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Scour and fill in cobble-bedded streams

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CONTENTS

Page

Summary

Results

Discussion

SUMMARY

Scour and deposition have been measured in two small cobble-bedded upland streams, for two years. Grids of scour chains were inserted in the bed and relocated after the passage of individual hydrographs. Scour, fill and the area of the bed affected by these processes were recorded. The relationship between mean scour or fill and maximum scour or fill is assessed. In addition, the relationship between the depth of scour and the sediment transport rate as bedload is discussed briefly. The following main Conclusion were derived for the two study streams;

1. Mean scour was 37.8 mm (s.e. 3.1 mm; N = 32); maximum scour was 65.0 mm (s.e. 7.7 mm; N = 32).
2. Mean deposition was 46.4 mm (s.e. 5.6 mm; N = 32) ; maximum deposition was 95.9 mm (s.e. 14.8 mm; N = 32).
3. Both mean and maximum deposition were correlated with peak discharge per metre bed width. Scour could not be correlated with discharge.
4. At least 50% of the bed area exhibited scour or fill once a threshold of 0.113 m^3 m^{-1} sec discharge was exceeded.
5. The depth of mean scour was two fifths of that recorded for a sand-bedded stream for an equivalent discharge.
6. Mean scour or fill was closely correlated with maximum scour or fill.
7. Only a small part of the 'active' bed-layer thickness is actually transported as bedload.
8. The new data presented here are broadly compatible with other published scour and fill data for sand/gravel and cobble-bedded streams.
9. Tentatively, it may be concluded that for fish up to 110 mm in length, redds were vulnerable to washout during 50% of all floods. For fish 185 mm long, the risk was less ~ 6%.

INTRODUCTION

Although scour and fill have been described for many river gauging stations these data are frequently of restricted value. In the first instance many gauging stations are sited at narrow natural or artificial 'semi-stable' channel sections which may not be generally representative of loose-boundary channels (Lane & Borland, 1954). Secondly, most gauging stations for which scour data are available are on large rivers; small streams commonly are gauged by flumes and weirs so that scour determinations are not possible from gauging data. Finally, some data reflect the passage of sandwaves (Colby, 1964; Foley, 1975, Andrews, 1979) across an otherwise stable bed. This report presents scour and fill data from natural sections in two small perennial cobble-bedded streams in Teesdale, U.K., at an altitude of 200-400 metres.

Carl Beck and Great Eggleshope Beck are upland channels in the River Tees system (Fig. 1). Sediment, catchment and hydrological characteristics have been described previously (Carling & Reader, in press; Carling, in press; Carling, 1981); only those characteristics pertinent to this report are presented here. Carl Beck has a catchment area of 2.18 km^2 and Great Eggleshope Beck - 11.68 km^2, stream widths vary between 1-3 m and 5-8 m; stream bed slope is 0.0394 and 0.0100 respectively. Channel banks are in the main stable and braiding only occurs where there is a local overloading of bedload in storage in the channel; here gradients are reduced and anabranch talwegs are unstable.

The bed material is poorly sorted coarse sandstone and limestone cobbles and granules of mean grain-size - 69 mm.

Both streams are flashy; hydrographs propagate rapidly consequent to heavy rainfall. The bed material is in an 'active' state frequently and considerable bedload transport has been recorded (Carling, unpublished).

METHODS

Two grids of scour chains across the full stream width of each channel were installed in straight single-channel reaches well clear of channel bends and pool-riffle sequences. Chains were 1 m apart. Data were collected for the water years 1979/80 and 1980/81. To minimise disturbance of the bed, chains were implanted vertically with several links left lying free on the bed surface using a hollow driving tube (Fig. 2). After the passage of a hydrograph the chains were relocated using a metal detector. If scour had occurred the increase in the length of chain free at the surface was a measure of the depth of scour. Alternatively, the depth of deposition over the horizontal chain length could be measured by careful sectioning of the deposits. Additional length of horizontal chain beneath the deposits would suggest that scour had occurred before deposition.

Data were collected for a total of 12 and 21 floods in Eggleshope Beck and Carl Beck respectively (Table 1). There was no evidence of any definable pattern in cross-sectional variation in scour. Data for each flood were analysed to yield mean depth of scour, maximum depth of scour, mean and maximum depth of deposition. In addition, the data for each chain were taken as being representative of the bed area (approx. 1 m^2) around each chain so that the percentage of the bed area that was subject to scour or deposition could be ascertained.

Data were checked for serial autocorrelation but there was no evidence of persistence in the data from spate to spate.

The method allows reasonable estimates of scour or deposition at a section to be made, but unfortunately it is not possible to relate these processes to rising or falling stages of a hydrograph. In addition, it is not known how different areas of the bed respond to the variable hydraulic conditions during the passage of a hydrograph.

Following the early observations of Leopold & Maddock (1953) that maximum scour coincided with the flood crest, later investigators have adopted or partially confirmed the a priori assumption that significant scour or fill should be related to discharge (e.g. Culbertson & Dawdy, 1964; Emmett & Leopold, 1965; Hickey, 1969; Pickup & Warner, 1976; Andrews, 1979). However, the relationship of discharge with bed level fluctuations, at least in sand-bedded streams, is complex (e.g. Colby, 1964; Andrews, 1979) and detailed observations are needed throughout hydrographs at several stations, to separate, for example, true scour or fill from fluctuations in bed level ascribable to bedform migration. In the present report, the peak mean daily discharge and the instantaneous (five minute integral) peak discharge preceding each scour survey, were obtained from continuously recorded discharge data at gauging sites adjacent to the scour/fill sections. No bedforms developed in the coarse gravels, so it was considered reasonable to seek a first order correlation of discharge with scour or fill. Exploratory analysis indicated that instantaneous peak discharge values produced better correlations with scour or fill than was the case using mean daily discharge. Consequently only the former are reported below.

RESULTS

Scour and deposition

No significant correlation could be obtained between maximum or mean scour and the peak discharge per metre of bed-width for Eggleshope or Carl Beck data. Although the chains were checked during a range of low discharges, no scour or deposition was measured for discharges less than 0.113 m^3 m sec^{-1}. This value may be regarded as an effective threshold for measurable scour or deposition.

Emmett & Leopold (1965) found a relationship between the mean scour depth (h) and discharge per unit bed-width (Q) for an ephemeral coarse sand-bedded stream using scour chain data,

$$h = a \sqrt{Q} \quad (1)$$

where a = 100 mm with *Q* measured in $m^3\ m^{-1}\ sec^{-1}$ and h is measured in mm. This relationship is shown in Figs. 3 and 4 along with the data for the perennial gravel-bedded streams, Carl Beck and Eggleshope Beck. The 32 data points have a mean value for scour of 37.8 mm (s.e. 3.1 mm) and a mean discharge of 0.83 $m^3\ m^{-1}\ sec^{-1}$. A discharge of this value substituted into equation (1) gives a predicted scour depth of 91.3 mm in sand. The ratio 37.8/91.3 = 0.4 indicates that mean scour depth in the coarse gravel in temperate Teesdale is about two-fifths of the predicted scour depth in the arid sand-bedded stream.

Maximum scour depth had a mean value of 65.0 mm (s.e. 7.7 mm; N = 32). The ratio 65.0/91.3 = 0.7 indicates that the mean value of the maximum scour depth in gravel is less than three quarters of the mean scour depth in sand as predicted from equation (1).

