Selecting and installing flowmeters for pressurized pipes

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In response to legislation passed during the 1994 and 1995 sessions of the Idaho Legislature, the Idaho Department of Water Resources (IDWR) is initiating a program for measuring groundwater withdrawals in the Eastern Snake River Aquifer. The statute allows irrigators two options for measuring groundwater diversion: (1) install a measuring device at the well pump discharge or (2) use power records to estimate water withdrawals (page 8). In 1995, irrigators were required to measure surface and groundwater withdrawals in Basin 36, an area north of the Snake River between Hagerman and Minidoka. The Department of Water Resources will expand water measurement requirements to the entire Eastern Snake River Aquifer in the next 3 to 5 years.

Acceptable water measurement devices for use in a closed-conduit system (both sprinkler irrigation and nonirrigation uses) must be able to measure and record the quantity of water used over a given period of time, typically acre-feet of water used during an irrigation season. Many devices also measure the rate of water flow (e.g., volume of water passing the measuring point in a relatively short period of time), typically expressed in gallons per minute (gpm) or cubic feet per second (cfs). IDWR requires these devices to have a design accuracy of ± 2 percent, with an installed field accuracy of ± 10 percent.

Water measurement concepts

The rate of fluid flow in a pipe of constant diameter can be calculated by the equation $Q = AV$, generally referred to as the continuity equation (figure 1). The most commonly used set of units would give

Q = flow rate through the pipe in cubic feet per second (cfs),

A = pipe cross-sectional area in square feet (area of a circle with a diameter equal to the inside pipe diameter), and

V = average velocity of flow in the pipe at the location where the cross-sectional area was determined.

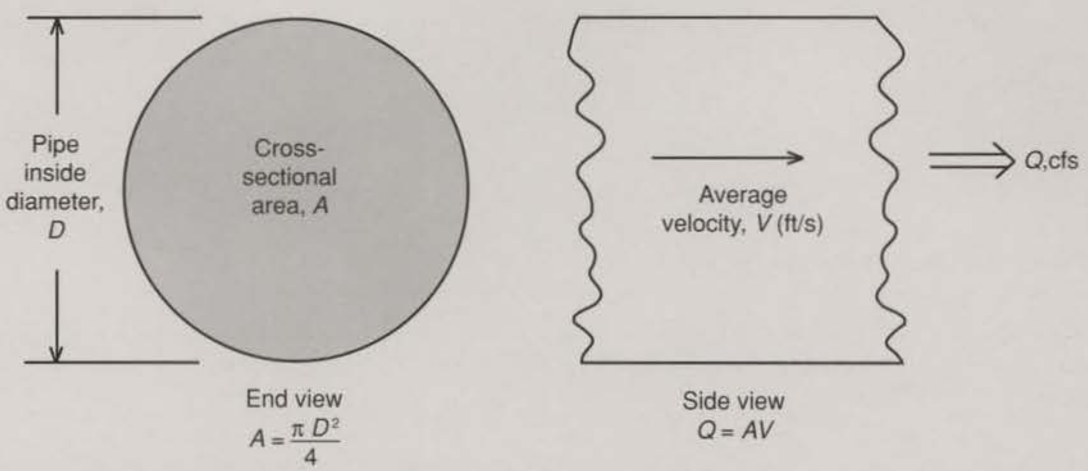

Figure 1. Flow rate (Q), velocity (V), and pipe cross-sectional area (A) in pipe flow conditions.

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The two factors necessary to correctly determine flow rate are then the actual inside diameter of the pipe and the average flow velocity. Pipe inside diameter can be measured directly. One of a number of methods discussed below are used to determine average flow velocity.

Determination of pipe inside diameter is very important. Because cross-sectional area varies with pipe diameter squared, an error of 10 percent in determining inside pipe diameter will give an error of 21 percent in cross-sectional area (and therefore flow rate). By comparison, an error of 10 percent in determining average velocity will give an error of 10 percent in flow rate because flow varies directly with velocity.

