Estimating discharge at an ungauged site

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SUMMARY: *This paper deals with estimating discharge at an ungauged site. Firstly, we discuss the use of modern data logging equipment to record water level depths at the site. Next, establishing a stage-discharge relationship at the site including measuring discharge by current meter is described. A technique using surface water slope for estimating discharge is outlined and, finally, an example application is discussed.*

1 INTRODUCTION

A question frequently asked by aquatic ecologists is 'how does one estimate discharge at an ungauged point in a stream?'. One answer often given by hydrologists is to apply a long record of daily rainfall to a (daily) rainfall-runoff computer model to compute daily flows. The model parameters are estimated from a nested or an adjacent catchment that is hydrologically similar to the ungauged one. Runoff modelling methods are widely available but they require accurate rainfall data and considerable modelling expertise. An alternative technique, especially if one is mainly interested in low flow data, is to establish a relationship between the ungauged site and a nearby gauged station and then to use the flow record established for the gauged station to estimate the flows at the ungauged site. This method can be refined by installing a simple but robust water level recorder at the ungauged site, which can then be correlated with the nearby gauge. Water levels recorded at the ungauged site are converted to discharge using a rating curve derived from direct measurements of discharge during the period of operation of the level recorder. Alternatively, the rating curve can be established using the slope-area method, which requires two water level recorders to be installed. This technical note describes the field measurement techniques used to derive a relationship between flow at an ungauged and a nearby gauged site.

In many projects there is a short but finite interval of time (often less than a year) between project initiation and analysis of field data. This window of opportunity is exploited in the approaches suggested here. As soon as the field site or sites are confirmed, a data logger that records variation in water depth (stage) with time is installed at each location. At the time of installation the discharge in the stream is measured and an observation is also made at a nearby streamgauging station with a flow record of length at least equal to that required by the ecologist. A relationship between the discharge at the candidate (ungauged) site and that at the gauged station is progressively built up over the following months so that the long gauged record can be used to estimate an equivalent length of discharge record at the ungauged site.

2 DEPTH LOGGING EQUIPMENT

The equipment consists of a commercially available data logger connected to a probe. In a setup we have used, the logger is attached to a capacitance measuring probe, which is an aluminium tube about

30mm diameter and between 2 - 3 m in length. The length controls the maximum depth that the logger can record. The logger can be programmed to take depth readings at a variety of time scales, from minutes to days and is capable of storing 114 kilobytes of data. Our experience suggests that the loggers, which are relatively cheap (approximately $Aus 600 in March 2001), are robust and reliable (with sub-mm accuracy). The probe is installed inside a galvanized steel pipe (standard water pipe) that acts as a stilling well. In dry sites the pipe can be secured with iron pickets, concrete and fencing wire. In water holes the pipe can be attached to boughs of trees and secured with iron pickets and wire. In a pool-riffle sequence it is suggested that the logger be located in a pool. Generally conditions in the riffle are so locally variable that any stage-discharge relationship obtained there would be rather unstable.

3 ESTABLISHING A RELATIONSHIP USING A NEARBY GAUGE

Over the short period of gauging time that is available during the field project, concurrent discharge measurements are made at both the candidate and the gauged sites. These measurements are used to establish a regression equation, which describes the relationship between them for all flows up to the maximum that has been measured manually (usually safe wading depth), and the equation allows flow at the candidate site to be estimated from flow at the gauged site. In this procedure the candidate site is the dependent variable in the regression. Observations of discharge at the gauged site are normally taken from the gauged record or by recording the level at this site and converting this to discharge using the site rating curve.

For higher discharges, which are generally independent of catchment geology, the ratio of the discharges is assumed to be equal to the ratio of the catchment areas to some power, b. The exponent b varies widely and reported values range from 0.5 to 0.85.[1, 2] Based on McMahon [3] we recommend a value of 0.6 unless local evidence suggests otherwise. Comparison of higher discharges at several gauge sites within the catchment may provide some guidance for selecting this exponent. The exponent depends mainly on the combined effects of the reduction in average rainfall intensity with increasing catchment area and the effect of natural storage in the catchment. The following equation is used to calculate the relationship at the higher discharges:

$$Q_u = \left(\frac{A_u}{A_g}\right)^b Q_g \qquad (1)$$

where Q_u and Q_g are the discharges (m^3/s or ML/d) at the ungauged and the gauged sites respectively, A_u and A_g are the respective areas (km^2) of the ungauged and gauged catchments, and b is an exponent.