The depth of deposition expressed as the mean or maximum depth is correlated with the peak discharge per metre bed width (Figs. 5 and 6).

$$\text{Mean deposition} = 47.38\ Q^{0.35} \qquad r^2 = 0.33 \qquad p < 0.001 \quad (2)$$

$$\text{Maximum deposition} = 94.37\ Q^{0.50} \qquad r^2 = 0.37 \qquad p < 0.001 \quad (3)$$

The maximum deposition data for Eggleshope Beck delineate an upper bound for the data plot in Fig. 5 and can be expressed;

$$\text{Maximum deposition} = 156.30\ Q^{0.64} \qquad r^2 = 0.53 \qquad p < 0.02 \quad (4)$$

Although significant, the r^2 values in equations 2, 3 & 4 are low. The value of $r^2 \times 100$ indicates the percentage of variance in the data explained by the regression; it does not indicate the degree of confidence that may be associated with the regression coefficient ß. The 95% confidence limits

(Draper & Smith, 1966) on ß, ± 0.50 in equation (2), ± 0.56 in equation (3) and ± 1.67 in (4) include 3 = 0 . Consequently we cannot reject the possibility that ß might be zero for these data sets.

Scour and deposition data for gravel-bedded rivers are rare. To ascertain whether or not the Teesdale data are representative of other gravel-bedded rivers and to extend the data range, additional data for large rivers are also included in Figures 3 and 5. Scour and fill data are from Culbertson & Dawdy (1964) for stream reaches with beds of mixed sand and gravel. Additional data for sand-bedded streams are also included for comparison. Discharge values are not necessarily peak values but are the largest recorded on each survey date during periods of high flow and rapid scour or fill.

Additional data for cobble-bedded streams are given by Hickey (1969). In the latter case discharge is the peak value of the December 1964 flood which swept northwestern California. In some of the streams Hickey investigated, the flood had an estimated recurrence interval of 400 yr (Helley & La Marche 1968; Brown & Ritter, 1971). Finally two values for an upland Welsh stream (Slaymaker, 1972) are also included.

Culbertson and Dawdy's scour data overlie the Teesdale data. There is no consistent trend of limited scour in coarse gravel to deep scour in sand, as one might have expected. Culbertson & Dawdy's deposition data overlap the Teesdale data, but exhibit a greater range, with most high deposition values associated with sand-bedded streams. Hickey's data are interesting in that discharges were high; deposition of cobble-material was greater than an extrapolation of the regression line through the Teesdale data would indicate.

An equation describing the trend of the 46 data points for scour in gravel-bed streams (i.e. excluding Culbertson & Dawdy's sand-bedded streams) in Fig. 3 is;

Mean scour $= 43.20\ Q^{0.27}$ $r^2 = 0.19$ $p < 0.01$ (5)

Similarly an equation for the 62 points for deposition in Fig. 5 is;

Mean deposition $= 54.23\ Q^{0.58}$ $r^2 = 0.54$ $p < 0.001$ (6)

Area of bed scoured or filled

No correlation was found between the area of bed subject to scour or fill and discharge when each was considered independently. However considering the area of bed which scoured <u>or</u> filled, a significant relationship was obtained. The relationship for percentage change in the active bed area (A) is;

$A\ \%(\pm) = 76.89 + 12.07 \ln Q$ $r^2 = 0.22$ $p < 0.01$ (7)

The hypothesis that β is zero was rejected at the 0.1% level, $\beta = 12.07 \pm 6.33$. The Eggleshope data considered alone gave a good correlation;

$A\ \%(\pm) = 61.50 + 27.23Q$ $r^2 = 0.78$ $p < 0.01$ (8)

which describes an approximate upper boundary for the maximum area of bed affected for a given discharge. The curve for equation (7) together with 95% confidence limits for the existing data are presented in Fig. 7. At the threshold for scour $Q = 0.113\ m^3\ m^{-1}\ sec^{-1}$ some 50% of the bed width may be expected to scour and fill, rising to 85% at a discharge of $2.0\ m^3\ m^{-1}\ sec^{-1}$; a value close to bankfull. Equations (7) and (8) are unsatisfactory in that, when the flow is sub-threshold, extrapolation of the equations yields a substantial area subject to scour or fill. However fitting a more complex equation to give $A\ \% = 0$ when $Q \sim 0.1$ would be unjustified with such a small scattered data set.

Relationship between maximum scour and mean scour

Colby (1964) believed that the maximum depth of scour recorded using scour chains is not always indicative of a change in mean bed elevation in the cross-section. This observation is not applicable to the present investigation as is explained below.

Preliminary data analysis suggested that both mean scour and maximum scour, mean deposition and maximum deposition are linearly related, with little variation in the regression slope in both Carl Beck and Great Eggleshope Beck. Consequently a single relationship was derived by plotting the ratio of individual scour or fill values (h') over the mean values of scour or fill (Fig. 8).

Both sample sets are logarithmically distributed. Data skewness was made approximately normal by taking $\log_{10}$ of each value. The least-squares equation, in which coefficients are non-dimensional, is;

$$\log\left(\frac{h'_{mean}}{\bar{h}_{mean}}\right) = 0.0124 + 0.6091 \log\left(\frac{h'_{max}}{\bar{h}_{max}}\right) \qquad (9)$$

N = 64 and with an r^2 value of 0.81 the relationship is statistically significant at the $p < 6.001$ level. However the equation is not completely determinative; as values on the abscissa approach zero the ordinate still has a finite value. As the variance was not significantly reduced by normalising the data sets, it could be argued that an equation using untransformed values might be equally acceptable (Mitchell, 1974), in which case the coefficient a = 0.31 and ß = 0.70. Assuming the least-squares method is robust, an equation with these latter coefficients can be fitted to the data with a degree of confidence similar to equation (9).

Thickness of active bed-layer

Values of scour used in this report represent not so much the depth to which the bed will be lowered permanently after a flood event but rather the depth to which the gravel is eroded immediately to be refilled subsequently. Data therefore represent the depth of the active bedlayer and this may be envisaged as a mobile carpet of material thickening or thinning as the flow strength increases or decreases. This model assumes a constant rate of sediment transport at any one time and the absence of source-dependent sediment supply rates; i.e the bed is the sole source of the bedload (e.g. Einstein, 1944). In general, friction has a tendency to level out the streambed. Erosion increases the cross-sectional flow area, current speed is reduced and erosion ceases or deposition may occur; i.e., negative feedback operates and steady-state is re-established, maintaining a constant carpet thickness.

For high flows capable of moving the bed material the mean scour depth may be regarded as indicative of the depth of the active bed-layer (h), which may be related to the bedload transport rate per metre bed width (I_b).

$$I_b = \bar{h}\,\bar{U}_b\,\rho_s\,(1 - \lambda) \qquad (10)$$

where $\bar{U}_b$ is the flow velocity in the bedlayer (Einstein, 1960) ρ_s is the density of the sediment grains and λ is the bed porosity.

