e., chemical concentration increases with decreasing stream flow). This is usually true for the concentrations of most chemical constituents that occur in higher concentrations in subsurface formations than in surface soils. Some chemical constituents, however, correlate positively with stream flow (increasing concentrations with increasing stream flow). This condition is typical of natural constituents that are associated with surface soils, land applied pollutants, such as pesticides, herbicides, and nitrates, or constituents that are transported as suspended particles.

IMPORTANCE OF FLOW MEASUREMENTS

The accurate measurement and monitoring of stream flow and discharge from mine facilities is extremely important for monitoring programs and programs designed to detect potential impacts to hydrologic, water quality, or aquatic resources. Flow measurements are extremely important for studies evaluating changes in water quality, pollutant loading, and surface and ground water interactions.

Flow measurements are also necessary to estimate flood frequency, both at the mine site and the watershed level. Peak flow data are used to plan or evaluate flood control and engineering structures. Low-flow data are required to estimate water supply dependability and drive water quality standards, NPDES permitting, development of Total Maximum Daily Loads (TMDL), and used in investigations conducted under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). Relationships and the importance of flow measurements to each these activities or programs is summarized below. Flow measurements are also important activities that support both basic and applied research being conducted by the MWTP.

Relationships to Hydrogeology

Dewatering of surface and underground mines can deplete aquifers, impact ground water recharge and discharge, and locally change the direction of ground water flow. Drawdown of an aquifer potentially can lead to reduced spring and seep flows and reduced surface water flows in streams that are gaining with respect to ground water. These effects can impact wetlands associated with springs and riparian zones associated with streams. Adequate characterization of ground water and hydrogeology and its relation to surface water flows is often difficult. However, sufficient characterization of surface water flow regimes and interactions with local ground water flows requires accurate analysis of watershed conditions and measurements of stream flow. The identification of influent and effluent stream reaches, and impacts that mining could have on hydrology within a watershed is dependent on accurate stream flow measurements taken synoptically, (e.g., samples collected at approximately the same time) and taken at key locations within a stream.

Water Quality and Pollutant Loading

Many studies designed to assess impacts and pollutant discharges from mine facilities and monitoring programs require water quality sampling taken at appropriate locations and at appropriate time intervals. However, stream flow or discharge measurements are often not required or not conducted in parallel to water quality samples. It should be noted, that constituent concentrations, which are subject to dilution in downstream surface water flows, provide limited information about the behavior of constituents, and specifically, metals in streams. EPA (1996) suggests that this shortcoming can be overcome by considering constituent loads, in which the instantaneous load equals concentration multiplied by stream discharge (e.g., stream flow) as follows:

$$L = C * Q$$

where L is the instantaneous load, C is the constituent concentration, and Q is the measured stream discharge. The constituent load downstream of a tributary inflow (L_D) is equal the sum of the upstream loads (L_U) and contributing tributary (L_T) loads:

$$L_D = L_U + L_T$$

(EPA, 1996). An increase or decrease in load reflects an increase or decrease in the mass of the constituent being transported per unit time. Increases in load along a stream reach can point to sources of contamination that may be recognized (i.e., tributary inflow) or unrecognized (i.e., ground water inflow) during conventional sampling. In contrast, decreases in load suggest that a constituent is being removed by one or more physical, chemical, or biological processes. Physical processes such as sedimentation and sediment transport, chemical processes such as adsorption and colloidal precipitation, and biological processes such as uptake can cause changes in constituent loads. Accurate evaluations of constituent loading, identification of pollutant sources, and analysis pollutant retardation and attenuation factors are dependent on accurate measurements of stream flow (i.e., discharge).

Water Quality Standards and NPDES Permitting

EPA's involvement under the CWA primarily relates to NPDES permitting under Section 402, and to a lesser extent, Section 404 (wetlands/dredge and fill). Under CWA Section 402, all point source discharges (see below) of pollutants to navigable waters of the United States must be permitted under NPDES. Effluent limits in NPDES permits may be technology- or water quality-based. In evaluating mine sources, EPA typically assesses the potential for exceedances of anticipated permit limits. These assessments often require characterization of both discharge quantity and quality and relationships to stream flow.

NPDES permits require the application of technology-based or water-quality-based limits to point source discharges, whichever are more stringent. Each State has water quality standards that are applied to individual streams based on its designated uses. In determining water quality based permit limits for effluent discharges, states generally have provisions for mixing zones. The size of mixing zones is typically determined based on dilution available during low flow conditions. The characteristic low flow condition used for most EPA water quality compliance programs in concert with chronic aquatic life criteria is the lowest 7-day average daily stream flow that occurs with a 10-year return period (i.e., 7Q10L). However, many mine sites discharge to streams with negligible low flows (i.e., available dilution is minimal).

Development of TMDLs

Finally, Section 303(d) of the CWA requires States to identify water bodies that are not meeting their promulgated designated uses. These lists may include hundreds of stream segments, many of which occur in historic or active mining districts and the source of degradation is discharges and increased sedimentation from abandoned mine wastes. Streams or stream segments which do not consistently meet designated uses could require development of a TMDL. A TMDL is a technical plan designed to attain water quality standards. The development of a TMDL requires accurate assessments of stream flow regimes, identification of sources, constituent loading for each source (see Water Quality and Pollutant Loading), identification of low flow regimes, such as the 7Q10L, and the loading capacity, defined as the water quality standard multiplied by a given stream flow. A TMDL is accomplished by establishing loading allocations for the constituent(s) of concern for each identified point source and non-point source occurring in a stream segment. TMDLs are implemented and accomplished by site remediation programs, modification of point source discharges, and other means necessary to achieve specified criteria.

CERCLA Investigations

Mining activities have often caused releases of contaminants or hazardous constituents to the environment, particularly surface and ground water resources. Examples include structural failures of impoundments or waste embankments, contamination by acid mine drainage, seepage from tailings, waste rock dumps, and heap and dump leach facilities, and spills of hazardous chemicals to soils or receiving waters. Remedial investigations (RIs) are often required to identify the nature and extent of contamination and to identify the fate and transport of contaminants in both surface and ground water systems. Feasibility studies (FSs) are then utilized to evaluate and select alternatives for remedial action. Both RI and FS investigations require the identification of sources, the quantification of loading from these sources, and assessments of health risk to both human and ecological receptors. Accurate assessments of stream flow, the characterization of flow regimes, as well as an assessment of the quality of discharges from sources are generally required in support of RI/FS investigations at mine sites. Flow and discharge measurements, therefore, often play an important role in identifying sources, quantifying contaminant loading, and providing assessments of risk.