

## **Water Quality Monitoring - A Practical Guide to the Design and Implementation of Freshwater Quality Studies and Monitoring Programmes**

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# **Chapter 12 - HYDROLOGICAL MEASUREMENTS**

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*This chapter was prepared by E. Kuusisto.*

Hydrological measurements are essential for the interpretation of water quality data and for water resource management. Variations in hydrological conditions have important effects on water quality. In rivers, such factors as the discharge (volume of water passing through a cross-section of the river in a unit of time), the velocity of flow, turbulence and depth will influence water quality. For example, the water in a stream that is in flood and experiencing extreme turbulence is likely to be of poorer quality than when the stream is flowing under quiescent conditions. This is clearly illustrated by the example of the hysteresis effect in river suspended sediments during storm events (see Figure 13.2). Discharge estimates are also essential when calculating pollutant fluxes, such as where rivers cross international boundaries or enter the sea. In lakes, the residence time (see section 2.1.1), depth and stratification are the main factors influencing water quality. A deep lake with a long residence time and a stratified water column is more likely to have anoxic conditions at the bottom than will a small lake with a short residence time and an unstratified water column.

It is important that personnel engaged in hydrological or water quality measurements are familiar, in general terms, with the principles and techniques employed by each other. This chapter provides an introduction to hydrological measurements for personnel principally concerned with water quality monitoring. More detailed information on hydrological methods is available in the specialised literature listed in section 12.5 and from specialised agencies such as the World Meteorological Organization. Further detail and examples of the use of hydrological measurements in water quality assessments in rivers, lakes, reservoirs and groundwaters are available in the companion guidebook *Water Quality Assessments*.

## **12.1 Rivers**

Proper interpretation of the significance of water quality variables in a sample taken from a river requires knowledge of the discharge of the river at the time and place of sampling (for further discussion see also section 2.1). In order to calculate the mass flux of chemicals in the water (the mass of a chemical variable passing a cross-section of the river in a unit of time), a time series of discharge measurement is essential.

The flow rate or discharge of a river is the volume of water flowing through a cross-section in a unit of time and is usually expressed as  $\text{m}^3 \text{s}^{-1}$ . It is calculated as the product of average velocity and cross-sectional area but is affected by water depth, alignment of the channel, gradient and roughness of the river bed. Discharge may be estimated by the slope-area method, using these factors in one of the variations of the Chezy equation. The simplest of the several variations is the Manning equation which, although developed for conditions of

uniform flow in open channels, may give an adequate estimate of the non-uniform flow which is usual in natural channels. The Manning equation states that:

$$Q = \frac{1}{n} A R^{2/3} S^{1/2}$$

where

$Q$  = discharge ( $\text{m}^3 \text{s}^{-1}$ )

$A$  = cross-sectional area ( $\text{m}^2$ )

$R$  = hydraulic radius (m) and  $= A/P$

$P$  = wetted perimeter (m)

$S$  = slope of gradient of the stream bed

$n$  = roughness coefficient

More accurate values for discharge can be obtained when a permanent gauging station has been established on a stretch of a river where there is a stable relationship between stage (water level) and discharge, and this has been measured and recorded. Once this relationship is established, readings need only be taken of stage, because the discharge may then be read from a stage-discharge curve.

Water quality samples do not have to be taken exactly at a gauging station. They may be taken a short distance upstream or downstream, provided that no significant inflow or outflow occurs between the sampling and gauging stations. The recommended distance is such that the area of the river basin upstream of the sampling station is between 95 per cent and 105 per cent of the area of the river basin upstream of the gauging station.

The stage-discharge relationship, or rating curve, usually includes the extremes of discharge encountered in a normal year. The rating curve should be checked periodically, ideally once a year, since minor adjustments may be necessary to take account of changes in the cross-section of the stream or instability in the flow characteristics, or to eliminate errors in previous measurements. Systematic variation as a result of unstable flow may be apparent if the stage-discharge relationship for a single flood event is examined. The discharge during the rising phase of a flood event is usually greater than that during the falling phase of the same flood event. While unstable flow can produce a loop in the stage-discharge plot for an individual storm event, it is not usually apparent in the annual rating curve that is commonly used in hydrological survey programmes. Unstable cross-sections cause stage-discharge variability and can produce sudden and significant shifts in the rating curve as a result of erosion or deposition of material in the river bed.

