

STREAM CHANNEL AND FLOW RELATIONSHIPS— RECENT TECHNIQUES ILLUSTRATED BY STUDIES ON SOME DARTMOOR STREAMS

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INTRODUCTION

MUCH effort has recently been expended developing techniques for the prediction of flood discharges in stream channels which are not continuously monitored. Large areas of the country, including many small streams, are still without direct records of run-off even though there were 782 stream gauging stations operating in Great Britain by 1970 (with 59% of the area of England and Wales, and 48% of Scotland gauged in at least one place). Data on flood peak discharges are required in planning engineering works, such as bridges or culverts, in the management of flood plains, and in estimating potential water volumes for abstraction. Most existing prediction techniques require extensive data on climate, soil and various topographical features (Institute of Hydrology, 1975) which are not available for many areas. Recently, however, methods have been proposed for predicting peak discharges from measurement of the stream channels. These methods are among the most promising applications to arise from the increased understanding of stream channel form and processes (Hedman, 1970; Rango, 1970; DeWalle and Rango, 1972; Hedman and Kastner, 1972; Gronwald and Pennell, 1972).

The stream channel is the basic erosional and depositional landform produced by flowing water. American research in the 1950s and 1960s showed how the cross-section, plan and profile of a natural stream channel are largely controlled by the sediment and water discharge—especially by the bankfull discharge (defined as that volume of water flowing down the stream above which water spills out from the channel onto the floodplain) (Leopold, Wolman and Miller, 1964). Opinions differ as to the average interval between successive bankfull discharges in individual streams, but something between 1.58 (Dury, 1973) and 2.33 (Leopold and Maddock, 1953) years appears characteristic of streams in the natural state.

If peak discharge controls channel form, it should be possible to predict such discharges from measurement of the channel, even in ungauged streams. This paper, based on a field study of some Dartmoor streams, tests the validity of the proposition. The relatively simple techniques involved could be readily applied by anybody in almost any stream.

THE FIELD AREA

Two stream systems, the West Okement and the River Dart (Fig. 1) were selected for study. Both flow over Dartmoor granite for much of their length. Most of the West Okement and the upper reaches of the Dart are over 400 metres O.D.. Channel form in the West Okement was measured at 13 mainstream and two tributary sites (Fig. 1B). The Dart, a substantially larger drainage system, comprises two headwater tributaries (the East Dart and the West Dart), from whose confluence at Dartmeet

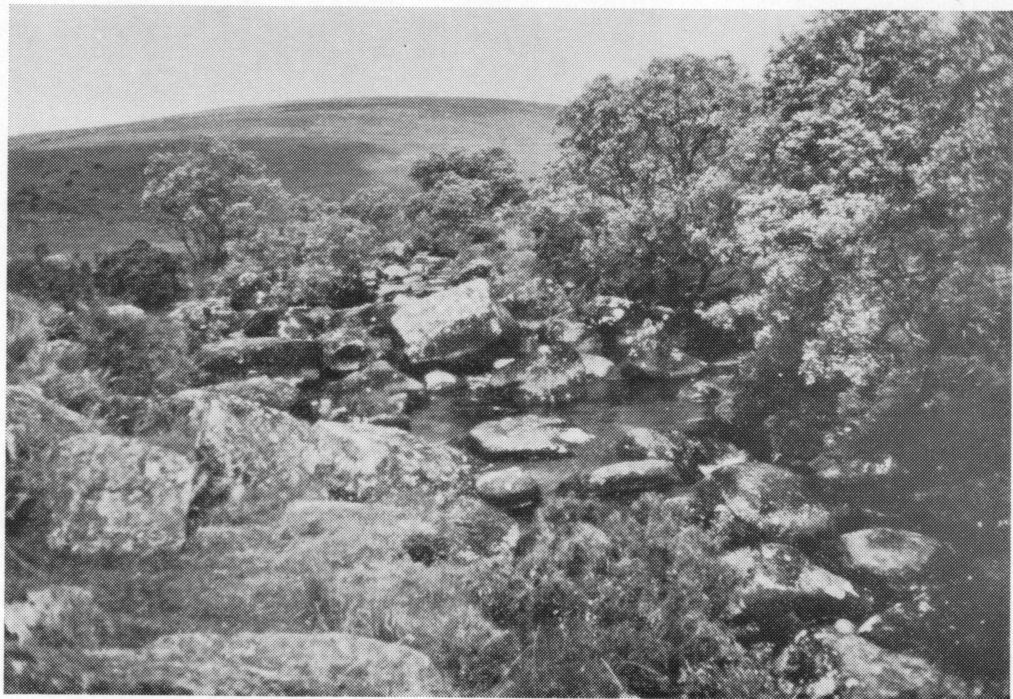


PLATE I.

