TECHNIQUES FOR MEASURING FLOW IN CHANNELS

by

George Okoye Krhoda
Department of Geography
University of Nairobi

INTRODUCTION

Determining the quantity of water has become an important facet in water resources development because of the rapidly increasing demand for water as a result of population growth. The pressure on water resources reflects itself in the form of conflicts of use and among users because the use of water in one direction may preclude its use in others. For this reason there must be ways of determining the quantity of water in order to apportion it for different uses.

The different uses of water include domestic and industrial consumption, the generation of hydroelectric power, for pollution control and for irrigation. The use of water for one function may preclude use for the others in any given situation. For this reason there is an increasing demand for well trained technical staff to work in the area of water resources development, especially in developing countries. The efficiency of the technical staff will be assisted by also improving the instrumentation and techniques and a more intensive application of modern computing.

The methods used for determining the quantity of water are many. One of the methods discussed in this paper involves the measurement of velocity using both mechanical devices and chemical electrical methods. A second method uses stage-discharge relations computed from the measurements of stage of flow and the historical records of discharge. The relations are shown in a graphical form by a rating curve.

The final group of methods discussed for determining quantities of water measure discharge directly by using structures such as weirs, notches and flumes.

This paper discusses the techniques for determining discharges in open as well as closed channels. Open channels include rivers, irrigation channels and many other conduits in which water flows with a free surface. The methods that have been adapted for measuring discharges in closed conduits such as pipes are also discussed. It will be shown that there are many methods that are easily adaptable for specific environments at minimum costs and which demand little training for the operators.

I THE BASIS OF DISCHARGE MEASUREMENTS

It is believed that the oldest hydrological records consisted of flood marks along the Nile River carved in its cliffs between Semneh and Kumneh (Boyer 1964). However the largest water supply works, which existed in China, India, Babylon, the Roman Empire and Central America, must have been based on some form of computation of the quantity of water distributed to any given user. The quantity of water passing through a point in a channel is called discharge. The measurement of discharge is based on the continuity equation. This equation expresses discharge, q, to be a product of the cross-sectional area of the channel, A, and velocity of the flow, V, and shown in the expression:

$$q = A.V \qquad (1)$$

in which A is the product of mean width and mean depth of the channel, in m^2.

Discharge may be expressed in cubic meters per second or in litres or gallons per unit given time, while velocity is measured in distance per unit time such as metres per second. The continuity equation states also that the discharge, q, is the same in all cross-sections of the conduit. In other words:

$$q = V_1 . A_1 = V_2 . A_2 \qquad (2)$$

where V_1 and V_2 are the mean velocities and A_1 and A_2 the cross-sectional areas in any two sections, respectively.

The other methods of measuring the quantity of water passing through a cross-section uses the energy equation. A liquid in motion possesses three kinds of energy, namely kinetic energy, pressure energy and elevation (potential) energy. The last two are forms of potential energy. During the flow of a liquid, energy can be transferred from one form to another. For example a hole punctured into a closed vessel full of water at a higher pressure than the atmosphere will form a jet. A percel of water forming the jet loses its pressure energy but obtains kinetic energy instead. The jet obviously rises to a certain height above the vessel and then falls because all the kinetic energy has been transferred into elevation energy.

The height above a reference plane to which a mass of liquid would rise if the kinetic energy as well as the pressure energy were transferred to elevation energy is the total energy of the mass of the liquid. The height is called the energy head and it consists of the elevation head, Z, the pressure head, P/α and the velocity head, $V^2/2g$; in which g is acceleration due to gravity and is equal to 9.81 $m/5^2$, α is the unit weight of the liquid in Mp/m^3. $V^2/2g$ and Z are calculated in metres.

The energy theorem of a perfect (ideal) fluid (Bernoulli's equation) states that

$$\frac{V^2}{2g} + \frac{P}{\alpha} + \quad \text{constant} \qquad (3)$$

However, in real fluid, the amount of energy decreases because of frictional losses that transforms energy into heat. The sum of such loss is measured by the total frictional head, Σhf. The expression (3) measured at two points in a channel becomes:

$$\frac{V^2}{2g} + \frac{P1}{\alpha} + \quad = \frac{V2^2}{2g} + \frac{P2}{\alpha} + Z_2 + \Sigma hf \qquad (4)$$

where V_1, P_1, and Z_1 refer to velocity, pressure and elevation head at point 1 in the channel and V_2, P_2 and Z_2 to the same quantities in another point 2 further downstream of point 1. Σhf is the total loss between points 1 and 2.