### **12.1.1 Measuring stream flow**

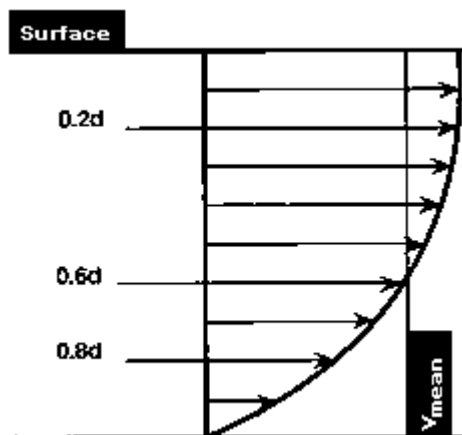
If samples are to be taken at a point where the stage-discharge relationship is either unknown or unstable, discharge should be measured at the time of sampling. Discharge measurement, or stream gauging, requires special equipment and, sometimes, special installations. The measurements should be made by an agency that has staff with expertise in the techniques of hydrological survey. The most accurate method is to measure the cross-sectional area of the stream and then, using a current meter, determine the average velocity in the cross-section. If a current meter is not available, a rough estimate of velocity can be made by measuring the time required for a weighted float to travel a fixed distance along the stream.

For best results, the cross-section of the stream at the point of measurement should have the following ideal characteristics:

- The velocities at all points are parallel to one another and at right angles to the cross-section of the stream.
- The curves of distribution of velocity in the section are regular in the horizontal and vertical planes.
- The cross-section should be located at a point where the stream is nominally straight for at least 50 m above and below the measuring station.
- The velocities are greater than 10-15 cm s<sup>-1</sup>.
- The bed of the channel is regular and stable.
- The depth of flow is greater than 30 cm.
- The stream does not overflow its banks.
- There is no aquatic growth in the channel.

It is rare for all these characteristics to be present at any one measuring site and compromises usually have to be made.

**Figure 12.1 Typical river velocity profile in the vertical plane**



Velocity varies approximately as a parabola from zero at the channel bottom to a maximum near the surface. A typical vertical velocity profile is shown in Figure 12.1. It has been determined empirically that for most channels the velocity at six-tenths of the total depth below the surface is a close approximation to the mean velocity at that vertical line. However, the average of the velocities at two-tenths and eight-tenths depth below the surface on the same vertical line provides a more accurate value of mean velocity at that vertical line.

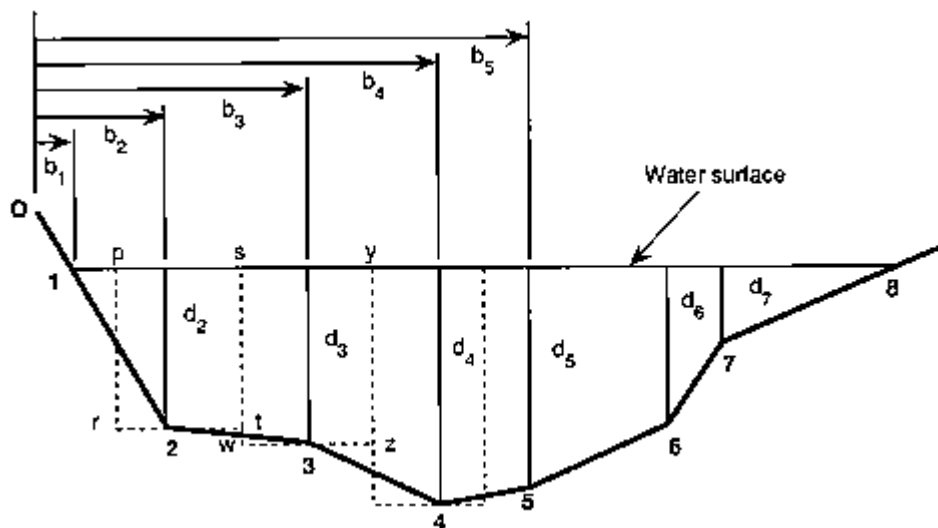
Velocity also varies across a channel, and measurements must, therefore, be made at several points across the channel. The depth of the river varies across its width, so the usual practice is to divide the cross-section of the stream into a number of vertical sections as shown in Figure 12.2 and measure velocity at each of these. No section should include more

than 10-20 per cent of the total discharge. Thus, between 5 and 10 vertical sections are typical, depending on the width of the stream.