Two examples of the boulder-strewn channels described in this paper, both from the East Dart above Postbridge. The lack of a clearly defined top to the banks is clear in both cases. The problems of field measurement include: the choice of representative cross-sections, the identification of the bankfull stage, and the difficulties and danger of wading across an irregular channel bed with potholes and concentrated areas of swiftly-flowing water.

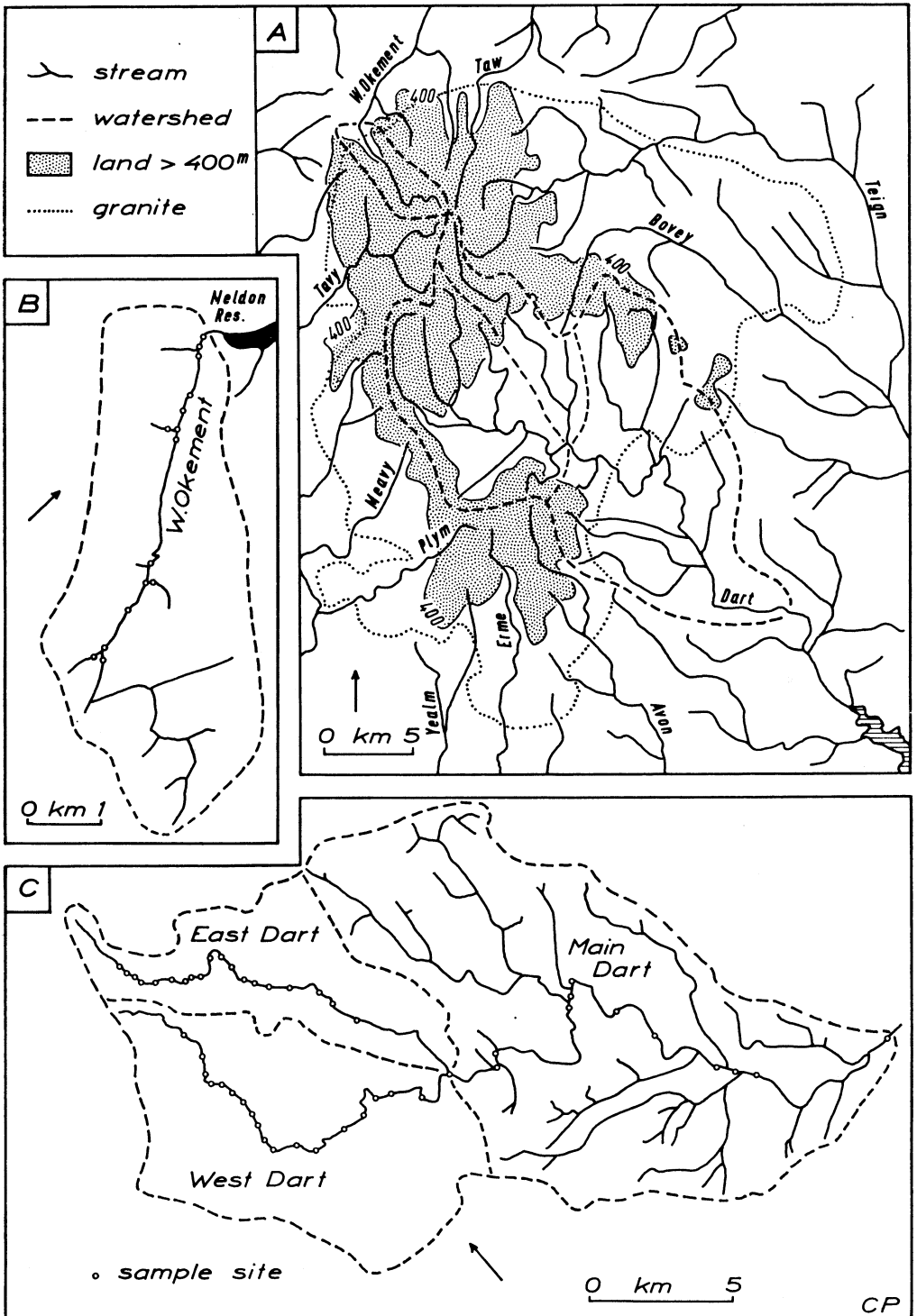


FIG. 1.