The concepts of the energy gradient and the hydraulic gradient are derived from expression (4). The hydraulic gradient shows the level to which the liquid rises in a vertical stand pipe, a piezometer tube, connected to a channel. It expresses the potential energy of a liquid. There are several pertinent truths that make a piezometer an instrument for measuring discharge of a channel.

One of such truths is that in an open channel, the pressure is zero at the liquid surface and the hydraulic gradient coincides with the liquid surface. If the flow of the liquid is uniform, the depth, velocity and velocity head are parallel to the bottom and have the same slopes downwards in the direction of the flow, because the energy of the liquid always decreases in the direction of the flow due to internal friction. Sometimes, for the ease of computation, the loss of head may be neglected and the energy gradient becomes horizontal.

The hydraulic gradient rises and falls in the direction of flow depending on changes of the velocity head. Using expression (2) above, the changes in velocity head are caused by changes of the cross-sectional area. Many discharge measuring devices that are discussed in the present paper use the principles of continuity equation and conservation of energy.

There are two categories of instruments that are used in measuring discharges. There are instruments that determine the velocity of flow directly from a conduit and uses the expression (1) to compute discharge while there are others that compute discharge directly using some co-efficients. In each case the hydraulic of the flow varies and one instrument determines discharge rather more accurately than the other. The discussion that follows describes some of the methods for determining velocity in channels.

II METHODS OF VELOCITY MEASUREMENTS

Introduction

The conditions of streamflow range from those that have extremely low velocities in irrigation cannals to the most turbulent flows in mountainous and flood-prone channels. These are open channels while others are closed conduits, as in pipes. The sizes of the channels and the nature of the boundary vary considerably. Because of these widely varying conditions several methods have been developed for velocity measurements, depending on the type of instrument (Nemec 1964). These methods use mechanical devices which are rotated or deflected by the current, instruments for the conversion of velocity head into potential head and chemical and electrical methods.

Mechanical Devices

The three principal mechanical devices used in velocity measurements include the rotating meters, the dynamometer and the float. The rotating meters are by far the most popular in Kenya and they include a whole range of current meters with horizontal or vertical axles. The rotation is accomplished by cups or vanes or propellers, and they come in a wide range of sizes and capabilities.

To ascertain the average velocity of water at a cross section, one divides the cross section into vertical bands. For each band an average vertical velocity is computed from point velocities measured at characteristic depths. The procedure involves an intergration of velocities at different depths of flow. The velocity varies also with time. It pulsates at short time intervals as a result of macro-eddy transport through the section. This pulsation is, however, intergrated into an average by the very principle of the current meter.

The current meter is composed of a propeller or cups on an axle, the body, a revolution-counting device and the electric contact. The whole current meter is suspended either on a rod or on a cable. There is a wire that leads from the contact to the buzzer or any other signal - or revolution-counting device. The relation between the number of rotations of the propeller or cup and the velocity is obtained by calibrating the propeller. Calibration of a current meter is done in the following manner. The current meter is fixed on a rod or cable and towed through still water in a long tank at a fixed speed. The number of revolutions are ascertained.

Velocity measurement may be made by wading across the channel, by using a cableway or from a bridge. The wading measurement is done for shallow (less than 1.0m depth) and small (15 to 20m wide) streams and channels. In addition to the current meter, the operator must have a stopwatch (unless included in the counter device of the current meter), a measuring survey tape and a levelling rod or portable staff gauge to obtain the measurement of the channel cross-section and a note book for recording the measurements. For measuring deeper and wider streams, a calibrated steel cable of 5 to 15mm diameter, marked every 1m, and 100 to 150m long should be used. A winch arrangement, 4 or 5 pieces of steel of 1.0m each and wooden or metal pegs are also required. If the measurement cannot be taken from a bridge, a flat-bottomed boat with stream-gauging gadgets mounted on it may be used to cross the river.

The measuring procedure involves selecting a suitable site.

