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3.3.5. Discharge Estimation: Techniques and Equipment

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ABSTRACT: Understanding the discharge of a stream or river is essential for many important hydrological and geomorphological uses across a broad range of scales. However, it is crucial that the correct techniques and instrumentation are used depending on the stream environment and flow conditions encountered. This will ensure that discharge estimations are as reliable as possible. This review discusses the processes and instruments by which data are collected to estimate discharge. This includes stream gauging using stage and rating curves, velocity point measurements and current meters (mechanical and electromagnetic), and dilution gauging (both sudden and continuous). Advantages and disadvantages of each technique are presented to ensure that the most appropriate method can be selected.

KEYWORDS: fluvial, stream gauging, discharge, current meter, velocity-area, dilution gauging

Introduction

The discharge (or streamflow) of a river relates to the volume of water flowing through a single point within a channel at a given time. Understanding this information is essential for many important uses across a broad range of scales, including global water balances, engineering design, flood forecasting, reservoir operations, navigation, water supply, recreation, and environmental management. Growing populations and competing priorities for water, including preservation and restoration of aquatic habitat are spurring demand for more accurate, high frequency, and accessible water data (Whiting, 2003; Hirsch and Costa, 2004).

To be most useful, stream flow data must be collected in a standardized manner, with an estimate of associated accuracy and uncertainty (Pelletier, 1988; Herschy, 1995), and for a continuous time period. (Hirsch and Costa, 2004). However, hydrometric networks have limited spatial (and sometimes temporal coverage) and therefore this paper aims to describe and evaluate the processes and instruments by which discharge can be estimated.

This will include stream gauging using stage and rating curves, velocity point measurements and dilution gauging (both sudden and continuous). Finally, current meters (both mechanical and electromagnetic) used in discharge measurements will be discussed, before a summary which will enable decisions to be made regarding the effectiveness of each technique under certain flow conditions.

Stream Gauging

Stream gauging is the technique used to measure the volume of water flowing through a channel per unit time, generally referred to as discharge.

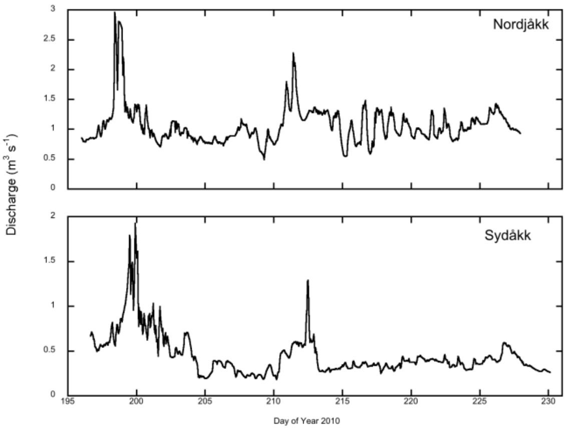

Figure 1. Examples of continuous discharge records collected at two outlet streams of Storglaciären, Sweden during the 2010 melt season. (Gravelle, 2014).

Stream discharge (Figure 1) is determined by the relationship between stream velocity and channel area and as a result, there are a number of variables that need to be recorded before discharge is calculated. Therefore, the measurement of discharge typically requires measurements of water depth, flow velocity and channel characteristics.

Quantifying the relationship between these variables allows continuous records of discharge to be estimated. The first step towards this is the measurement of stage.

Stage measurement and rating curves

Stage describes the depth of water within a channel and is quantified by the height of water at a gauging site above an arbitrary datum (Fenton and Keller, 2001). Stage can be measured in a range of ways from simply reading from a height gauge, or by using instrumentation such as float gauges (Saxon and Dye, 1995), submersible pressure transducers (Liu and Higgins, 2015) or ultrasonic gauges (Tsai and Yen, 2012).

By taking such measurements for a number of different stages and corresponding discharges (as discussed in the next section) over a period of time, a number of points can be plotted on a stage-discharge diagram, and a curve drawn through those points to give a unique relationship between stage and flow; the rating curve (Figure 2; Rantz *et al.*, 1982; Fenton and Keller, 2001; Schmidt, 2002). Understanding this relationship means that when stage is routinely measured, it is assumed that the corresponding discharge can be obtained from the equation of the line that best describes the stage-discharge relationship (Fenton and Keller, 2001).