4 DISCHARGE ESTIMATES

In practice, discharge is estimated as the product of flow velocity and the cross-sectional area of flow. Flow velocity meters are commercially available and most hydrologic textbooks describe the procedure[4]. We recommend dividing the cross-section of flow into say 10 vertical sections and for each estimating average velocity from 5 velocities taken at 0.1, 0.3,..., 0.9 times water depth at that location. Obviously for shallow flows this may not be possible and fewer measurements in the vertical will be made. Discharge is then computed by summing the products of the sub-section area by the mean velocity for that sub-area as follows:

$$Q = \sum_{\substack{over\ all \\ sub-areas}} v_i a_i \qquad (2)$$

where Q is the estimated discharge, v_i is the average measured velocities for sub-area a_i.

Current meter measurements would be made as often as possible so that the discharge relationship between the ungauged and the gauged sites was established up to the maximum feasible discharge. Under normal circumstances this will be restricted to wading depth. Where a temporary water level recorder is installed at the ungauged site, the current meter measurements are used to construct the rating curve – a relationship between flow depth and discharge, which is used to convert the logged depths to discharge.

5 SLOPE-AREA METHOD

The relationship between stage and flow (the rating curve) can be developed sometimes using the slope-area method. The key to the slope-area method is to estimate the longitudinal slope of the free water surface of the stream using two water level recorders. To do this satisfactorily two water level loggers need to be located on a straight reach at least equivalent to ten stream widths apart. This distance will ensure that the measured water slope is representative of the reach. The loggers need to be accurately surveyed to a common datum and the readings of the water level changes should be made at a suitably short time step relative to the rate of rise of the hydrograph. This enables the slope of the water surface to be determined. It is important that the flow be steady flow such that the flow depth and the velocity do not change over a short time period.

In natural channels variability in the flow depth generally increases at low flows. For this reason, the slope-area method is most useful for extending the rating curve to higher flows rather than developing the low flow rating curve.

Discharge is calculated using Manning's equation:

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

where Q = discharge (m^3/s), n = Manning's coefficient,

$$A = \frac{A_1 + A_2}{2} \tag{4}$$

$$R = \frac{1}{2}\left(\frac{A_1}{P_1} + \frac{A_2}{P_2}\right) \tag{5}$$

$$S = \frac{h_2 - h_1}{L} \tag{6}$$

and A = average cross-sectional area of flow, A_1, A_2 = cross-sectional area (m^2) of flow at water level loggers 1 and 2, R = hydraulic radius, P_1, P_2 = wetted perimeter (m) of wetted contact between the water and bed and banks (at loggers 1 and 2), S = water level slope (m/m), h_1, h_2 = water level height (m) at the loggers above a common height datum, and L = length (m) between loggers. This equation only applies when the cross-section area at the two water level recorders are similar.

Values of Manning's coefficient are discussed in Gordon, McMahon & Finlayson[4] and visual comparisons with photographic keys are presented in Barnes[5] and Hicks & Mason. [6] Cowan's[7] method is sometimes used to estimate Manning's n. It is based on adding the individual contributions of roughness as follows:

$$n = (n_0 + n_1 + n_2 + n_3 + n_4)m_5 \tag{7}$$

Alternatively, n can be estimated by measuring discharge and calculating n from Eq (3). It should be noted that the computed n value will be reasonably accurate for the waterway conditions at the measured discharge, however it will only be a guide to the value at other discharges.

6 EXAMPLE – ALLYN RIVER AND CHICHESTER RIVER, NSW

To illustrate the technique using concurrent measured discharges at adjacent sites, data from two New South Wales (Australia) gauging stations – Allyn River at Halton 210022 (205 km^2) and Chichester River at Chichester 210136 (197 km^2) – are used. The discharge data extracted from DLWC[8] consists of 10 selected daily flows (ML/day) assumed to have been measured concurrently at each site one per week over 10 consecutive weeks beginning on 20 February 1998.

Figure 1 shows the concurrent discharge data plotted on arithmetic scaled axes. Figure 2 shows the same data as a 5th root plot of both axes together with the estimated relationship for high discharge data computed using Eq (1) with b = 0.6. The observed non-linearity at the low discharge end of the curve is due in this example to the geology that influences the relevant baseflows. Non-linear curves like that displayed figure 2 are sometimes found in practice. The 5th root transformation (that is, $Q^{0.2}$) is an alternative to a logarithmic transformation, which is normally used if all the data are non-zero.