For the data presented in this report,

$$\bar{h} = 0.55\bar{d} \qquad (11)$$

contrary to the common assumption in sand-bedded streams that $\bar{h} = 2\bar{d}$ (Simons & Senturk, 1976, p. 504), where $\bar{d}$ is the mean grain-size of the bed material. Equation 11 implies that large sediment particles are not in motion or very few are in motion at a given time. Consequently a process of selective winnowing of the surface bed-layer can be envisaged with coarser grains remaining stable or settling to a lower equilibrium level. However scatter about the mean value of scour and the maximum values recorded indicate that locally scour may be greater, $\bar{h}_{max} = 0.94\,\bar{d}$ i.e.;

$$\bar{h}_{max} \approx \bar{d}\ (\bar{h}_{max} + s.e. = 1.05\bar{d}) \qquad (12)$$

To solve equation (10) a value for $\bar{U}_b$ is required. The depth averaged velocity $\bar{U}$ is known from field surveys and this value represents the current speed at 0.4 Z. Using an equation for the velocity distribution over a hydro-dynamically rough bed $\bar{U}_b$ may be estimated;

$$\ln Z = \frac{\chi}{U_*} U_z + \ln z_o \tag{13}$$

where Z is the height above the bed, U_* is the shear velocity, χ is von Karman's constant (0.40 in water with only a low suspended sediment concentration) and Z_o is the roughness length = $K_s/30$, where K_s is the bed roughness. K_s was estimated from the relationship given by Charlton (1977) for British gravel-bedded rivers.

$$K_s = 3.67\ d_{50}^{1.11} \tag{14}$$

Equation (13) can be solved for U_* using $\bar{U}_{0.4}$. Consequently Equation (13) can be solved for $\bar{U}_b$ by introducing U_* into the equation and taking the height above the bed as the middle of the active layer i.e. $0.27\bar{d}$.

Alternatively $\bar{U}_b$ can be estimated using the procedure of Einstein *et al.* (1949) reported more recently by Graf (1971, p. 146).

The term $\bar{h}\ \bar{u}_b\ \rho_s\ (1 - \lambda)$ was solved for the field data in Great Eggleshope Beck. Similarly the mean sediment transport rate (I_b) associated with each flood was calculated from a streampower (ω) sediment transport function derived from field data for Great Eggleshope Beck (Carling, unpubl.);

$$I_b = 0.0015\ \omega^{2.68} \qquad r^2 = 0.93 \qquad p < 0.001 \tag{15}$$

The relationship between I_b and $\bar{h}\ \bar{u}_b\ \rho_s\ (1 - \lambda)$ is shown in Fig. 9. If all the bedlayer which is disturbed contributed to the bedload, I_b would equal $\bar{h}\ \bar{u}_b\ \rho_s\ (1 - \lambda)$.

DISCUSSION

Hydraulic Implications

The data presented are by no means conclusive. The limited range of discharge values (only two orders of magnitude) in the Teesdale streams coupled with the large variance inherent in data from scour chains results in constricted plots and considerable scatter in data. Consequently it is difficult to achieve precision in statistically defining a non-zero regression slope, especially if it is likely to be as low as that expected from Emmett & Leopold's analysis i.e. $\beta = 0.5$. The small values of the exponents in equations (2) to (6) suggest that scour and deposition of gravels have a functional relationship with discharge very similar to that of scour of sand, if $\beta = 0.5$ is indeed definitive for sand. Because of the large variance in the data used in this report, equations (2) to (8) are included only for comparative purposes. It should not be construed that any confidence is placed in these equations for precise predictive purposes. The equations, and Figures 3 to 8 may only be used to assess the likely range of values of scour or fill that might be expected for a given discharge.

Additional evidence is available however, to verify that the scour-chain data from Carl Beck and Eggleshope are reasonably representative of the thickness of the active bed-layer. Ottaway *et al*. (1981) recorded scour by repeated levelling in the same reach as the scour-chain grids in Great Eggleshope. A maximum depth of scour of 200 mm and of deposition, 170 mm were recorded. In Carl Beck, Ottaway *et al*. (1981) buried artificial colour-coded fish eggs at various depths of up to 130 mm below the gravel surface. After a season of spates, eggs were relocated by digging the gravel over. Recovery of eggs buried at 120 mm + was close to

100% whilst recovery of eggs buried at 60 mm depth was very low - 2%. These data compare favourably with the mean value of maximum scour depth obtained from scour chains - 65.0 mm.

Better correlation with discharge was obtained for deposition than was obtained for scour. This may be because measured deposition probably occurs during the last phase of a waning hydrograph (e.g. Colby, 1964); deposits consequently are undisturbed when chains were relocated. In contrast, chains recording scour may have been subject to a degree of infilling during the falling stage of the hydrograph so that the record is less clear and the overall pattern blurred. Nevertheless measurable scour or fill were not recorded at discharges less than 0.113 m^3 m^{-1} sec^{-1}, which represents a practical threshold for scour or fill in these two streams.

The percentage of the bed area scoured or filled during the passage of a hydrograph is only a crude estimate (Fig. 7). Notwithstanding the approximate nature of the data it is clear that at least 50% of the stream bed area can be expected to be active once the threshold is exceeded.

The sediment transport rate as indicated by the depth of scour (Fig. 9) is much greater than the measured transport rates. Even allowing for experimental error and the assumptions explicit in deriving equation (10), the discrepancy suggests that many sediment grains disturbed by the flow are not actively transported but remain as an unstable bedlayer (Emmett & Leopold, 1965). Grains close to the threshold of motion may be envisaged as vibrating and bouncing in scour hollows in the bed (e.g. Urbonas quoted in Simons & Senturk, 1977, p. 675) whilst slightly larger grains may remain virtually stationary in an activated bed-layer (Milhous & Klingeman, 1973). The data plotted in Fig. 9 only become coincident with equation (10) at a sediment transport rate (I_b) associated with bankful discharge when the bedlayer is presumably fully activated and all grain-sizes present in the bed material have been recorded moving as bedload (Carling, unpubl.).

Biological Implications

Although the bed is active frequently, the discrepancy between the measured depth of scour and the measured bedload transport rate indicated that much of the bed material, although disturbed, is not violently rolled downstream for any distance. In addition, within the limits of the data, it is apparent that there is no trend to deep scour at high discharges although the area of bed affected increases with discharge. Consequently invertebrates are equally vulnerable to displacement owing to gravel disturbance across a range of discharges. However, many cobbles will remain relatively stable at the surface providing shelter and local points of attachment.

The implications for the washout of salmonid eggs remain unclarified owing to the availability of only a few data concerning fish size and the depth to which the fish bury their eggs. Nevertheless a preliminary analysis can demonstrate the potential value of suitable data when these become available. The essential details are summarized in Fig. 10. Open data points are the depth to the base of egg pockets for given fish lengths (Ottaway _et al_., 1981). Closed data points are unpublished data representing the depth at which the mean number of eggs in a pocket is located. Horizontal lines are various scour depths (see Fig. 10). Given adequate data a relationship may be plotted relating the depth of the egg pocket to fish size. From this one can predict the size range of fish, the egg pockets of which are vulnerable to various degrees of scour. For example, a provisional linear equation relating h and 1n F1 for the solid data points in Fig. 10 indicated that the redds of fish up to a length of 11 cm will be washed out by mean scour and those of fish up to 18 cm by mean maximum scour. It may be implied from the data that no fish dig redds which are deep enough to be safe from scour under any condition. Naturally the probability of deep scour is less than for mean scour, however deep scour occurs every year. For example in Carl Beck the maximum depth of scour (160 mm) occurred on 2 occasions in a series of 20 floods over two winter seasons. Similarly the mean scour depth (37.8 mm) was exceeded on 8 occasions and the mean maximum depth (65 mm) was exceeded on 3 occasions (Table 1). For the total 32 floods in both streams mean scour was exceeded on 50% of occasions and mean maximum scour was exceeded 6% of the time. These figures correspond to fish lengths of 11 and 18.5 cm (Fig. 10). Consequently the redds of fish up to c. 18 cm are vulnerable each year.