The streams studies on Dartmoor; (A) the general setting; (B) the sites in the West Okement; and (C) the sites in the River Dart mainstem and tributaries.

the Main Dart flows south-eastwards to the Dart Estuary (Fig. 1A). The channels were measured at 19 sites along the East Dart, 18 along the West Dart, and 12 along the Main Dart between Dartmeet and Staverton (Fig. 1C). Downstream from Staverton the river is too large for safe surveying by wading.

THE ESTIMATION OF BANKFULL DISCHARGE

Discharge is the product of the cross-sectional area of flowing water and its velocity. The simplest method of estimating bankfull discharge is thus to measure the cross-sectional area of the bankfull channel and multiply it by an estimate of bankfull velocity.

Data were obtained from field measurements, and from analysis of the 1:25,000 Ordnance Survey map.

(a) *The cross-sectional area of the bankfull channel*

The field measurements of channel width and depth were plotted on graph paper and the area measured from the scale drawing with a planimeter (although one could total up the graph paper squares as an approximation). Field observations were taken in metres, so the resulting area was expressed in square metres.

It is very important to identify the bankfull level correctly and consistently at each site. In an ideal, symmetrical, channel with banks of equal height, this level may be unambiguously located at the junction between the vertical channel banks and the relatively horizontal floodplain. Natural channels, however, are rarely simple and asymmetrical or compound sections are common. Often one bank is formed by a terrace at a level higher than the opposite bank.

In this survey the bankfull levels were identified as major breaks of slope on the cross section, and by extensive bench levels adjacent to the bank tops.

The sample sites were selected in coarse gravel (riffle) sections of reasonably straight reaches. At all the smaller sites a metric staff—or tape stretched taut—was placed horizontally across the top of the channel at right angles to its main orientation. Depths were measured down from this datum line to the channel perimeter (the sides and bed of the channel). The accuracy of the subsequent area measurement depends on a reasonable number of these depth measurements being taken—between 20 and 30 at each site (Park, 1977a). Accuracy also assumes that the datum line is truly horizontal (this can be checked in the field with a spirit level or clinometer) and that each depth measurement is truly vertical. Errors between sites should be minimized if one person takes all the measurements.

At the 12 Main Dart sites, with large wide channels, an Autoset level was used to obtain the horizontal datum line whilst distances across the channel were obtained by the surveying technique of tacheometry. This requires two people: one to use the level and the other to measure the depths.

Measuring bankfull channel dimensions when the flow is low assumes that the river will flow over the same bed when in flood. In alluvial channels this may not be valid because of the extensive scouring associated with the passage of flood discharges. However, the Dartmoor channels are heavily armoured by the large granite blocks which form much of the bed and banks; so extensive scouring is unlikely to occur often.

(b) *The estimation of bankfull velocity*

The Manning Flow Equation (Manning, 1891) is widely used by engineers to estimate velocity, and was used for this purpose at the sites along the Dartmoor streams. The flow equation describes the empirical relationship between four variables:

- v The velocity (speed of flow) of the water in metres per second.
 - s The slope of the energy grade line (similar to the slope of the stream bed) in metres per metre.
 - R The hydraulic radius of the channel—in this case the bankfull channel—in metres. This is the ratio of the cross-sectional area to the length of the channel perimeter—at the bankfull stage.
- and n' A roughness factor related to the frictional forces created by perimeter and water turbulence.

$$v = 0.453 \times \frac{R^{0.66} s^{0.5}}{n'} \quad (1)$$

The slope of the energy grade line (s) is usually taken from the Ordnance Survey map since map slope is easier and less ambiguous to measure. It is taken as the slope along the blue line (indicating the stream) on the 1:25,000 map between the 25 foot (7.62 metre) contours above and below the sample site, and is the contour interval divided by the horizontal distance between the contours concerned. Problems can arise, however, because although the 100-foot contours were accurately surveyed the intermediate ones, at 25, 50 and 75 feet, are often only form lines based on interpolation (Clayton, 1953). However, field studies in other parts of Devon have shown that the correlation between map slope and ground slope is close enough for all practical purposes (Park, 1976).

The bankfull hydraulic radius (R) is a measure of the efficiency of the channel shape, obtained by dividing the cross-sectional area of the bankfull channel by its wetted perimeter. Both of these variables can be taken from the scale drawings already mentioned on p. 731.