Water may be measured as either a volume (gallons, cubic feet, acre-feet) or a flow rate (gallons per minute, cubic feet per second, or Idaho miners inches). In closed-conduit water measurement, we measure flow rate. To determine the volume of water flowing past a point in a given amount of time, the flow rate is multiplied by the time interval. For example, to determine the volume of water flowing through a section of pipe in one hour if the flow rate is 100 gallons per minute, we would multiply 100 gallons per minute by 60 minutes and get 6,000 gallons. The relationships between a number of different volume measurements and between flow rate measurements are given in table 1.

Velocity distributions in closed-pipe flow

A number of factors can affect the manner in which water flows in a pipe. All meters are influenced to one degree or another by deviation from the ideal flow distribution for which they are designed. It is important to understand these factors so you can properly install and reliably calibrate these meters.

A typical velocity profile of water flow in a long, smooth, straight section of 5-inch-diameter pipe free from any fittings, valves, bends, or enlargements is depicted in figure 2. Velocity is maximum at the pipe centerline, and the velocity reduction with distance from the centerline is symmetrical. In this case, a measurement taken at any point other than the centerline will be less than that at the center but will vary in a predictable manner, allowing approximate preinstallation calibration of a flowmeter.

The presence of elbows or valves will affect the shape of the distribution as shown in figures 3 and 4. If we were to install an impeller meter just downstream of an elbow or partly open gate valve, the resulting error in water measurement could be as high as 39 percent for an elbow and 182 percent for the partly open gate valve.

Water swirling through the pipeline will give additional flow measurement problems. Swirling fluid can be caused by spiral welded pipe, multiple injection points, centrifugal pumps, two 90-degree elbows out of plane, or any repetitive, rough pattern on the pipe wall. Swirl can be reduced by the use of straightening vanes placed upstream of the flow measuring device. Propeller-type meters are more sensitive to swirl than are other devices.

Devices such as impeller meters that sample a point in the flow require that the flow distribution be symmetric about the centerline or that any deviation from symmetry be constant with varying discharge to allow field calibration. Measurement devices that sample a large portion of the flow cross section (such as the propeller meter) are not as greatly affected by local flow disturbances cause by bends, valves, or fittings.

Table 1. Common water conversion factors.

Volume	Flow rate
1 cubic foot of water = 7.48 gallons = 62.37 pounds of water	1 cubic foot per second (cfs or second-foot) = 448.8 gpm
1 acre-foot = enough water to cover 1 acre to a depth of 1 foot	1 cfs = 50 Idaho miners inches
1 acre-foot = 43,560 cubic feet	1 cfs = 1.9835 acre-foot per day
1 acre-foot = 325,850 gallons	1 Idaho miners inch = 9 gpm = 0.02 cfs
	1 cfs for 24 hours = about 2 acre-feet
	1 cfs is approximately equal to 1 acre-inch per hour

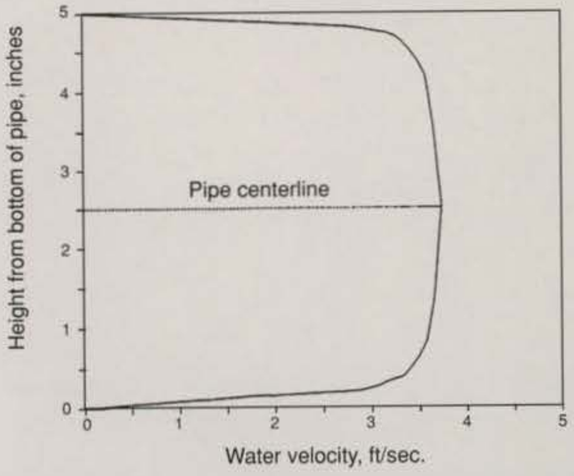

Figure 2. Typical velocity distribution in a long, straight section of 5-inch-diameter pipe. (Modified from: Brockway, C. E., and C. Robison. 1987. Evaluation of closed-conduit measuring devices for irrigation diversions. Research Technical Completion Report. Moscow, Idaho: Idaho Water Resources Research Institute.)