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Table 1. Summary scour and fill data and associated peak discharge data

Carl Beck					G. Eggleshope Beck				
Scour (mm)		Fill (mm)		Discharge ($m^3 m^{-1} sec^{-1}$)	Scour (mm)		Fill (mm)		Discharge ($m^3 m^{-1} sec^{-1}$)
Mean(-)	Max(-)	Mean(+)	Max(+)	Q max	Mean(-)	Max(-)	Mean(+)	Max(+)	Q max
20.00	20	26.67	70	0.89	46.67	60	69.79	180	0.96
20.00	20	-	-	0.91	54.10	160	57.00	110	0.85
20.00	20	40.00	40	0.74	43.80	120	25.00	40	0.76
20.00	20	37.50	60	1.18	38.00	100	66.30	160	3.58
28.33	40	60.00	80	1.34	38.60	80	36.70	90	0.76
76.76	160	33.33	60	0.58	41.40	70	23.80	50	0.94
40.00	60	30.00	60	0.35	34.29	70	36.36	100	0.52
40.00	60	80.00	180	2.14	30.00	40	47.50	110	2.53
55.00	60	23.33	40	1.19	35.83	60	52.33	180	4.60
26.67	40	26.67	50	1.63	96.67	150	196.67	470	4.59
62.50	160	46.00	120	0.79	44.44	90	60.00	110	3.26
40.00	40	17.50	20	0.14	20.00	30	56.88	180	2.53
-	-	53.50	100	1.87					
26.70	40	65.00	100	0.81					
30.00	40	40.00	60	0.21					
40.00	40	20.00	20	0.11					
20.00	20	30.00	40	0.16					
26.70	40	33.33	60	0.80					
20.00	20	40.00	40	No data					
45.00	100	30.00	50	No data					
27.50	50	24.00	40	0.63					

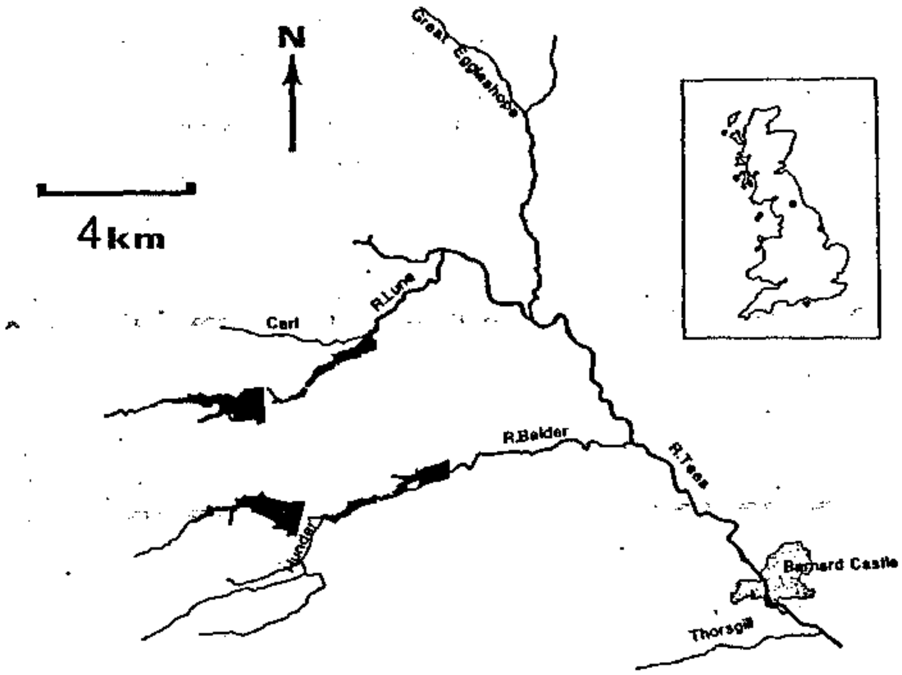

Fig. 1. Location of study streams in respect to other major rivers and streams in the area. Map scale: 1 cm represents 2 km.

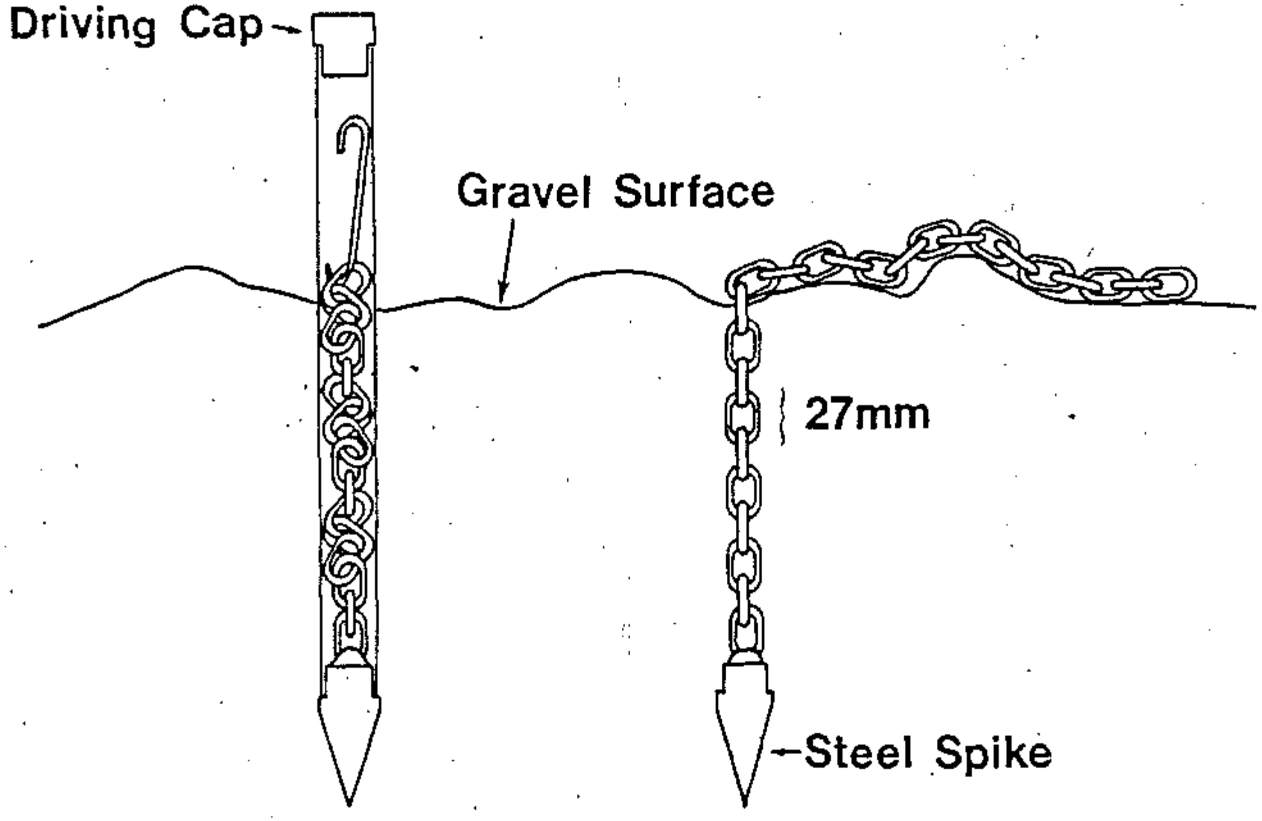

Fig. 2. Method of implanting scour chains. A mild-steel machine-turned spike welded to a 27 mm link size chain is threaded into a 28 mm diameter driving tube. A short wire hook is attached to retrieve the chain. A driving cap is used to insert the driving tube into the gravel to the required depth. The wire hook is "fished out" of the tube and used to straighten the chain as the driving tube is withdrawn.