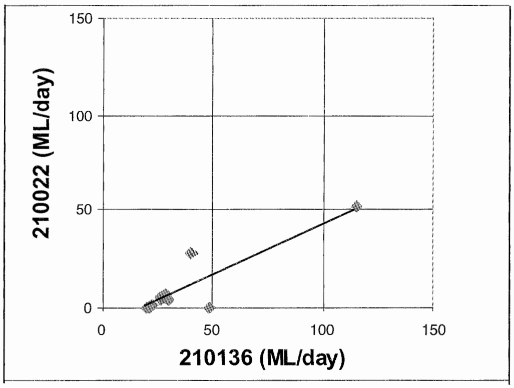

Figure 1: Concurrent estimates of discharge at candidate and gauged sites

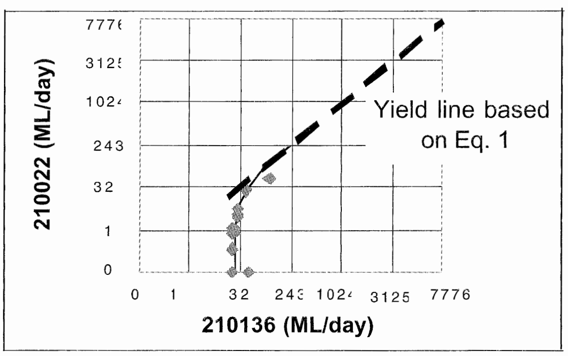

Figure 2: Relationship between discharge at candidate and gauged sites (Note the 5th root scaled axes)

Basic n value, n_0:

earth	0.020
rock	0.025
fine gravel	0.024
coarse gravel	0.028
cobble	0.030 to 0.050
boulder	0.040 to 0.070

Surface irregularity, n_1:

smooth	0.000
minor (slightly eroded or scoured)	0.005
moderate (moderate slumping)	0.010
severe (badly slumped,eroded banks, or jagged rock surfaces)	0.020

Variation in cross-section shape causing turbulence, n_2:

change occures gradually	0.000
occasional changes from large to small or side to side shifting of flow	0.005
frequent change	0.010 to 0.015

Effect of obstructions (debris deposits, roots, boulders) n_3:

negligible (few scattered obstructions)	0.000
minor (obstructions isolated, 15% of area)	0.010 to 0.015
appreciable (interaction between obstacles which cover 15-50% of area)	0.020 to 0.030
severe (obstructions cover >50%; or cause turbulence over most of area)	0.040 to 0.060

Vegetation, n_4:

none or of no effect	0.000
supple seedling or dense grass/weeds	0.005 to 0.010
brushy growths, no g rowth in streambed; grass height of flow	0.010 to 0.025
young trees intergrown with weeds; grass twice depth of flow	0.025 to 0.050
brushy growth on banks, dense growth in stream; trees intergrown with weeds; full foliage	0.050 to 0.100

Meandering (multiplier), m_5:

minor (sinuosity 1.0-1.2)	1.00
appreciable (sinuosity 1.2-1.5)	1.15
severe (sinuosity >1.5)	1.30

7 ADDITIONAL REMARKS

To reduce the streamgauging effort, one could forego making current meter measurements at the gauged station as it should be rated and hence a discharge estimate would normally be available. However, measuring water level at the gauged station ensures that in the event of gauge failure data integrity is ensured.

Although it is not necessary to install a data logger at the ungauged site, it provides a continuous record of the stream stage during the field program as well as providing a continuous discharge record, which will be accurate up to the highest current meter gauging. At remote sites there may be no gauged catchment within the region (particularly in arid areas) and the stage data constitute the only available hydrologic data along with any current meter measurements.

In situations when time permits only one or two gaugings to be undertaken at the ungauged site, the slope-area method could be used so long as steady uniform flow conditions could be assumed at the site. The method could also be used if a more accurate rating curve is required for discharges above wading depth than that available using Eq (1).

Loggers installed in water holes have an added advantage of recording drawdown as a result of evaporation and seepage. Depth loggers at candidate sites also allow a more accurate record of streamflow changes in areas of high spatial rainfall variability, particularly in defining flow events in ephemeral streams or resulting from isolated rainfall events.

8 CONCLUSIONS

This paper deals with estimating discharge at an ungauged site. Modern data loggers provide a means of gathering water levels cheaply, quickly and accurately. This information combined with information at a nearby gauged site or through at-site stream gauging, or possibly using two gauges to measure the water slope, will allow a stage-discharge relationship to be developed or discharges to be estimated.

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