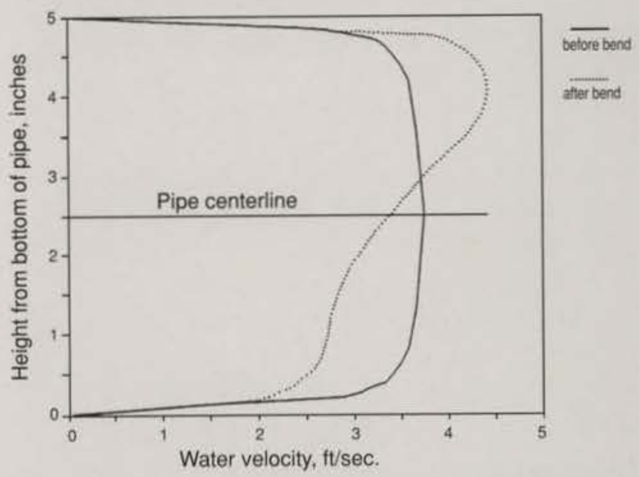

Figure 3. Velocity distribution before and after a 90-degree bend in a 5-inch-diameter pipe. (Source: Brockway, C. E., and C. Robison. 1987. Evaluation of closed-conduit measuring devices for irrigation diversions. Research Technical Completion Report. Moscow, Idaho: Idaho Water Resources Research Institute.)

Closed-conduit measuring devices

Several types of closed-conduit (pipe) measuring devices are typically used in agricultural applications. Some, such as differential pressure and force-velocity meters, are practical and yet sufficiently economical for permanent installation in individual irrigation systems. Others, such as ultrasonic devices, are portable, nonintrusive (they strap onto the outside of the pipe), and more accurate and reliable, but they are considerably more expensive.

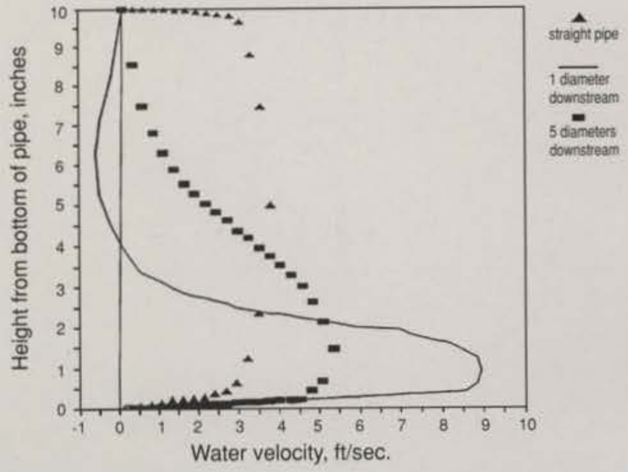

Figure 4. Velocity distribution upstream and downstream of a partially open gate valve. (Modified from: Brockway, C. E., and C. Robison. 1987. Evaluation of closed-conduit measuring devices for irrigation diversions. Research Technical Completion Report. Moscow, Idaho: Idaho Water Resources Research Institute.)

Differential pressure meters

These meters require a constriction in the pipe. As the flow accelerates through the constricted zone, pressure is reduced. As flow exits the constricted section, velocity slows and pressure rises, but not back to the original upstream pressure because some pressure loss occurs due to turbulence in the measuring section. Flow through a venturi-type meter is determined by measuring pressures upstream and in the constricted zone. Pressure measurements are taken upstream and downstream of an orifice meter. A relationship between pressure drop and flow rate for a particular device is used to relate a measured pressure drop to the actual flow rate. Flow must then be accumulated over time to give the total volume diverted.

Orifice and venturi meters. Orifice meters (fig. 5) use an abrupt constriction, while a venturi meter (fig. 6) uses a more streamlined shape. The orifice meter is easier to construct and install because it can be bolted into a flanged connection. Net pressure drop will be less in the venturi meter because of its more streamlined control section.

These meters have the advantages of no moving parts and the ability to shed trash easily. However, off-the-shelf electronics to accumulate total seasonal flow as required by IDWR are currently available from only a very limited number of suppliers. These units also require custom construction and calibration because they are not necessarily constructed to standard dimensions.