It is important to note that whilst rating curves are commonly used, they are based on an assumption of the stage-discharge relationship, and have to describe a range of variation from low flow to extreme flood events (Fenton and Keller, 2001). In practice, discharge is often not measured (or, not measured accurately) during flood events, so discharge estimation at the extreme ends of the hydrograph may not be accurate. The effectiveness of rating curves can also be reduced in channels where sediment transport or deposition can alter the channel area. In this situation, a new rating curve would be required if it was believed that the channel characteristics had changed.

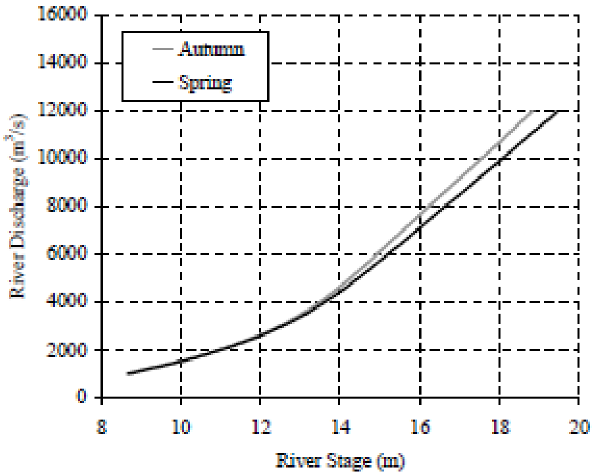

Figure 2. Examples of steady flow rating curves for spring and autumn flow regimes of the Po River, Italy (Di Baldassarre and Montanari, 2009).

Discharge Estimation

Combining continuous stage data with manual discharge measurements to form a rating curve will allow discharge data to be extrapolated to form a longer time series.

Stream discharge can be simply calculated using the equation:

$$Q = VA \qquad (1)$$

where: Q is the stream discharge, V is the stream velocity, and A is the cross-sectional area of the channel perpendicular to the predominant flow direction.

The velocity-area method

The most common and direct method of estimating discharge is the velocity-area method. This technique requires measurement of stream velocity, channel width and the depth of water flow at cross-stream vertical sections (Herschy, 1995). Typically, the width of the river channel is divided into at least 20 vertical sections, with each section having no more than 10% of the total flow (see Figure 3; Shaw, 1994; Pelletier, 1988). Discharge is derived from the sum of mean stream velocity, and the channel cross-sectional area.

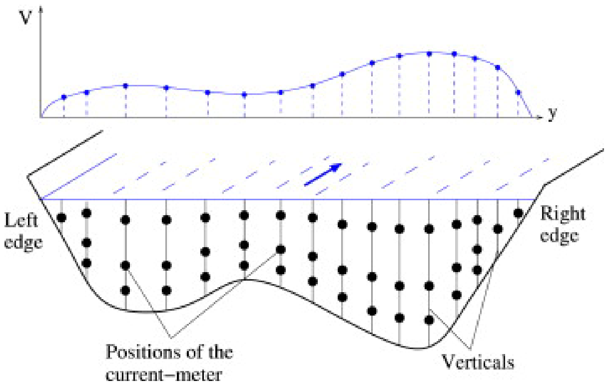

Figure 3. Principle of the velocity–area method: discrete sampling of velocity and depth throughout a cross-section, and the corresponding profile of depth-averaged velocity (Le Coz et al., 2012). Current meter positions are shown at 0.2, 0.6 and 0.8 depth.

The measurement of velocity in rivers is achieved using instruments such as current meters, and these are discussed later in the chapter. However, regardless of the instrument used, there are a number of measurement techniques which can be employed depending on river flow conditions and the time available to carry out measurements.

The most commonly used techniques are (Figure 4; Herschy, 1995):

1. the velocity distribution method;
2. the 0.6 depth method;
3. the two points method; and,
4. the three point method.

The velocity distribution method involves measurements being taken at a number of vertical sections distributed across a river channel (Carter, 1970). Measurements are taken at several points between the channel bed and the water surface, and are used to plot a vertical velocity curve. The mean velocity is obtained by dividing the area beneath the curve with the water depth (Herschy, 1995). The velocity distribution method is most accurate if conducted under steady stage conditions. However, it is generally considered too time consuming for routine gauging (Herschy, 1995).

The 0.6 depth method (sometimes referred to as the sixth-tenth depth method) involves measurements being taken at a single point at each vertical section, at 0.6 (or 60%) of the water depth (Figure 4; Herschy, 1995). This value is assumed to be the mean velocity for that vertical, based on the analysis of many vertical velocity curves which showed acceptable accuracy of 0.6 depth measurements (Herschy, 1995). Advantages of using this method are found in the diminished number of measurements required in this technique, and therefore the reduced time taken to complete a gauging (Herschy, 1995).