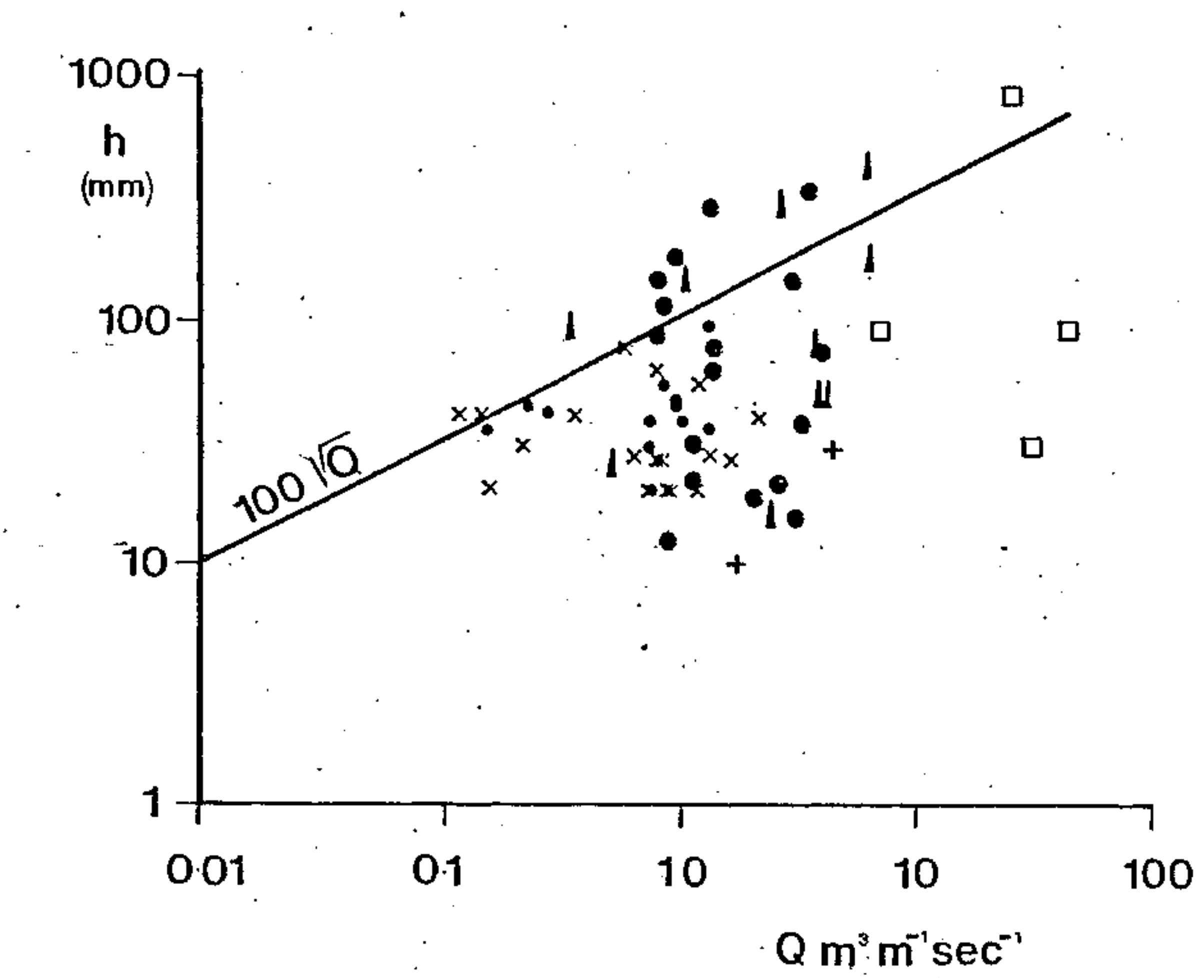

Fig. 3. Mean scour depth (h) as a function of discharge per metre of bed width (Q) . • = G.Eggleshope Beck, X = Carl Beck, O = Culbertson & Dawdy - sand, Δ= Culbertson & Dawdy - sand and gravel, • = Hickey - cobbles, + = Slaymaker - gravel. Regression line from Emmett & Leopold (1965).

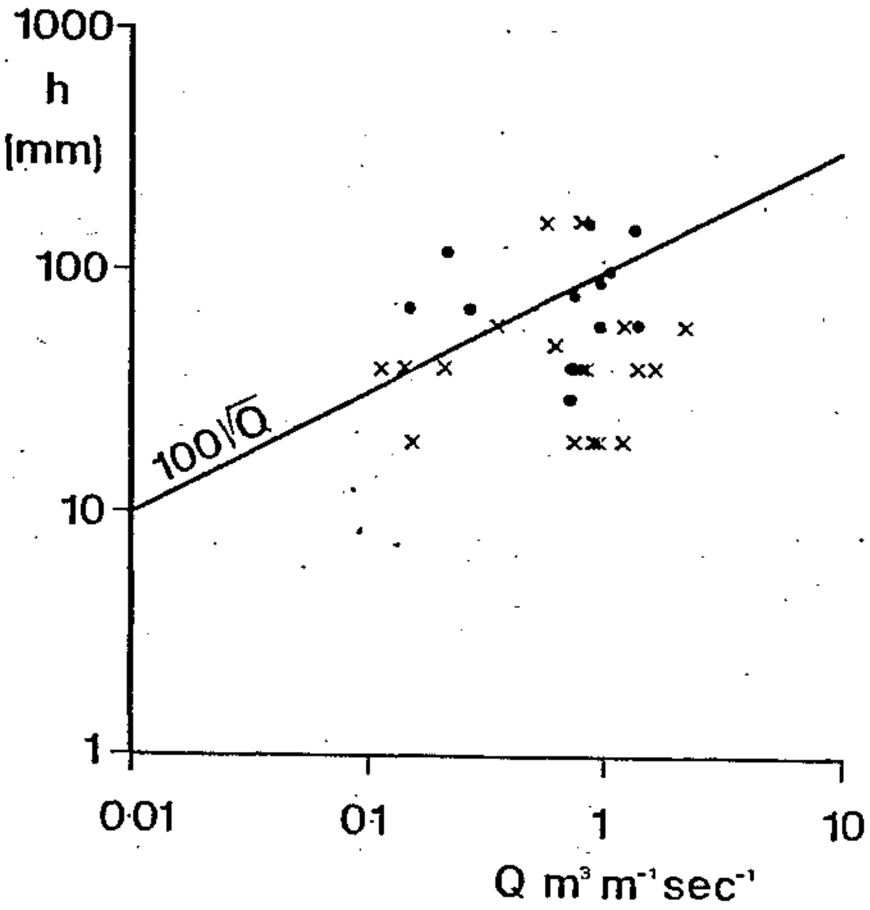

Fig. 4. Maximum scour depth (h) as a function of discharge per metre bed width (Q) . • = G.Eggleshope Beck, X = Carl Beck. Regression line from Emmett & Leopold (1965).