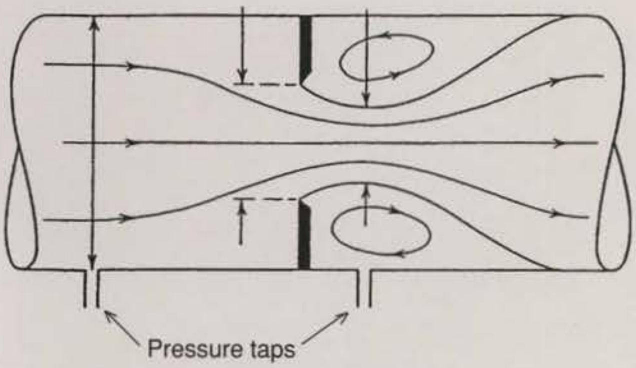

Figure 5. Orifice meter. (Source: *Elementary Fluid Mechanics.* 6th ed., by J. K. Vennard, and R. L. Street. © 1982 John Wiley & Sons, Inc. Reprinted by permission)

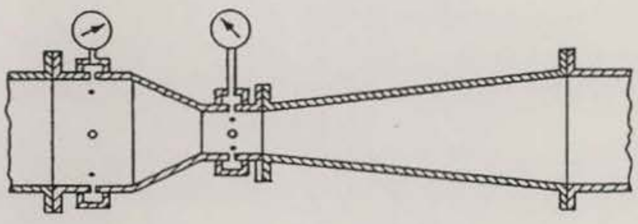

Figure 6. Venturi flowmeter. (Source: *Principles of Farm Irrigation System Design* by L. G. James. © 1988. John Wiley & Sons, Inc. Reprinted by permission)

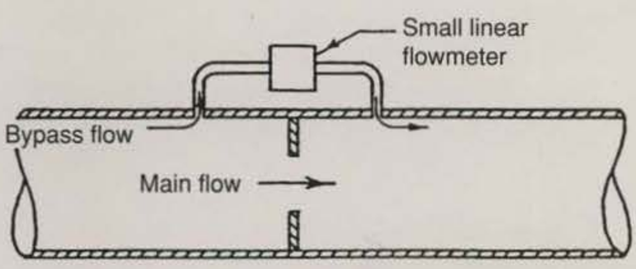

Figure 7. Orifice shunt meter. (Source: *Principles of Farm Irrigation System Design* by L. G. James. © 1988. John Wiley & Sons, Inc. Reprinted by permission)

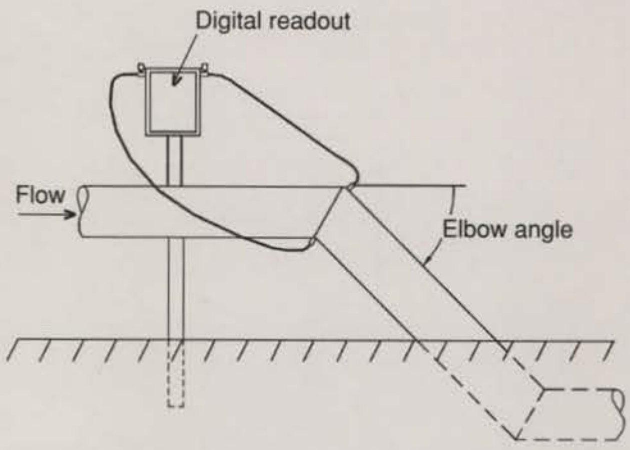

Figure 8. Standard elbow meter. (Source: ID TECH, Inc., Blackfoot, Idaho)

Shunt or bypass meters. Several types of venturi or orifice shunt meters are commercially available. They use a calibrated commercial water meter to measure the flow through a pipe running from the high- to low-pressure taps on a venturi or orifice section (fig. 7). The rate of flow is proportional to the pressure difference, and therefore an indicator of flow through the venturi or orifice section. With proper calibration, they provide both instantaneous flow rate and total flow, thus satisfying the IDWR requirement for determination of total annual diversion. Because the velocity through the water meter is low, these meters should be used only with clean well water (no sand) and not with surface water containing sediment or debris.

Elbow meters

Elbow meters (fig. 8) relate flow rate to the pressure difference between the inside and outside of a regular mitered pipe bend. The higher the flow, the greater the pressure differential. In a commercially available model, 1/4-inch pressure ports are installed on either an existing or new elbow at locations shown in figure 8. Either smooth radius or miter bends can be used effectively. Bend angle, as measured from an extension of the prebend direction, can be from nearly 0 (an almost straight pipe) to 60 degrees.