The two points method involves measurements being taken at 0.2 (20%) and 0.8 (80%) depth at each vertical section (Figure 4). Similarly to the 0.6 depth method, the accuracy of this technique has been established through analysis of vertical velocity curves (Shaw, 1994). However, it is recommended that this technique only be used in rivers where the minimum depth of flow is 0.75 m (Herschy, 1995).

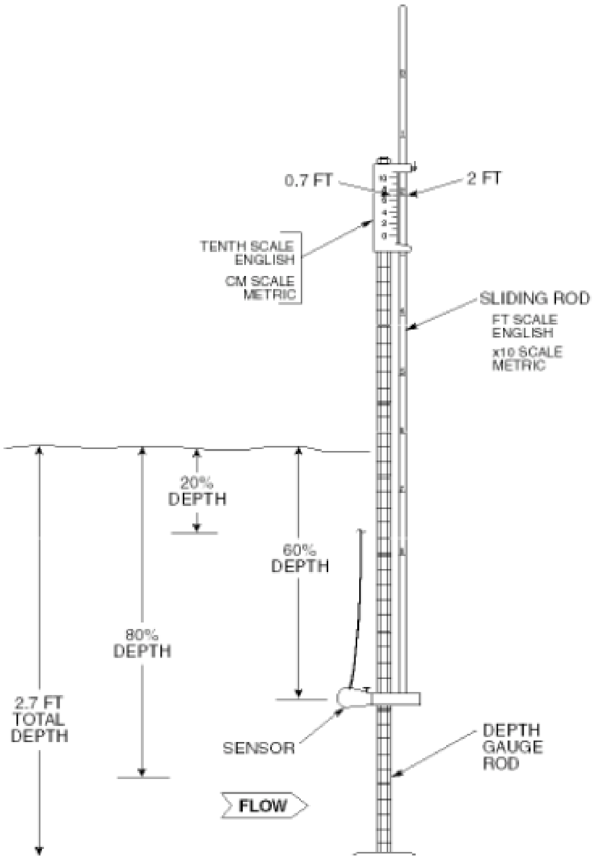

Figure 4. Diagram showing velocity measurement locations at 0.2 (20%), 0.6 (60%) and 0.8 (80%) depth within a channel, and how these are measured using a wading rod and current meter (Nolan and Shields, 2000).

The three point method is effectively an amalgamation of the 0.6 depth, and 0.2 and 0.8 depth methods, requiring measurements at each of the three depths to be taken (Figure 4). The average of the three measurements is taken as the mean vertical velocity (Herschy, 1995). Whilst accurate due to the number of measurements required, this technique is very time consuming and is therefore less widely used than the 0.6 depth method.

Regardless of the technique used, the time required to obtain an accurate velocity measurement is uncertain, with several studies suggesting differing times from 45 seconds (Carter and Anderson, 1963) to 3 minutes (Herschy, 1975). In practice, the time taken to record the measurement should reflect the level of accuracy desired (Pelletier, 1988).

Dilution gauging

Dilution gauging was originally developed as a means to measure discharge in closed channels such as pipes (Allen and Taylor, 1924; John *et al*., 1982). However, it has become an important technique in streams where turbulent flow or non-uniform channel shape (e.g. in boulder streams) are present, limiting the accuracy of other methods of discharge calculation (e.g. the velocity-area method). For this reason, it is commonly used in studies of glacier hydrology and mountain environments (e.g. Elder *et al*., 1990; Nienow *et al*., 1996; Richards and Moore, 2003; Orwin and Smart, 2004).

Figure 5. Photograph showing injection of a fluorescent tracer into a channel (courtesy: http://www.openchannelflow.com/blog/archives_article).

Dilution gauging involves the injection of a tracer into a channel reach and subsequently, detection of the tracer a known distance downstream when complete mixing has occurred (Figure 5). Although this can be carried out using a number of chemical, fluorescent, or radioactive tracers (Wilson *et al.*, 1986), the most commonly used tracer is sodium chloride, in the form of common salt. Sodium chloride is preferable due to its availability and inexpensiveness, and also the ease with which it dissolves. The amount used largely depends on the length of the reach measured and the volume of water it contains, although in natural water with low background conductivity, 0.2 kg of salt per m^3s^{-1} is considered sufficient (Herschy, 1995). Detection of salt as a tracer involves the measurement of electro-conductivity (EC), the ability of a material to conduct an electrical current (Figure 6). EC can be measured using an EC probe which measures conductivity between two electrodes. Tracer injection can occur either as: (1) a single sudden injection; or, (2) a continuous injection. In both techniques, the underlying principle is the conservation of mass. Calculation of discharge is determined by the dilution of the tracer at the sampling point (Herschy, 1995).