Empirical observations suggest that the roughness factor (n') is about 0.03 in alluvial channels, rising to 0.04 or 0.05 for those lined with boulders (Barnes, 1967). The Dartmoor channels are lined with boulders and coarse gravel so a value of 0.04 was considered appropriate. In some streams the roughness characteristics decrease downstream (Wolman, 1955) because sediment size decreases and the relative loss of energy from the flowing water decreases as the channel gets bigger. One way of deciding whether it is necessary to decrease the value of n' downstream in any particular study would be to compare the sample sites with the standard photographs of Barnes (1967) for which the roughness factors have been empirically determined. It is not easy to do this objectively, and, where field sites differ in degree rather than in kind, any adjustment of the n' value can only be arbitrary. In the present work therefore a uniform value of 0.04 was adopted, but this means that the estimates of peak velocity may be slightly low at the larger downstream sites.

A predicted value for the bankfull velocity was calculated for each site by substituting the appropriate figures for map slope (s), hydraulic radius (R) and roughness (n') into equation 1. Rough checks on the accuracy of such predictions can be made in the field using floats or a current meter. It is unlikely that the observer will

visit all sites at times of bankfull discharge, but clearly the estimates of bankfull velocity will usually be somewhat higher than the figure obtained at a lower flow stage.

(c) *Checks on the estimates of bankfull discharge*

An estimate of the bankfull discharge at each site was calculated as the product of the measured cross-sectional area of the bankfull channel and the estimated bankfull velocity. There are several ways in which the accuracy of such predictions can be checked, given suitable circumstances.

Firstly we can usually assume bankfull discharge to be more or less constant between two successive tributary junctions, provided they are not too far apart. The assumption may not be tenable if the junctions are widely separated because of bank seepage and possible changes in groundwater conditions along the intervening reaches. Nevertheless the predicted discharge for the lower junction should be the same as, or greater than, that of the upper in Dartmoor streams, as we can assume that losses through bed and bank seepage will be small in this type of environment.

A second check can be made at the tributary junctions. The discharge predicted for the stream below a junction should equal the sum of the discharges predicted for the two tributaries above it.

Unfortunately there were few occasions in the present study where such checks could be made and an alternative method of checking the accuracy of discharge predictions was required.

Dury (1973) showed that the peak discharge with a recurrence interval of 1.58 years ($Q_{1.58}$) approximates to the bankfull discharge in many streams.

Table 1. *Relationships between estimated bankfull velocity, estimated bankfull discharge and drainage area for some Dartmoor streams*

Each relationship is of the form: $y = (\text{constant}) x^{(\text{exponent})}$, in which x is the drainage area (D_a), y is the dependent variable; r is the correlation coefficient and p is the significance level of the correlation (based on Student's 't' test).

Dependent variable	Stream	Constant	Exponent	Sample size	r	p
i. Velocity	All data	1.0069	0.0177	64	0.0835	—
	East Dart	0.6094	0.2484	19	0.4332	—
	West Dart	0.9784	0.0030	18	0.0126	—
	Main Dart	0.0050	-1.0386	12	-0.8085	99 %
	W. Okement	0.9131	0.1565	15	0.5790	95 %
ii. Discharge	All data	0.5258	0.8454	64	0.9421	99.9%
	East Dart	0.2299	1.2710	19	0.8829	99.9%
	West Dart	0.4285	0.8930	18	0.9186	99.9%
	Main Dart	1.6466	-0.6033	12	-0.5147	—
	W. Okement	0.4697	0.9440	15	0.9388	99.9%

The estimated bankfull discharge (Q_b), based on channel characteristics, is related to drainage area (Da) for the Dartmoor streams by the equation:

$$Q_b = 0.5258 Da^{0.8454} \quad (2)$$

which gives figures similar to those plotted in Fig. 2A which were based on observations of peak discharges having a recurrence interval of 1.5 years ($Q_{1.50}$) at a sample of stream-gauging sites throughout South West England. That relationship is described by:

$$Q_{1.50} = 0.51 Da^{0.88} \quad (3)$$

The similarity of these two relationships suggests that the estimates of bankfull discharge are at least of the the correct order of magnitude. Fig. 2B compares the calculated values (Q_b), based on field measurement of channel form, with the values of $Q_{1.50}$ derived from equation 3, the drainage area of each site being measured from the 1:25,000 map. Despite the scatter most of the data points lie close to the best-fit regression line, which is described by the equation:

$$Q_b = 1.009 Q_{1.50}^{0.96} \quad (4)$$

This best-fit line is seen to lie very close to the line of equivalence ($y = x$) in Fig. 2B. It is thus concluded that the estimates of bankfull discharge for the Dartmoor streams are acceptable for further analysis.