The signal from a differential pressure transducer is related to flow rate for the specified bend angle and inside pipe diameter. The meter can display flow rate or total flow in several sets of units, thus satisfying IDWR requirements for determination of total annual diversion. This type of meter has the advantages of no added pressure drop, no intrusive components to catch trash or obstruct flow, and no moving parts.

Force-velocity meters

This category of meters uses a propeller (fig. 9) or impeller (fig. 10) placed inside the pipe to sense the velocity of the flowing water. Flow rate is then determined by considering both the velocity of the flowing water and the cross-sectional area of the pipe. As with the differential head meters, the rate of flow must be accumulated over time to give total volume of water measured, typically in acre-feet.

Meter hardware to provide both flow rate and total volume of water measured is readily available. Accuracy is acceptable if the meters are properly installed and proper upstream and downstream flow conditions exist.

Propeller meters. Propellers meters sample the average velocity of water over a large portion of the inside diameter of the pipe. In the case of a propeller meter, the motion of the spinning propeller is transferred to the recording head through either a flexible cable, a right-angle gear drive, or by magnetic pickup. Flow rate is displayed by a needle much like automobile speed, and water volume is displayed like the odometer reading on an automobile.

Because propeller meters sample a larger portion of the flow, they are less sensitive to changes in velocity distribution in the pipe than are impeller meters. Therefore, they require a shorter section of straight pipe upstream than do the impeller meters and are less affected by disturbances caused by upstream fittings or partially open upstream valves.

Impeller meters. Impeller meters sample a point velocity at the depth of insertion into the pipe. The spinning sensor is much smaller than on the propeller meter (typically 1/2- to 3/4-inch diameter) and rotates about an axis crosswise to the flow. It must be inserted into the pipe to the distance specified by the manufacturer to be accurate. Typical insertion depths are one-eighth the pipe diameter for diameters greater than 6 inches and one-half the pipe diameter for pipes less then 6 inches in diameter. This means that in most Idaho installations, the sensor is located nearer to the pipe wall than to the center of the pipe. As a result, impeller meters shed large and small trash better than propeller meters. Typical bearing wear and failure problems are less frequent for impeller meters than for propeller meters.

Ultrasonic meters

Two types of ultrasonic meters are commercially available. One type uses the Doppler effect to measure the downstream velocity of air bubbles or sand grains in the water (fig. 11).

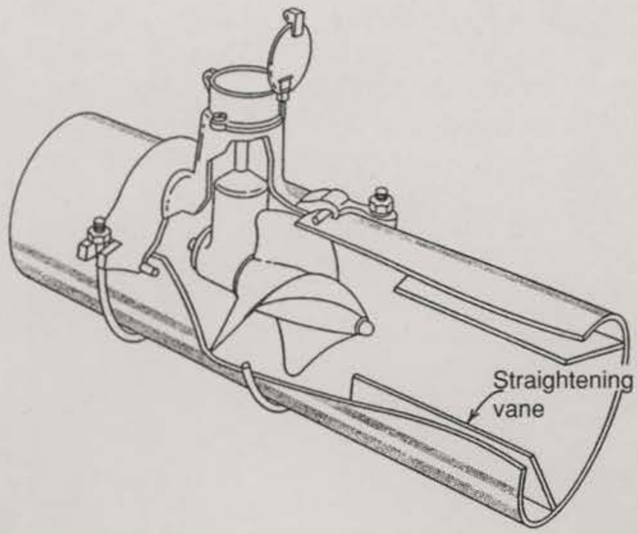

Figure 9. Bolt-on propeller meter. (Source: SCS National Engineering Handbook, 1962)