*Procedure for measuring discharge*

1. All measurements of distance should be made to the nearest centimetre.
2. Measure the horizontal distance  $b_1$ , from reference point 0 on shore to the point where the water meets the shore, point 1 in Figure 12.2.
3. Measure the horizontal distance  $b_2$  from reference point 0 to vertical line 2.
4. Measure the channel depth  $d_2$  at vertical line 2.
5. With the current meter make the measurements necessary to determine the mean velocity  $\bar{v}_2$  at vertical line 2.
6. Repeat steps 3, 4 and 5 at all the vertical lines across the width of the stream.

**Figure 12.2 Cross-section of a stream divided into vertical sections for measurement of discharge**



The computation for discharge is based on the assumption that the average velocity measured at a vertical line is valid for a rectangle that extends half of the distance to the verticals on each side of it, as well as throughout the depth at the vertical. Thus, in Figure 12.2, the mean velocity  $\bar{v}_2$  would apply to a rectangle bounded by the dashed line p, r, s, t. The area of this rectangle is:

$$a_2 = \frac{b_3 - b_1}{2} \times d_2$$

and the discharge through it will be:

$$Q_2 = a_2 \times \bar{v}_2$$

Similarly, the velocity  $\bar{v}_3$  applies to the rectangle  $s, w, z, y$  and the discharge through it will be:

$$Q_3 = \frac{b_4 - b_2}{2} \times d_3 \times \bar{v}_3$$

The discharge across the whole cross-section will be:

$$Q_T = Q_1 + Q_2 + Q_3 \dots Q_{(n-1)} + Q_n$$

In the example of Figure 12.2,  $n = 8$ . The discharges in the small triangles at each end of the cross-section,  $Q_1$  and  $Q_n$ , will be zero since the depths at points 1 and 8 are zero.

If the water is shallow, the operator may wade into the stream holding the current meter in place while measurements are being made. Where the water is too deep for wading (more than 1 metre) the current meter must be lowered from a bridge, an overhead cableway or a boat. The section where flow measurement is made does not have to be at exactly the same place as either the monitoring station or the water level indicator provided that there is no significant inflow or outflow between these points along the stream.

Bridges are preferred as stream gauging stations because they usually allow easy access to the full width of the stream, and a water level indicator can be fastened to a bridge pier or abutment. Aerial cableways are often located at places where characteristics of the stream cross-section approach the ideal. However, they necessitate a special installation, and this is often impractical for a water quality monitoring team. Velocity measurements made from a boat are liable to yield inaccurate results because any horizontal or vertical movement of the boat will be identified as velocity by the current meter. In shallow streams the water velocity close to the boat will be affected and this may distort the meter readings.

Floats should be used for velocity measurement only when it is impossible to use a current meter. A surface float will travel with a velocity about 1.2 times the mean velocity of the water column beneath it. A partially submerged float made from a wooden stick with a weight at its lower end (so that it floats vertically) may be used. The velocity of a float of this type will be closer to the mean velocity and a correction factor of about 1.1 is appropriate if the submerged part of the float is at one-third to one-half the water depth. The velocity of any float, whether on the surface or submerged, is likely to be affected by wind.

Discharge measurement may also be made by ultrasonic or electromagnetic methods, by injecting tracers into a stream, or by the construction of a weir. None of these methods is recommended because they either interfere with the natural water quality or they are prohibitively expensive and complex to install and operate.

## 12.2 Lakes and reservoirs

In lakes and reservoirs, hydrological information (particularly water residence time) is needed for the interpretation of data and the management of water quality (for further discussion see also section 2.1). These hydrological measurements are required in two different situations:

- when samples are to be taken from tributaries and outflowing streams, and
- when samples are to be taken from the lake or reservoir itself.