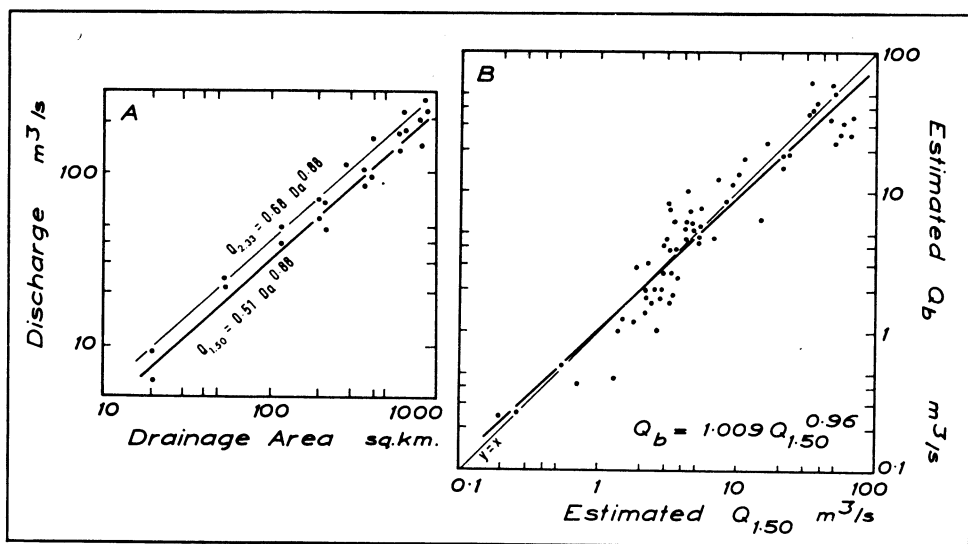


FIG. 2.

Relationships between estimated bankfull discharge (Q_b) and the estimated 1.5 year discharge ($Q_{1.50}$). (A) the regional discharge versus drainage area relationship for both the 2.33 and 1.50 year discharges (from Gregory and Park, 1974). In (B) the estimated bankfull discharge at each site in Dartmoor is plotted relative to the estimated 1.50 year discharge for that site derived from (A).

CHANGES IN DISCHARGE AND VELOCITY DOWNSTREAM

The Dartmoor data can be used to illustrate the manner in which discharge and velocity change downstream by relating the information for each site to the drainage area. Drainage area (the total area, in square kilometres, contributing water to the stream channel at the point of observation) can be measured from the 1:25,000 map for each site, using a planimeter or the "squares-counting" alternative. The values are not adjusted to take account of local slope variations and represent planimetric rather than actual ground surface areas. (Sloping ground is of greater area than its projected representation on a flat map.)

Fig. 3 shows the estimates of bankfull velocity plotted against the measured drainage area for each site. In Fig. 3A it is seen that there is no overall increase or decrease downstream. There are slight differences for the individual streams (Fig. 3B) but these are rarely significant. Estimated bankfull velocity appears to increase downstream quite substantially in the West Okement and East Dart; to decrease downstream in the Main Dart; and to remain almost unchanged in the West Dart.

The estimated discharge clearly increases downstream overall (Fig. 3A) and the regression exponent of this relationship, which is over 0.8, is similar to values quoted for other areas (e.g. Brush, 1961, for the American Appalachians). There are only slight differences between the individual streams (Fig. 3B). In the Main Dart discharge appears to decrease downstream but this is not statistically significant.