The cross section should be determined and staked out by pegs or stakes perpendicular to the streamline. A tape is then stretched across then stream. In larger rivers, the cables are stretched across from a flat boat and the cable is anchored to the bank in such a way that the zero of the calibrated cable is on the left bank to an observer looking downstream.

The depth is frequently measured simultaneously with the velocity. A staff gauge is established to record any change in the surface water elevation during the period of measurement. The velocity and depth measurements are taken at discrete and regular distances. The readings are recorded into a prescribed record sheet.

The dynamometer translates the momentum force of a stream velocity into either deflection or stress. The deflection or stress. is then measured and calibrated against velocity measurement. However, dynamometers are used relatively less often.

The most practical and cheapest method of velocity measurement is by timing a float that travels downstream. Many varieties of floats may be designed by the hydrologist to measure velocity at various depths of flow in an open channel.

The use of floats in measuring velocity is the simplest method and probably the one which involves the least cost in terms of equipment. The method is used if there is no current meter available and also during floods when it is nearly impossible to use a meter because of the volume of flow and its turbulence. The method does not provide precise measurements but differs less than 15% from measurements made with a current meter.

Any sort of floating object may be used as float. However, it should not be allowed to protrude out of the water so much that it could be influenced by the surface winds or be too light. It is recommended that a number of floats be timed. The time each float takes to run a known distance along the channel can be measured using a stopwatch. To obtain the area of the channel's cross-section a levelling or sounding rod and tape may be used to measure its depth and width.

The operation may be done by a single person, but using two people makes the operation relatively easy and improves accuracy. After the cross-sectional area of the channel is determined, a decision is made on the number of floats that are going to be used, depending on the size of the channel. The channel reach (width) should be divided into three sections although measurements are taken in the middle reach only. The floats are then put in the channel. As they reach the beginning of the measurement section, the upstream operator signals, using a whistle or by waving hands, to the downstream operator. The downstream operator records the time the float takes to reach the downstream cross-section. Several floats may be run and an average velocity is obtained.

A fourth device, the pilot tube, is based on the principle that if a rounded body is immersed in a liquid, the pressure at its nose has a maximum value, the velocity head in expression (3) being converted into static head. A pilot tube has a small hole drilled at the nose connected to a pressure gauge. The gauge measures the sum of the pressure in the fluid and the pressure created by the conversion of the velocity head. Another hole is drilled in the flow boundary at 90^{0} angle with the direction of flow. The pressure gauge that measures static pressure in the fluid is attached to the second hole. The method is well adapted for measurements of high velocities in chuts, overfalls, or pressure conduits.

Electrical and chemical methods

Salt velocity, dilution method and detection of radio-active tracers are some of the most common methods of measuring velocity. Salt velocity is an electrical method based on the principle that salt introduced into the stream will increase its electrical conductivity. The operation involves introducing a small quantity of concentrated salt solution at several points across the cross section of a stream by means of a quick-operating valve. Electrodes are connected to a recording galvanometer with a return circuit through the water. These are mounted at the ends of a uniform reach beginning a short distance downstream from the injection point. When the salt solution passes through each electrode, it produces a hump in the graph and the time between the centre of gravity of these humps divided by the length of the reach gives an average velocity of the stream. The method is cumbersome however and needs skilled operators.

The chemical methods include the use of dilutions and tracers. The dilution method is recommended for sites where conventional methods cannot be employed. This is often the case when the depth of the river or channel is shallow, when velocities are extremely high and when there is excessive turbulence. The solution may be injected at a constant rate, usually referred to as plateau gauging. Or it may be injected instantaneously in the gulp method. Whichever method is used the relation of the concentration of the injected solution at an up-stream cross-section and the concentration of the tracer at the down-stream cross-section permits the computation of discharge.

Any substance may be used as a tracer if it dissolves readily in channel water at ordinary temperatures. However the substance must be absent or be present only in small quantities otherwise confusion may arise as a result of the variations of the substance. The solution neither decompose in the stream's water nor be retained or absorbed by sediments, plants, or organisms, which could result in inaccuracies in the final measurement. Above all, the substance should be one that is easy to detect by simple methods, is harmless to the ecosystem and is of minimum cost. The cheapest tracer is common salt although sodium dichromate is preferred in many cases because of its colouring which permits measurements at very low concentrations.