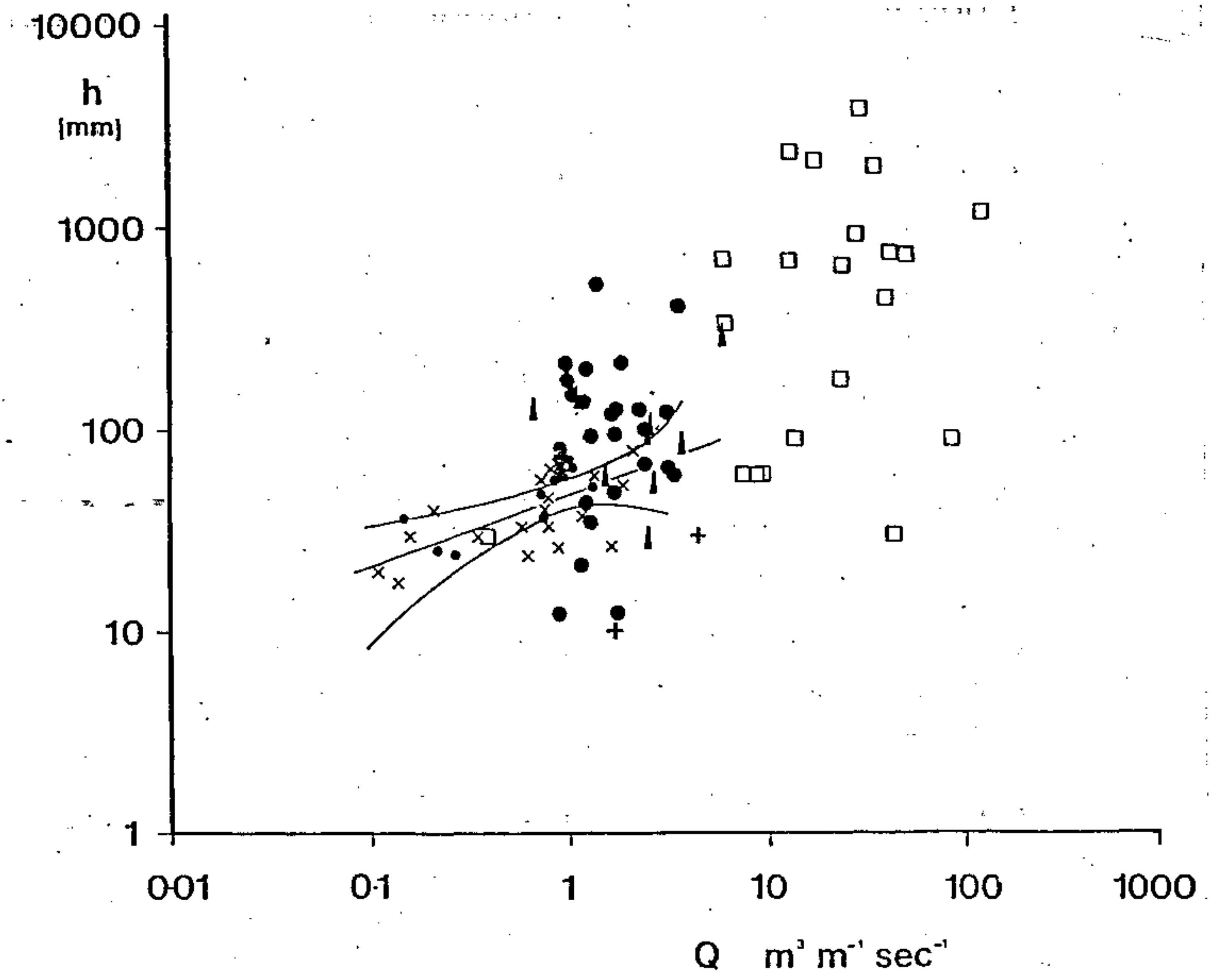

Fig. 5. Mean depth of deposition (h) as a function of discharge per metre bed width (Q). • = G. Eggleshope Beck, X = Carl Beck, 0 = Culbertson & Dawdy - sand, Δ = Culbertson & Dawdy - sand and gravel, • = Hickey - cobbles, + = Slaymaker - gravel. Regression line and 95% confidence limits are for Equation (2).