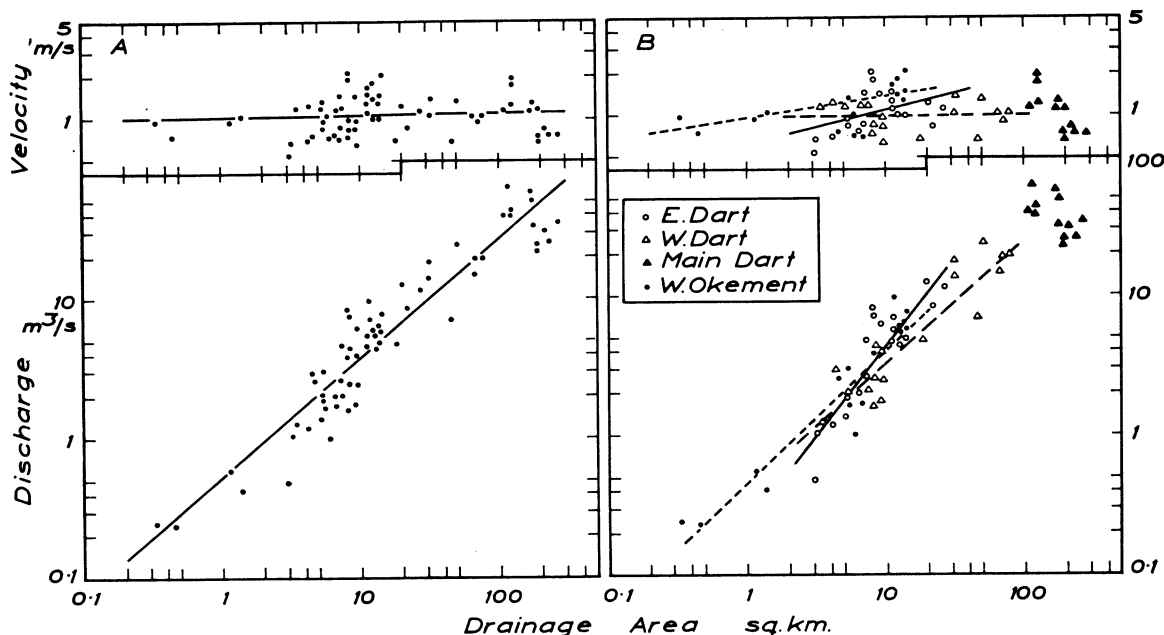


FIG. 3.

Relationships between estimated bankfull velocity and discharge values and drainage area for some Dartmoor streams; (A) all of the data together; (B) data for individual streams, West Okement - - - - - , West Dart - - - - - , East Dart - - - - - . Best fit regression lines for these relationships are listed in Table 1. The data in this and Figures 2 and 4 have been plotted on logarithmic graph paper (a) to yield power function forms of relationship (of the form $y = a \cdot x^b$) (b) to increase the normality of the data distribution for statistical analysis (c) to facilitate the plotting of wide ranges of values (for example the drainage area values range from 0.3 to over 200 sq. km.).

DERIVED DOWNSTREAM HYDRAULIC GEOMETRY

The main aim of the present study was to derive discharge values for each of the sample sites so that the relationships between discharge and channel form could be considered. One means of characterising these relationships, which has been applied widely in the last two decades, is to examine the "hydraulic geometry" of the stream channels. Leopold and Maddock (1953) illustrated the mutual adjustment between channel form and peak discharge. That is between the width, depth and velocity of water in the channel and the discharge, as these relationships varied both with changing discharge at individual sites (the "at-a-station hydraulic geometry") and with increasing discharge downstream (the "downstream hydraulic geometry"). The relationships were of the form:

$$\text{width} = a Q^b \quad (5)$$

$$\text{depth} = c Q^f \quad (6)$$

$$\text{velocity} = k Q^m \quad (7)$$

Table 2. *Summary of derived downstream hydraulic geometry relationships for some Dartmoor streams*

Each relationship is of the form: $y = (\text{constant}) x^{(\text{exponent})}$, in which x is the estimated bankfull discharge (Q_b), y is the dependent variable, and the constants and exponents are as in equations 5 to 7. r and p are as in Table 1.

Dependent variable	Stream	Constant	Exponent	r	p
i. Width		(a)	(b)		
	All data	2.2459	0.6713	0.9499	99.9%
	East Dart	2.7861	0.5017	0.9022	99.9%
	West Dart	2.5728	0.6591	0.9352	99.9%
	Main Dart	9.8969	-0.2705	-0.5469	—
	W. Okement	1.8741	0.6993	0.9377	99.9%
ii. Depth		(c)	(f)		
	All data	0.4865	0.2436	0.8457	99.9%
	East Dart	0.5155	0.1847	0.6943	99.9%
	West Dart	0.4435	0.2679	0.8903	99.9%
	Main Dart	0.3279	0.3899	0.6077	95 %
	W. Okement	0.5295	0.0989	0.4712	—
iii. Velocity		(k)	(m)		
	All data	0.9143	0.0860	0.3632	99 %
	East Dart	0.6961	0.3135	0.7869	99.9%
	West Dart	0.8762	0.0727	0.2985	—
	Main Dart	0.0405	0.9027	0.8237	99.9%
	W. Okement	1.0081	0.2022	0.7522	99.9%
iv. "Capacity" (Cross-sectional area)		(axc)	(b+f)		
	All data	1.0927	0.9150	0.9724	99.9%
	East Dart	1.4365	0.6865	0.9415	99.9%
	West Dart	1.1410	0.9272	0.9702	99.9%
	Main Dart	22.8507	0.1196	0.1910	—
	W. Okement	0.9920	0.7978	0.9762	99.9%