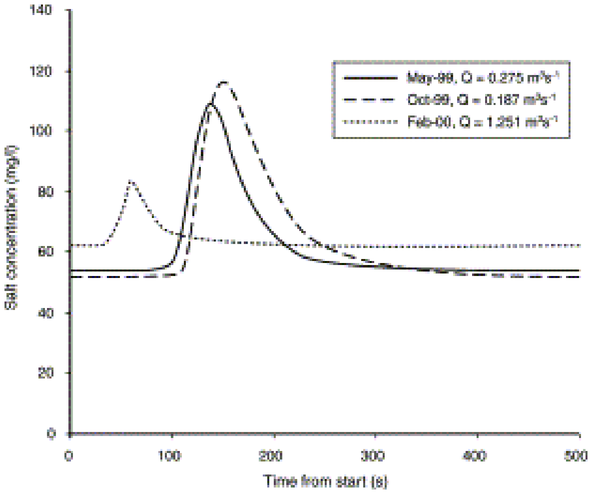

Figure 6. Variations in concentrations of dissolved salt (mg l^{-1}) with time following injection of the salt solution, 50 m downstream of the injection point in the River Holme (Wood and Dykes, 2002).

The sudden injection technique involves a single but steady injection of tracer in solution. Detection of the tracer occurs downstream at a distance sufficient to allow complete mixing of the tracer. Sampling at this location should also be carried out over a time period which allows the whole volume of tracer to reach the sampling point (Herschy, 1995). After the injected tracer passes the sampling point, discharge can be calculated using:

$$M = vC_1 = Q \int_{t_0}^{\infty} C_2(t)dt \qquad (2)$$

where M is the mass of injected tracer, v is the volume of injected tracer solution, C_1 is the concentration of the tracer solution, $C_2(t)$ is the concentration of tracer measured at the sampling point over the time interval dt, t is the elapsed time from injection to measurement, and t_0 is the time interval of the first detection of the tracer at the sampling point (Herschy, 1995).

Using the continuous injection technique, discharge can be calculated using equation 3:

$$Q = \frac{(c_1 - c_2)}{(c_2 - c_0)} q \qquad (3)$$

Where c_0 is the background concentration already present in the water, c_1 is the known concentration of tracer added at a constant rate (q), and c_2 is the final concentration of tracer in the flow (Shaw, 1994).

The effectiveness of dilution gauging can be reduced where there is either inflow of water into, or abstraction of water from the reach being measured. Either of these occurrences will result in loss or excessive dilution of the tracer being used (Herschy, 1995). Dead water zones, or infiltration of the tracer into hyporheic pathways (Moore, 2004) may have a similar effect, preventing the tracer from reaching the sampling location. It is therefore crucial that the measurement reach be carefully selected before dilution gauging is attempted (Herschy, 1995). However, both the sudden and continuous injection techniques suffer from problems due to the uncertainty in ensuring adequate mixing of the tracer, and also from environmental concerns associated with the addition of chemical substances into streams (Butterworth *et al*., 2000; Wood and Dykes, 2002). Generally, the continuous injection technique is used less commonly due to the difficulty of sustaining a constant rate of tracer flow, and the bulkiness of the equipment required to do so (Butterworth *et al*., 2000).

Instrumentation

The most common means of measuring stream velocity is through the use of current meters (Whiting, 2003). These can be divided into two general categories: mechanical and electromagnetic. Typically, water depth and magnitude of velocity will determine the selection of current meter for deployment. Whilst both current meter types vary in design, they are generally deployed in similar ways. Deployment of current meters can be carried out by means of a wading rod, although at greater water depths and velocities, cableways, bridges or boats may also be used (Whiting, 2003).

Mechanical current meters

Mechanical current meters (Figure 7) measure flow velocity through the rotation of a bucket wheel or impeller (Whiting, 2003). Measurement is based on the relationship between water velocity and the resulting velocity of the current meter rotor (Herschy, 1995). By counting the number of rotations of the current meter rotor during a given time period, the velocity of water can be established.