Radioactive elements such as gold 198 and sodium 24 may also be used as tracers. Although such radioactive tracers provide more accurate measurement than other tracers, the health risks limit their use in ordinary circumstances.

Other methods of measuring velocity include the use of hot-wire amemometers, electromagnetic flowmeters and ultrasonic flowmeters. These methods are complicated and the time and cost of operation may not warrant their use in ordinary circumstances.

Velocity measurements are taken at various depths of flow. Most current meters that are used for measuring velocity have graduations on the wading rods or on tags on the cable which supports the meter-and-weight assembly from which depth measurements may be taken. The calculation of discharge integrates the product of velocity and channel area for a cross-section of the channel.

III STAGE-DISCHARGE DETERMINATION

Stage measurements

"Stage" is used in river flow measurement to refer to the water elevation at a point along the stream, measured above an arbitrary datum. Stage differs from the actual depth of flow because the latter is based on the distance from the water surface. The most important devices used to determine stage include the staff gauge, chain, tape or wire gauges (mechanical gauges), and water level recorders, bubble gauges and transducers (automatic gauges).

Among the many types of gauges the staff gauge is the most popular in Kenya. A staff gauge is a graduated scale set in a stream by fastening it to a pier, wall or supporting block, or other structure. It is read by observing the level of the water surface in contact with it, noting carefully the influence of the meniscus. The gauge may be tall enough to cover a wide range of water levels, including the floods, or several gauges maybe set on higher ground along the river bank. Some of the major problems with setting up staff gauges are vandalism, damage by floods or siltation of the channel.

Chain, tape, and wire gauges work by lowering a weight to the water surface. While the chain gauge is read from a reference bead moving along a graduated scale, the tape gauge is read at a pointer in contact with the tape and the wire gauge is read by means of a mechanical counter attached to the reel on which the wire is wound.

Among all the automatic water-stage instruments, the recorder which uses a float is the most common. The float is connected to the recorder by a wire or tape passing over a wheel and counterweighted. As the float moves, the wheel is turned and drives a pen on a rack-and-pinion mechanism. More sophisticated instruments have been developed in the last three decades that are able to transmit data to a processing data centre.

Some of these gauges are used also to determine the water level in lakes and reservoirs. Using a simplified continuity equation in finite form, the storage equation becomes:

$$I_t = O_t + \frac{\Delta S}{\Delta t} \qquad (5)$$

where I_t is the mean inflow in period Δt, O_t is the mean outflow in period Δt and S is the change of storage in period Δt. From expression (5) it is possible to obtain the amount of water discharged into and out of a reservoir.

Stage-discharge relations

Regular discharge measurements are expensive to take in terms of movement and time. In order to cut costs, the hydrologist sets up regular gauging stations from which regular discharge measurements and stage records are taken. When several measurements, covering a wide range of stages and discharges, have been taken for a specific station, the discharge values are plotted against the stage measurement and a rating curve is drawn. A rating curve is a line that relates the discharge values to stage records for a specific river cross-section. The value of a rating curve is that it is no longer necessary to take discharge measurements as regularly because stage measurements can be read from the rating curve. There are standard methods of establishing regular river gauging stations (see for example Corbett, et al, 1943).

Discharge measurements are classified according to the manner in which a river cross-section is made. A river cross-section may be crossed by wading if the stream is not deep and swift. Or it may be made by using a boat tied across the channel section, from a bridge or by using a cableway in wide and torrential rivers. Each method uses different complementary equipment. The accuracy of measurements may also vary and depends on the type of instrument used, the methodology and computation used, the nature of the flow and the skill of the operator.

Some methods of directly measuring discharge

Discharge can be measured directly by using a container or with the help of hydraulic structures, such as flumes and weirs and using volumetric calibration. Many of these structures are based on the basic principles of the continuity equation and conservation of energy.