As discharge = width \times depth \times velocity (i.e. $Q = w.d.v$) the sum of the exponents ($b + f + m$) and the product of the constants ($a.c.k$) should each equal 1.00. Leopold and Maddock (1953) established these relationships from stream gauging station data, using observed peak discharges. Brush (1961) suggested an alternative approach, based on regional relationships between gauged discharge and drainage area, for streams without gauging stations. Fig. 2A is based on such data for South West England.

A second alternative is to use peak discharge data estimated from channel characteristics, as has been done here for the Dartmoor streams. This has the advantage of being independent of gauging station data.

The downstream hydraulic geometry relationships for the Dartmoor channels are shown in Fig. 4. The measured bankfull cross-sectional area ("capacity"), estimated bankfull velocity, measured width and mean depth are plotted against the estimated bankfull discharge. The hydraulic geometry relationships (equations 5, 6 and 7) apply to these graphs.

Combining the data from the separate streams (Fig. 4A), velocity is seen to increase only slightly with increasing discharge; the increase in discharge being due to increasing channel size rather than velocity. The width of the channels increases faster, relative to discharge, than does mean depth; which indicates a change in channel shape downstream towards a relatively wider and shallower channel. There appear to be no significant differences between the individual streams (Fig. 4B).

The exponents (for equations 5, 6 and 7) derived from Fig. 4 show reasonable

Table 3. Comparison of downstream hydraulic geometry exponents from Dartmoor streams with published data

Stream	b	f	m
1. a. All Dartmoor data (Bankfull discharge)	0.67	0.24	0.09
b. East Dart (Bankfull discharge)	0.50	0.18	0.31
c. West Dart (Bankfull discharge)	0.66	0.27	0.07
d. W. Okement (Bankfull discharge)	0.70	0.10	0.20
2. a. Theoretical (Leopold and Langbein, 1962)	0.55	0.36	0.09
b. Theoretical (Smith, 1974)	0.60	0.30	0.10
3. a. Mid-west United States (mean annual discharge) (Leopold and Maddock, 1953)	0.50	0.40	0.10
b. Brandywine Creek, United States (2% discharge) (Wolman, 1955)	0.58	0.40	0.02
c. River Ter, England (Bankfull discharge) (Harvey, 1967)	0.30	0.55	0.15
d. River Nar, England (Bankfull discharge) (Harvey, 1967)	0.40	0.20	0.40
e. Wallop Brook, England (Bankfull discharge) (Harvey, 1967)	0.40	0.20	0.40
f. Bollin Dean, England (2% discharge) (Knighton, 1974)	0.61	0.31	0.08
g. River Hodder, England (Bankfull discharge) (Wilcock, 1967)	0.40	0.40	0.16

agreement with those derived from the theoretical considerations of Leopold and Langbein (1962) and of Smith (1974) (Table 3). The theoretical expectation is for a large width (b), medium depth (f) and very low velocity (m) exponent; and in this respect the Dartmoor channels are similar to both the Brandywine Creek in the United States and the Bollin Dean in Cheshire, whilst differing considerably from