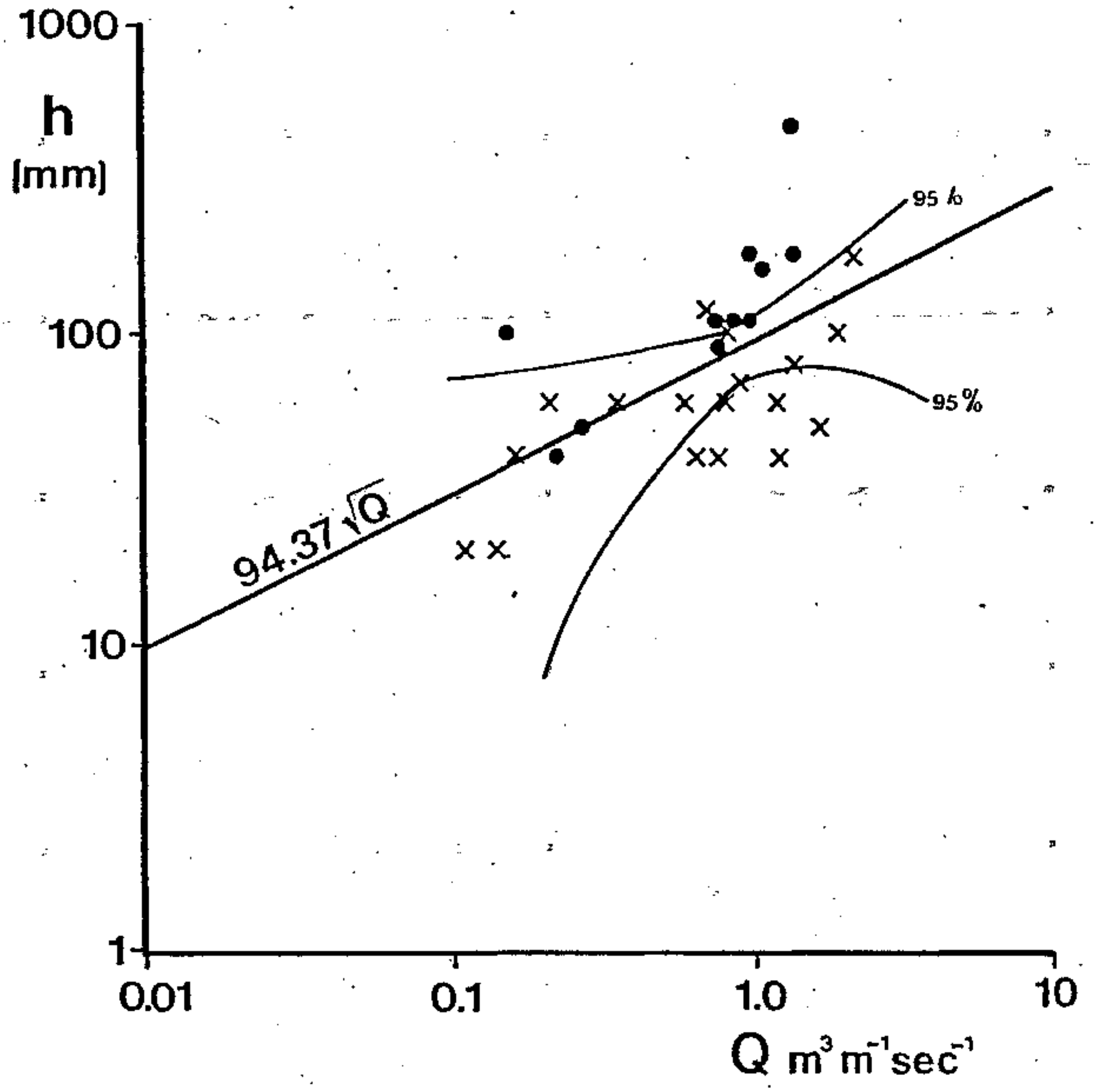

Fig. 6. Maximum depth of deposition as a function of discharge per metre bed width. • = G. Eggleshope Beck, X - Carl Beck.

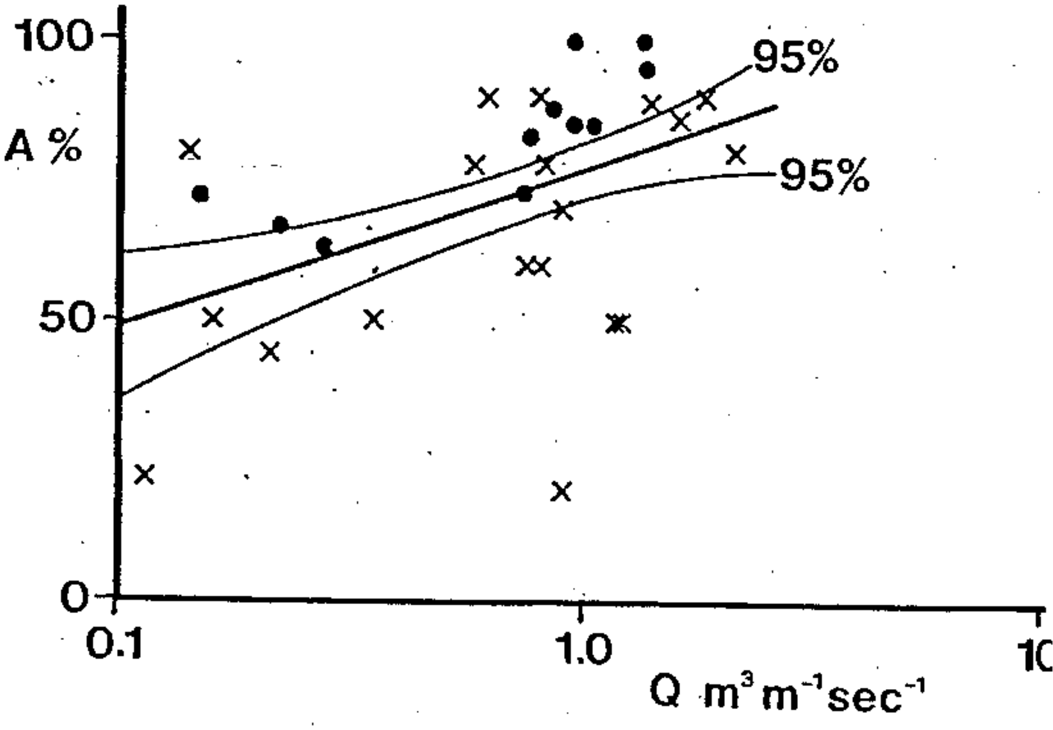

Fig. 7. Percentage of the bed area showing scour or deposition (A) as a function of discharge per metre bed width (Q). • = G. Eggleshope Beck, X = Carl Beck.