One of the simplest instruments for measuring discharge directly is by using a Venturi meter. The Venturi meter consists of a conical pipe whose diameter is smallest in the middle and greater towards the ends. Two piezometer tubes are inserted at the wide and narrow sections respectively. Using expression (4) we obtain

$$Z_1 + \frac{P_1}{\alpha} = h_1 \text{ and } Z_2 + \frac{P_2}{\alpha} = h_2 \qquad (6)$$

Neglecting the energy losses and inserting h_1 and h_2 in expression (4)

$$\frac{V_1^2}{2g} + h_1 = \frac{V_2^2}{2g} + h_2 \qquad (7a)$$

and, in expression (2), inserting A_1 and A_2 to be the cross-sectional areas of the pipes at the wide and narrow points, we obtain

$$V_2 = V_1 \cdot \frac{A_1}{A_2} \text{ and thus } \frac{V_2^2}{2g} = \frac{V^2}{2g} \left(\frac{A_1}{A2}\right)^2$$

which after inserting into (7a) gives:

$$\frac{V_L^2}{2g} + h_1 = \frac{V_1^2}{2g}\left(\frac{A_1}{A_2}\right)^2 + h_2$$

$$\frac{V_1^2}{2g} \cdot \left[\left(\frac{A_1}{A_2}\right)^2 - 1\right] = h_1 - h_2$$

$$V_1 = \sqrt{\frac{2g}{\left(\frac{A1}{A_2}\right)^2 - 1}} \cdot \sqrt{h_1 - h_2}$$

Because A_1 and A_2 are given, terms within the first square root are constant. In other words,

$$\sqrt{\frac{2g}{\left(\frac{A1}{A_2}\right)^2 - 1}} = C_1$$

and so $V_1 = C_1 \cdot \sqrt{h_1 - h_2}$

Because $q = A_1 . V_1$ or

$$q = A_1 . C_1 . \sqrt{h_1 - h_2}$$

In the last expression A_1 and C_1 are constants, hence

$$q = C_1 . \sqrt{h_1 - h_2} \qquad (6)$$

Discharge measurements through orifices

Orifices are small openings in the walls of open containers. Expression (4) can be used, neglecting the energy losses due to friction between two points 1 and 2 of which $V_1 = 0$ and $P_1/\alpha = h$. V_2 is equal to the velocity in the jet and $P_2 = 0$ because it is surrounded by the pressure of the atmosphere. Expression (4) takes the form

$$0 + h + z_1 = \frac{V^2}{2g} + 0 + z_2$$

where $z_1 = z_2$ and, thus, $h = \frac{V^2}{2g}$ and $V = \sqrt{2gh} \qquad (7)$

The discharge q, is calculated by finding a coefficient for the area, A, of the orifice because the area of the orifice is smaller than area of the jet due to contraction. There are three types of circular sharp-edged orifices: sharp-edged orifice in thin wall, in thick walls and converging orifices.

For a circular orifice in a thin wall, A = 0.64 A. In a similar manner there are energy losses that reduce the velocity by a coefficient of 0.97. $\sqrt{2gh}$. In other words, for a sharp-edged orifice in a thin wall the discharge is:

$$q = 0.64.A.\ 0.97 \sqrt{2gh}$$

$$q = 0.62.A. \sqrt{2gh}$$

The general expression takes the form:

$$q = \mu.A. \sqrt{2gh} \qquad (8)$$

where μ is the discharge coefficient

A is the area of the orifice in m^2
h the head in metres.

A rectangular orifice with a height a and width b can be used for measuring discharge using an expression

$$q = 2/3.\mu.b\sqrt{2g}\,(h_e^{3/2} - h_u^{3/2}) \qquad (9)$$

There are two types of rectangular orifices, namely submerged orifices and non-submerged orifices. For the submerged orifice expression (9) takes the form:

$$q = \mu_1.A\sqrt{2g\,(h_1 - h_2)} \qquad (10)$$

where A is the cross-sectional area of the orifice and $\mu_1 = 0.98\ \mu$. The quantities on the left-hand side are constants except $(h_1 - h_2)^{\frac{1}{2}}$.

<u>Discharge measurements using notches and weirs</u>

Discharge may be computed from the flow over weirs and notches where the downstream water surface is lower than the lower edge of the weir. Weirs may be used in open channels, or they may be built along spillways (Chow, 1969 p. 360).