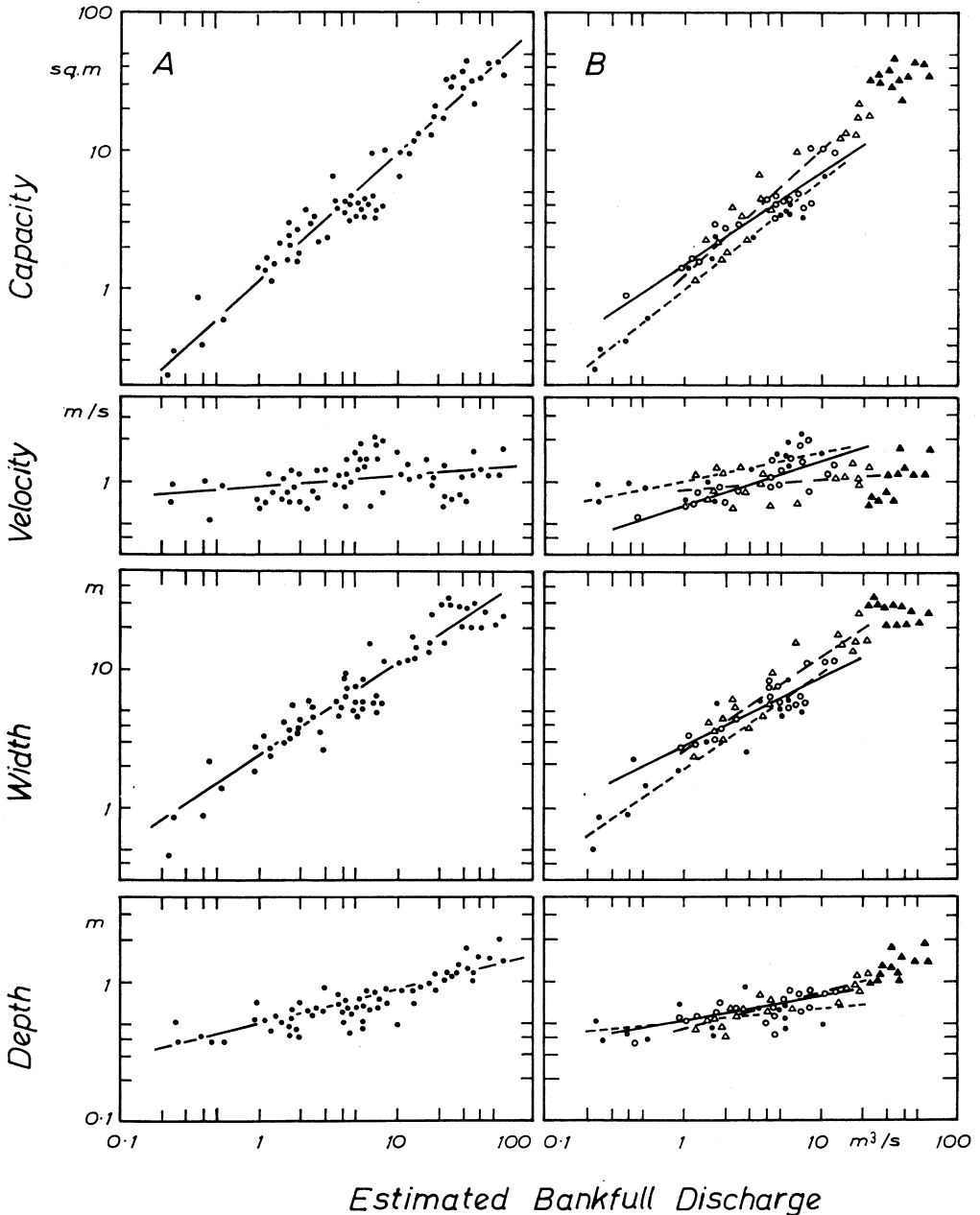


FIG. 4.

Derived downstream hydraulic geometry relationships in the Dartmoor streams. (A) composite relationships for all data; (B) relations for individual streams (see Figure 3 for key).

several other streams (Table 3). It is not surprising to find these differences when comparing such different streams which vary in, for example, bank erodibility, channel instability, suspended sediment load, channel slope, and man-induced modifications to the channels (Park, 1977b).

SUMMARY

One of the main problems that has hampered the study of stream channels in Britain is the paucity of suitable direct observations on the variations in discharge; both along and between streams. Techniques are thus required to predict the characteristics of peak discharges.

In many areas the size of the natural stream channel is closely adjusted to the peak discharge characteristics of that stream, and it is thus a logical, and logistically simple, procedure to use observations of the channel form to predict the discharge.

The use of the Manning flow equation to estimate peak velocity is illustrated with data collected from some Dartmoor streams, and the estimates of discharge so derived show reasonable agreement with peak discharges recorded at gauging stations in South West England generally.

Downstream variations in the estimated bankfull velocity and discharge were evaluated for individual sites along the streams, and analysis of these data lead to consideration of the downstream hydraulic geometry of the Dartmoor streams. Such analysis, relating channel capacity, width, depth and velocity to the estimated bankfull discharge, showed that the streams have similar hydraulic geometry exponents to those derived on theoretical grounds, and, moreover, are similar to some other streams in other parts of the world.

The simple techniques employed in this study could be profitably applied to any stream with a resistant bed, so increasing our knowledge of stream channels.

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