Both types of sampling may aim at the estimation of the mass flow of some variable in the water body and, consequently, hydrological data are essential.

### 12.2.1 Sampling from tributaries and outflowing streams

In outflowing streams, hydrological measurements should be obtained in the same manner as described above for rivers. In tributaries, the location of sampling stations and flow measurement stations should be selected so that backwater effects (water backing up the river from the lake) will be avoided. If this is not possible, the water level at the mouth of the tributary should be measured and recorded to provide data on the magnitude of the backwater and its variation with time.

### 12.2.2 Sampling from a lake or reservoir

The water level at the time of sampling must be measured. If the water surface is calm and a water level gauge has been installed, a single reading may be sufficient. If there is no official gauge, the water level should be recorded in relation to a conveniently located, identifiable point on a rock outcrop, large boulder or other landmark that is reasonably permanent. If there is any reason to suspect that this water level marker might move or be moved, reference should be made to a second landmark. The use of landmarks as a water level reference is a temporary measure and a water level gauge should be installed as soon as possible.

Waves and the inclination of the water surface (seiches) may cause problems in observing water levels. High waves may make it difficult for the observer to see the gauge and the continual motion of the water makes it impossible to determine the exact water level. In such conditions the observer should try to record the highest and lowest positions of the changing water level and calculate the average of the two. The wind condition should also be noted, together with an estimate of the height of the waves.

In certain conditions, current measurements in lakes or reservoirs provide information that is helpful in the interpretation of the results of analyses of water and sediment samples. Currents may cause water quality to vary appreciably within short distances or time periods. The flow velocities that normally occur in lakes are measured with sensitive recording current meters anchored at given depths. Sometimes, however, a rough estimate of the flow field (the general pattern of flow within a lake) can be made by observing the motion of surface floats. In reservoirs, the operation of valves or sluices can create localised currents which can affect the water quality in their vicinity. The special characteristics of reservoirs and their operation, in relation to water quality monitoring, are described in *Water Quality Assessments*.

## 12.3 Mass flux computation

Water quality monitoring often seeks to obtain two main types of estimations related to the physical and chemical variables being measured:

- the instantaneous values of the concentrations of water quality variables, and
- the mass flux of water quality variables through river sections, lakes or reservoirs over specified periods of time.

For a river, if only one sample has been taken at a point, provided the concentration  $c$  of the variable of interest has been determined and the instantaneous discharge  $Q$  has been

obtained, the instantaneous mass flux  $Q_m$  of that variable can be calculated from the formula  $Q_m = cQ$ .

When samples have been taken and discharge has been measured in each of the vertical sections across a stream, the instantaneous mass flux is given by:

$$\sum_{i=1}^n C_i \bar{V}_i A_i \text{ g s}^{-1}$$

where

$n$  = number of vertical sections

$C_i$  = concentration of the variable in section  $i$  (mg l<sup>-1</sup>)

$\bar{V}_i$  = mean velocity in section  $i$  (m s<sup>-1</sup>)

$A_i$  = cross-sectional area of section  $i$  (m<sup>2</sup>).

The average concentration at the cross-section can be obtained from:

$$\frac{Q_m}{Q} \text{ mg l}^{-1}$$

where

$Q$  = the instantaneous discharge (m<sup>3</sup> s<sup>-1</sup>)

$Q_m$  = the instantaneous mass flux of the variable (g s<sup>-1</sup>).

Calculation of the mass flux over a period ( $t_0 \dots t_m$ ) may be determined quite accurately, but this requires many measurements of water quality and the use of a complex formula. Normally, water quality determinations are carried out at relatively long time intervals (weekly or monthly). By contrast, discharges are often determined daily, based on daily observation of the water level and the stage-discharge relationship. The simplest way to estimate daily concentrations of a variable is to assume that each measured value of concentration is valid for half of the preceding and following intervals between the collection of samples. However, this assumption is valid only when variations in the concentration of a variable are small. It is usually necessary to use complicated interpolation techniques.