There are three types of weirs: sharped-edged weirs, such as with v-notches, broad crested and rounded weirs. A weir is usually made of a steel plate set into wooden or cement supports. The notches are in the form of triangles in the edge of the weir. The edge is called a crest, and is sharp and thin-walled. When

When the water fills the entire opening of a notch in a vertical direction the upstream water surface will sink a distance ahead of the weir. The discharge is obtained using an expression

$$q = 2/3.\mu.b\sqrt{2g}\,h^{3/2} \qquad (11)$$

where h is the head in metres and b is the width in metres. μ is determined by experiment.

The coefficient μ in expression (11) varies with ratio of height above the crest and the depth of the water below the crest, and ranges between 0.60 and 0.75. In V-notches, the expression (10) becomes

$$q = 8/15.\mu \sqrt{2g.} \tan \frac{\theta}{2} . h\ 5/12 \qquad (12)$$

in which h is the head in m and θ is the angle of the V. For a sharp crested V-notch the μ value is about 0.6, thus expression (12) become

$$q = 0.59h\ 0.42 \qquad (12b)$$

Broad-crested and rounded weirs are sometimes used in order to increase the discharge. Because of the lip of the weir, the head is smaller and consequently μ in the expression (12) becomes greater, being 0.70 to 0.75 for weirs without lateral contraction.

Discharge measurement using a Parshall Flume

A Parshall Flume is usually installed in canals and streams. It is used where the installation of weir is unsuitable because of lack of head. Small flumes measure discharges upto 2.0m 3/s while bigger ones have a relatively higher capacity. The flumes may be built of cement or wood depending on whether the station is permanent or temporary.

The depth-discharge relations of a Parshall flume is non-linear and they depend on the width of the throat. For throat widths ranging from 7.6 c.m. to 22.9 cm, the expression for calculating discharge takes the form:

$$q = \alpha H^{B} \qquad (12)$$

in which q is as defined earlier, H is the gauge height and α and B are coefficient and exponent respectively. From throat widths of 30 cm upto about 2.4 metres, the expression for calculating discharge becomes

$$q = \alpha W H^{BWP} \qquad (13)$$

Some of the largest flumes have throat widths of about 15 metres. In these cases the expression used for calculating discharge becomes

$$q = (\alpha w + y) H^{B} \tag{14}$$

IV CONCLUSION

Water quantities need to be measured as precisely as practible, apportioned to different uses/users and the infrastructure need to be oriented towards management rather than development. This paper discusses methods of measuring flow in channels.

Measurements of quantities of water can be very precise or approximated. The decision depends on the needs of the user and the cost of taking the measurement. However in developing countries, where automated instruments are plagued by a lack of spare parts, the simple mechanical methods discussed above have been found to be useful. Moreover, the operators do not need to be skilled in handling the devices.

BIBLIOGRAPHY

Bruce J.P. and R.H. Clark. 1966. Introduction to Hydrometeorology. Oxford: Pergamon Press.

Linslay, R., M.A. Kohler and J.C.H. Paulhus. 1958. Hydrology for Engineers. Toronto: McGraw-Hill.

Linford, A. 1961. Flow Measurement and Metres. London: E & F.N. Spon Ltd.

Hayward, A.T.J. 1979. Flowmeters: A basic guide and source book for users. London: Macmillan.

Boyer, M.C. 1964. "Streamflow Measurement". in V.T. Chow (ed.) Handbook of Applied Hydrology. McGraw-Hill.

Corbett, D.M. et. al. 1943. "Stream-gauging procedure". U.S. Geological Survey Water Supply, Paper No. 8888.

Nemec, J. 1964. Engineering Hydrology. McGraw Hill.

Chow, V.T. 1964. Open-Channel Hydraulics. McGraw Hill.

BASSIN DU NIGER

ETATS DU BASSIN VERSANT DU FLEUVE NIGER			
Etat	Population totale	Superficie totale	Superficie appartenant au bassin du Niger (km^2)
Bénin	2 940 000	116 000	43 000
Cameroun	7 500 000	474 000	80 000
Côte d'Ivoire	6 350 000	322 500	25 000
Guinée	4 420 000	250 000	104 000
Haute-Volta	6 030 000	274 000	90 000
Mali	6 040 000	1 204 000	589 000
Niger	4 970 000	1 189 000	465 000
Nigeria	75 000 000	924 000	535 000
Tchad	4 500 000	1 284 000	19 000
Total	117 750 000	6 037 500	1 950 000