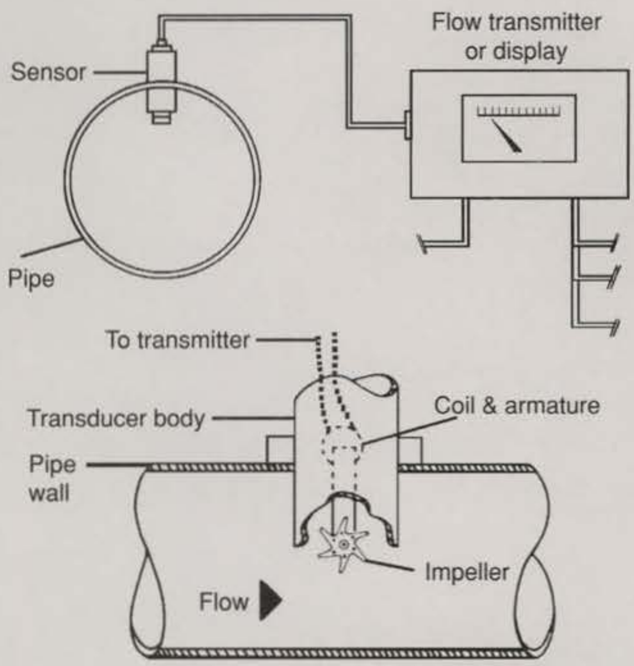

Figure 10. Impeller meter. (Source: Peek Measurement, Inc., Houston, Texas)

Another type measures the difference in time required for sound waves to travel from an upstream transmitter to a downstream detector through flowing water (fig. 12). A microprocessor connected to the sensors by a cable analyzes wave travel time and converts the information into water flow velocity then to a flow rate and to total volume. Typical readout is digital for flow rate and odometer-type for total volume.

These devices are noninvasive because nothing is placed inside the pipe. They can be installed as permanent or portable devices, although due to their high cost they are usually used as portable instruments for measuring a large number of systems. Most experience in Idaho has been with the second type of meter (fig. 12); very few Doppler-type meters are in use. Several years of extensive field experience have shown that these meters are reliable and highly accurate if properly installed under proper upstream and downstream flow conditions.

Electromagnetic meters

Magnetic or electromagnetic meters set up a magnetic field around the conduit containing the flowing water. The voltage generated is then related to the velocity of the water. Flow rate and total volume are then determined and recorded by a microprocessor. These meters are typically installed by removing a section of pipe and replacing it with a flange-mount section containing the meter.

They give the most accurate measurements if a straight section of pipe is not available, probably 5 percent error just downstream of fittings. They are competitively priced in the smaller pipe sizes (e.g., 4-inch) but are more expensive in the larger pipe sizes.

Meter cost

Meter cost for 6-inch and larger pipes ranges from $600 to $2,000 for propeller and impeller meters to $6,000 to $10,000 for ultrasonic or magnetic meters. Smaller (4-inch) magnetic meters can be purchased for under $2,000.

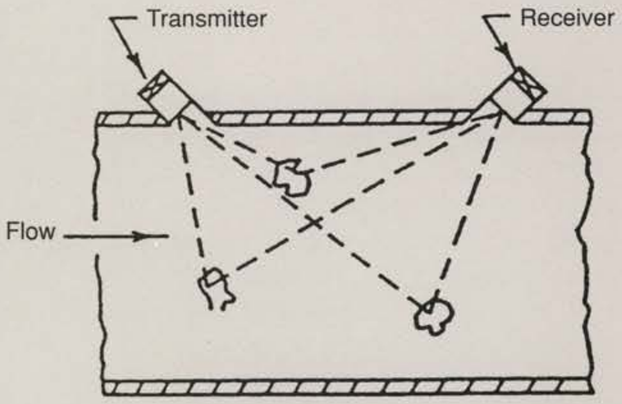

Figure 11. Doppler-effect ultrasonic flowmeter. (Source: *Principles of Farm Irrigation System Design* by L. G. James. © 1988. John Wiley & Sons, Inc. Reprinted by permission)

Propeller and magnetic meters must be ordered for the exact inside pipe diameter. Impeller meters typically use the same sensing and display hardware for a range of pipe diameters. The impeller is inserted into the pipe the distance specified for a particular pipe diameter, and settings on the display unit are changed to fit the actual pipe size.

The cost of an elbow meter is $1,500 for any pipe diameter. Both elbow and ultrasonic meters can accommodate a range of pipe sizes and a variety of materials (aluminum, PVC, steel, copper, etc.).

Meter installation

Accurate flow measurement requires a symmetrical, uniform velocity distribution with respect to the pipe centerline. Therefore, a minimum upstream distance of straight pipe free of valves and fittings is usually given as 10 pipe diameters. For a 10-inch diameter pipe, this means 100 inches of straight uniform pipe upstream from the measuring device. The downstream requirement is usually 5 pipe diameters.