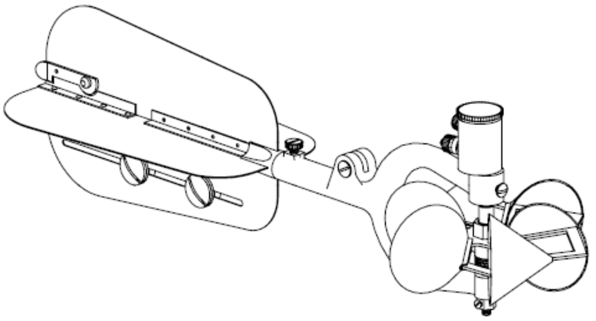

Figure 7. Price Type AA vertical axis current meter (Hubbard et al., 1999).

Mechanical current meters can be classified by whether the instruments rotors are aligned on a horizontal or vertical axis. Current meters with a horizontal axis rotor are referred to as propeller-type current meters. Current meters with a vertical axis rotor are referred to as cup-type current meters (Herschy, 1995). A study comparing vertical- and horizontal-axis current meters (Fulford *et al*., 1994) concluded that vertical-axis meters perform better in low flow velocities than horizontal-axis meters. Horizontal-axis meters are also more prone to becoming tangled by weeds and debris, potentially reducing the accuracy of the meter (Rantz *et al*., 1982; Fulford *et al*., 1994). Generally however, Fulford *et al*. (1994) suggest that the uncertainties associated with vertical and horizontal- axis meter measurement are very similar, although it is thought that vertical-axis meters have an overall greater accuracy of measurement.

Electromagnetic current meters

Electromagnetic current meters (ECMs) (Figure 8) measure flow velocity using electromagnetic induction, in which the movement of water through a magnetic field generated at the head of the ECM produces a voltage which is linearly proportional to its flow velocity (Herschy, 1995; Whiting, 2003; MacVicar *et al*., 2007). Electrodes mounted within the probe head detect changes in the electric potential of the water, caused by its movement through the magnetic field. This potential is then amplified, and converted into a readable format (Herschy, 1995).

The use of ECMs can be advantageous in channels where flow direction may be reversed (e.g. in the lee of bedforms). This is due to the ability of ECMs to measure bi-directional flow (albeit with an uncertainty of ±2%) (Whiting, 2003). However such bedforms are capable of causing turbulence and flow separation which subsequently result in changes in flow velocity (Robert *et al*., 1992; Roy *et al*., 1996). If this is the case, then uncertainty can be introduced into the data collection. Roy *et al*. (1996) therefore suggest that a correction be applied to ECM results where rotation of the ECM or flow direction is suspected.

Figure 8. Ott electromagnetic current meter (Turnipseed and Sauer, 2010).

One disadvantage of ECM use is the possibility that ECMs can be affected by electrical and magnetic fields. This includes other ECMs within a 0.6 m range (Whiting, 2003). In cold environments where ice formation is likely, ECMs can be affected by the formation of frazil ice (Derecki and Quinn, 1987). Frazil ice formation can coat current meter sensors, reducing sensitivity and producing low velocity readings, even as little as zero.

Summary of Techniques

As outlined in the sections above, each technique described may have specific advantages or disadvantages of use depending on the circumstances. Table 1 gives an indication of where a specific advantage or disadvantage exists for a given technique during certain channel or flow conditions. Although not designed to be exhaustive, this will assist in decision-making where options exist for the use of different techniques or instruments in discharge estimation.

Table 1: Matrix of the techniques and methods and their use under certain conditions. Ticks and Crosses indicate where an advantage or disadvantage has been identified. A blank space indicates that none have been identified.

	ECM	Mechanical Current Meter	Dilution/tracer gauging	Velocity distribution method	0.6 depth	Two-point method	Three-point method
Turbulent flow	×		✓	×			
Steady stage	✓	✓		✓			
Irregular channel	✓	×	✓			×	
Regular channel	✓	✓		✓	✓	✓	✓
Low flow	×	✓			✓	×	×
Reversing flow	✓	×					
Icing	×		✓				
Channel dilution			×				
Time				×	✓	✓	×

Conclusions

This review has presented several methods of stream gauging and discharge estimation with a particular focus on their appropriateness in differing flow conditions and stream settings. Although often assumed to be a single process, the estimation of stream discharge brings together a range of techniques and can be performed using a number of methods and instruments. The accuracy (and therefore uncertainty) of a measurement is minimised when the techniques and equipment are chosen in consideration of channel and flow conditions

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