Regression techniques are appropriate if a reliable relationship can be established between the concentrations of the variable of interest and some other chemical or physical variable that is measured at frequent intervals. The most suitable variable will often be discharge (determined easily from water level). Thus the consistency of the relationship between the concentration of a variable and the discharge should always be checked. If the relationship is reasonably consistent, discharge can serve as the basis on which to estimate the mass flux of a variable. If it is inconsistent, however, some other relationship should be sought.

In small streams and during flood peaks, the discharge may vary considerably over a 24-hour period. A variation in the concentration of a variable in excess of an order of magnitude is typical, and both sampling and discharge measurements need to be frequent. If the daily maximum flow is two to three times the average flow, a 4-hour interval between samples is recommended. If the maximum is greater than three times the average, discharge should be

measured and samples taken every hour. This information can be obtained during a short-term pilot study. Examples of the measurement of discharge in river and particulate matter monitoring are given in *Water Quality Assessments*.

## 12.4 Groundwater

Groundwater is important as a significant water resource, in its own right, and also because of its interaction with surface water. Groundwater recharges streams and rivers in some areas, while in others it is itself recharged by surface water.

The hydrogeological conditions of water-bearing rocks or aquifers have a significant influence on the quality of groundwater in much the same way that hydrological conditions influence surface water quality. The rate of flow through the aquifer, residence time, inflows and outflows from the aquifer all influence the groundwater quality (a full discussion is available in *Water Quality Assessments*).

As the rate of flow of groundwater is much lower than that of surface water, there is a significant risk that contaminants can build up in aquifers to the point where the water becomes unusable. This could force the abandonment of boreholes and result in a permanent reduction in the quantity of usable groundwater.

There are certain influences that are unique to groundwater quality. These are the nature of the aquifer, the presence or absence of contaminants in unsaturated layers above the aquifer, the presence of naturally occurring contaminants in the aquifer and the interaction of groundwater, surface water and contaminant movement. Further detail can be found in section 2.2.

### 12.4.1 Groundwater flow

Detailed investigation of groundwater flows over a large area requires specialist knowledge and equipment and the manipulation of predictive formulae. Groundwater flow is three-dimensional and, therefore, more difficult to predict than surface water. In addition, whereas surface water flow direction can be easily predicted by topographical survey, groundwater flow direction depends on aquifer type and hydraulic conditions in the aquifer and is difficult to assess without carrying out pump tests and tracer studies. Information on the direction of groundwater flow can be obtained by mapping out water levels in boreholes within the same aquifer. This gives an indication of the hydraulic gradient (or piezometric surface) and, thus, an idea of groundwater movement.

Groundwater flow information will assist in the prediction of contaminant movement in groundwater, in particular the spread and speed of movement of contaminants after a polluting event. However, this prediction is a complex procedure which is often inaccurate and is complicated further by the lack of knowledge of contaminant behaviour in groundwater.

Flows within aquifers on the medium scale may be assessed through tracer studies, which will indicate direction and rate of flow. The rate of movement of water into particular wells can be quite easily evaluated by pump tests. These tests will also provide information on the depression of groundwater level around a well during pumping.

The usual procedure for a field pump test is that water is pumped from a production borehole at a constant rate, which is controlled and measured. This may be done using a flow meter on the discharge pipe. The change in the level of the water table (or piezometric surface)

around the borehole is monitored by measuring the change in depth to the water table at observation wells surrounding the borehole.

Pump tests provide valuable information for calculating aquifer properties which, in turn, provide information of importance to water quality, such as rate of movement of groundwater into boreholes, the area of the aquifer that will be exploited by the borehole and where land use restrictions may need to be applied.

Full inventories of boreholes should be prepared and should include information concerning the pumping depth, yield, aquifer transmissivity and storage coefficient. This will permit groundwater movement and water quality to be modelled. Pumping from adjacent boreholes will influence the yield and draw-down of a production borehole.

It is important to collect information on any changes of static water level. In some areas where initial intensive groundwater abstraction leads to a drop in the water table, there has been significant contamination of the unsaturated soil layers overlying the aquifer. When abstraction was later decreased, the water level rose and became contaminated through the dissolution of contaminants held in the soil profile. This may cause problems if water is withdrawn in the future and may also increase the risk to the rest of the aquifer, thus potentially reducing the quality of groundwater available.

## 12.5 Source literature and further reading

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