This means a total length of 15 pipe diameters of straight, uniform pipe without valves or fittings is the

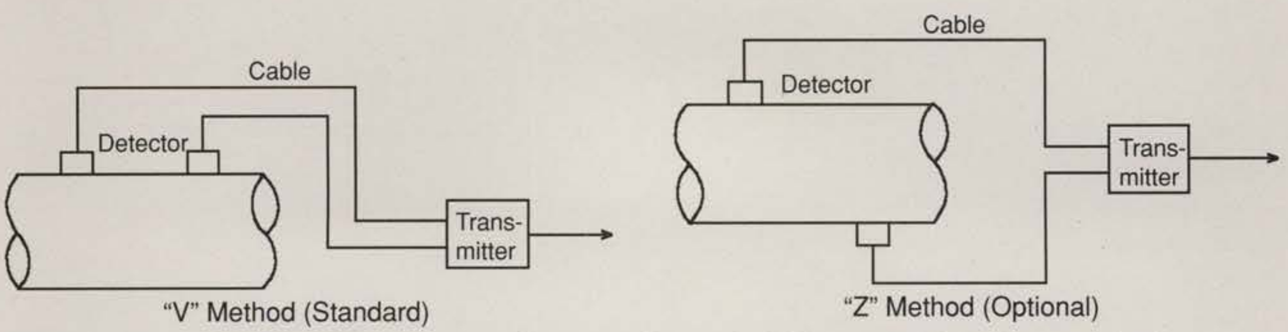

Figure 12. Single-path, diagonal beam ultrasonic flowmeter. (Source: Peek Measurement, Inc., Houston, Texas)

minimum required to get an adequate measurement. Any new installations should provide for a section of at least this length to accommodate a water measurement device. Upstream and downstream pipe length requirements can be reduced somewhat by the addition of straightening vanes.

Meter maintenance

Maintenance is critical for accurate, long-term meter operation. Maintenance requirements vary with meter type and the specific manufacturer, so reading and following manufacturer maintenance instructions is critical. For example, propeller meter manufacturers recommend removing the meter and storing it in a dry location where it will not freeze. Failure to do this typically results in bearing or cable failure. The shunt meter must also be removed from shunt-venturi meters and stored under nonfreezing conditions in the winter. Some impeller meter manufacturers specify disconnecting the display unit and storing it in a dry, nonfreezing area during the winter.

Propeller meter repair costs are often quite high, up to 80 percent of the purchase price. Repair items on an impeller meter typically include repair or replacement of the impeller/axle assembly for a cost of about $100. Repair or replacement of the display unit will be higher. Repair or replacement cost of the shunt meter on a shunt-venturi meter is also low.

Because it has no moving parts, repair or maintenance costs for the elbow meter should be quite low, primarily for replacing the display battery once in several years. Repair of the display unit would be the other possible cost.

Meter selection

No one meter is the best choice for all applications. Table 2 summarizes factors to consider when selecting a meter. Actual selection will depend on which factors you consider most important at a particular site. For example, a propeller meter may be the best choice when working with clean water at a site where only a short section of straight pipe is available and lightening strikes are a problem. On the other hand, in a location where aquatic weeds can be a problem, lightening strikes are rare, a sufficient section of straight pipe is available, and pipe diameter is large, an impeller meter with electronic readout and mechanical totalization may be the method of choice.

Field observations

The types of meters discussed here will adequately measure flow and generally perform well over time if they are properly installed and maintained. However, many times seemingly small details can produce major errors in flow measurement. Three actual situations from summer 1995 field testing are presented here to illustrate some common pitfalls. IDWR uses a portable ultrasonic flowmeter like that shown in figure 11 as the standard measurement method to which all installed flowmeters are compared.

Beware of small fittings just upstream from the meter

On one farm west of Paul, an impeller meter was installed in a straight section of 10-inch pipe with more than 10 pipe diameters of long straight pipe upstream of the meter. The entire installation was according to manufacturer's recommendations except that the

Table 2. Comparison of meter costs and characteristics.