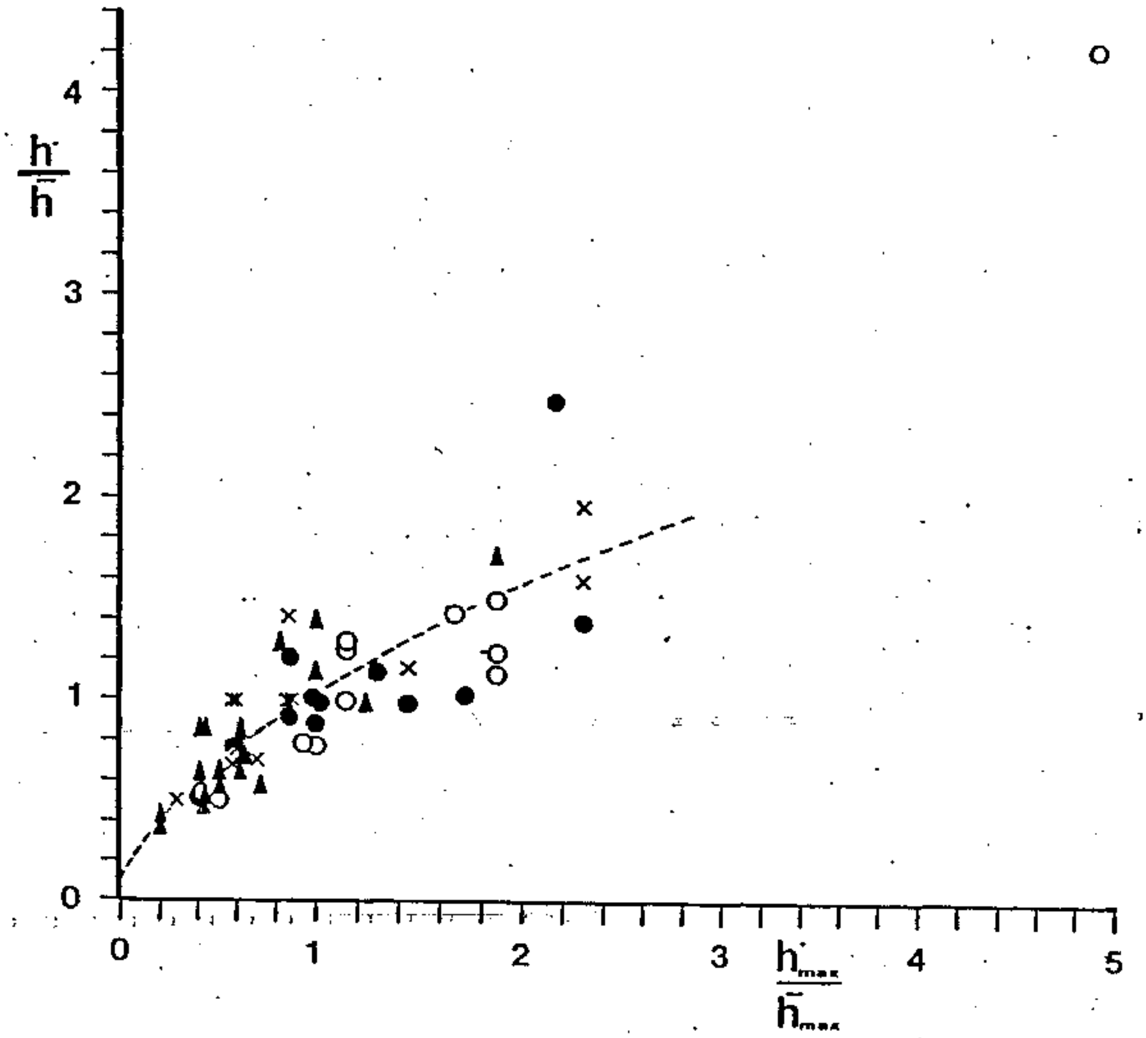

Fig. 8. Relationship between non-dimensional mean scour or fill ($h'_{mean}/\bar{h}_{mean}$) and maximum scour or fill ($h'_{max}/\bar{h}_{max}$). ● = Scour G. Eggleshope Beck, O = Deposition G. Eggleshope Beck, X = Scour Carl Beck, Δ = Deposition Carl Beck. The pecked line represents Equatio (9).

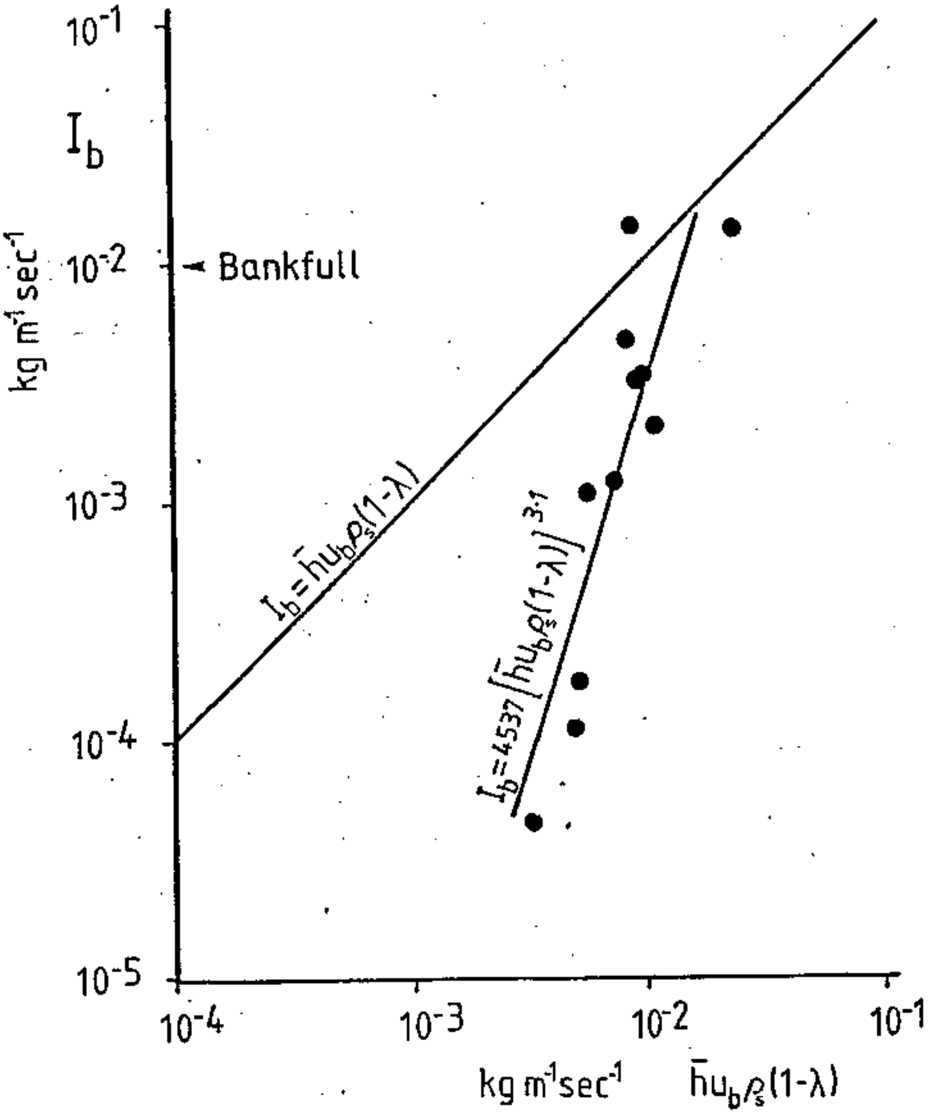

Fig. 9. Relationship between the bedload transport rate, Ib, and the active layer "transport rate", $\bar{h}\ u_b\ \rho_s\ (1 - \lambda)$. See text for details.

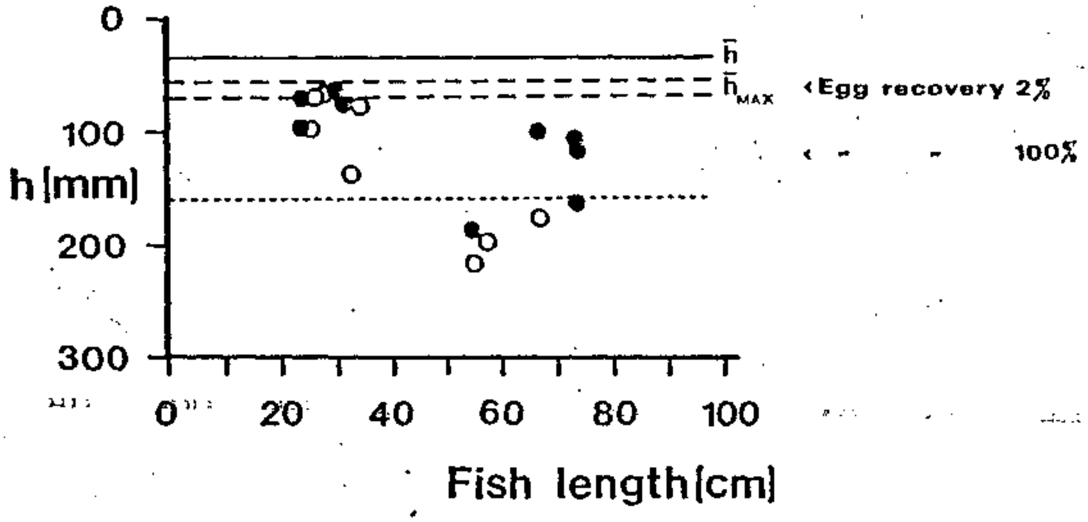

Fig. 10. Relationship between female fish fork length, depth of egg pocket and scour depths. Data for fish lengths greater than 40 cm are for sea trout/salmon. Remaining data are for brown trout. Open data points from Ottaway <u>et al</u> (1981), closed data points are unpublished data (present contract phase). The solid horizontal line is the mean depth of scour (h) for 32 floods, the thickness of the line represents twice the standard error of the estimate. The two dashed lines represent the limits of the standard error about the mean value of maximum scour depth (h_{max}) for 32 floods. The dotted line represents the maximum scour depth recorded. Also shown are the percentage of artificial fish eggs recovered at given depths by Ottaway; <u>et al</u>. (1981) after a season of floods.