Meter	Approximate cost	Field calibration	Required upstream/ downstream pipe diameter[1]	Trash shedding ability	Nonvolatile display
propeller	800-3,000	No	10/1 (5/1)	medium	Yes
impeller	500-800	Yes	10/5	good	Yes
orifice	300-500[2]	Yes[3]	10/10 (3/2)	good	depends
venturi	500-1,700[2]	Yes[3]	10/10 (3/2)	v. good	depends
venturi shunt	800-1,200	Yes[4]	5/3 (3/2)	poor	Yes
elbow	1,500	Yes	3/1 (2/1)	v. good	Yes
ultrasonic	6,000-10,000	Yes	30/5 (10/5)	v. good	Yes
magnetic	8,000-10,000[5]	Yes	4/1 (2/1)	v. good	Yes

[1]Values from manufacturers' literature. Values in () are for use with straightening vanes.
[2]Custom electronics required for total flow will add to cost.
[3]Calibration possible if electronics allow.
[4]Calibrated by altering the control orifice diameter.
[5]$2,000 for some smaller pipe models.

meter was installed about 1 foot downstream from a 2-inch air vent that was welded into the mainline. When field tested against an IDWR ultrasonic meter installed upstream of the air vent, the impeller meter was found to be in error by about 12 percent. Even the small disturbance caused by this fitting just upstream was enough to produce this error. Fortunately, this meter allowed easy field calibration and was adjusted to read within 2 percent of the ultrasonic meter.

Field calibrate newly installed meters

On another farm northwest of Paul, an impeller meter was installed exactly according to manufacturer's recommendations and workmanship was excellent. This meter was found to undermeasure by 16 percent, while another installation with poor workmanship was found to read within 1.5 percent of the standard. These two cases illustrate the need to field check all new meter installations, recalibrating if necessary.

Carefully measure the actual inside diameter of the mainline

Since both propeller and impeller meters measure a velocity and then calculate flow by multiplying velocity by pipe cross-sectional area, an error of 10 percent in pipe diameter will give an error of 21 percent in area and flow rate.

A propeller meter was installed in a 10.77-inch OD steel pipe with 3/16-inch (0.188) wall thickness. The meter was ordered assuming a 10.00 inch OD and 0.105-inch wall thickness. As a result, when installed and tested, it undermeasured flow by 12 percent. Since propeller meters cannot be field calibrated, the meter was sent back to the factory where the proper gears were installed. When reinstalled with correct gearing, the meter was within 2 percent of the standard.

Power consumption coefficient

The Power Consumption Coefficient (PCC) is the number of kilowatt-hours required to pump one acre-foot of water. The PCC method of determining water volume pumped uses two pieces of information obtained on-site while the pump is running at or near normal operating conditions. One is the flow rate of the water being pumped, and the other is the kilowatts of electrical power required to pump that flow rate. The PCC is unique to each well and pumping plant due to the physical attributes of the system. It will vary somewhat if pumping water level in the well varies, if flow changes considerably due to changes in the number or type of sprinklers served, or if there is other valving of the pump.

To determine the flow rate, a portable, ultrasonic, noninvasive meter like that shown in figure 11 is preferred as the standard. This flowmeter has been shown to measure the flow rate within the required accuracy under a variety of conditions, if properly installed. Simultaneous with the flow measurement, readings are taken from the watt-hour meter to calculate kilowatts of power used. With the flow rate and kilowatts used, the PCC can be calculated with the following equation:

$$PCC = \text{kWh/acre-foot}$$
$$= (\text{kW} \times 5{,}431)/\text{gpm}$$

With the PCC, an annual volume of water pumped can be calculated from the total annual kilowatt-hours of energy consumed by the pumping plant:

$$\text{Total volume pumped} = \text{Total seasonal kWh}/PCC$$

The electric utility will supply IDWR with total power usage for each pumping plant. A qualified individual with the necessary equipment will be required to perform the field pump testing measurements.

The PCC method is not recommended where multiple pumps are linked together with a common mainline and/or where significant flow rate differences occur in operation of the system. For example, pumps with "flat" curves (little pressure change with considerable flow change) can have a large change in PCC with just a 5 to 10 psi change in system pressure.

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