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Survey of Physical Characteristics of Salmon Spawning Riffles in the River North Tyne

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CONTENTS

Symbols

(All calculations in metric units)

$\bar{U}_c$	critical mean velocity
h	depth of flow
d	grain size
γ_s^1	specific weight of bed material
ρ	fluid mass density
$\bar{Q}_c$	critical mean discharge
W	stream flow width
g	acceleration due to gravity

Summary

(i) The gravels within the spawning riffles examined are within the 'Good' category of Fraser (1975). The small percentage of fine material (< 1 mm.) within each gravel bed is notable and may be related to flushing experienced in riffle areas where cross-sectional areas are restricted and gradients steepen.

(ii) Flow velocities are maintained at the four salmon spawning riffles examined, for a wide range of discharges. Potential spawning areas are maintained in those riffles with mid-channel bars in comparison to a riffle examined on a channel bend.

(iii) No progressive change in bed material mean or modal grain size occurs, at present, within a distance of 26 km. below the dam site at Yarrow Moor. Below 26 km. there is a progressive reduction in the modal grain size and an improvement in sorting.

(iv) Typical pre-impoundment cross-sections of the channel of the River North Tyne are recorded for the four selected riffles.

(v) It is not anticipated that gravel beds within the River North Tyne will achieve mobility under less than bankfull discharge except in conditions of artificial 'freshet' releases. If siltation became a problem, the form that the hydrograph of these freshets should take to rework gravels in the spawning beds, and the frequency of discharges of this nature would need to be further evaluated within the management policy of the Kielder reservoir.

(vi) Qualitative assessments, by experienced personnel, of salmon spawning riffles are adequate for general management decisisons, but should be supplemented by detailed quantitative scientific investigations.

(vii) At spawning time a discharge greater than 30 to 40 $m^3 sec^{-1}$ would be disadvantageous in terms of excessive velocities and depths for successful spawning. Low discharges only become limiting in terms of greatly reducing available spawning area below 10 $m^3 sec^{-1}$. Within these constraints no adverse effects are anticipated on the spawning ability of salmon in the 48 km. study reach under regulated conditions. It is recommended that during the spawning season a 'maintenance' discharge of 10 $m^3 sec^{-1}$ would be desirable and spawning 'enhancement' discharge of 10 - 20 $m^3 sec^{-1}$ preferable.

Kielder Survey, March 1978

1.0 Introduction

This report summarizes, briefly, the results of a survey of salmonid spawning riffles on the River North Tyne, in a 42 km. reach below the Kielder dam site at Yarrow Moor. Dam closure will result in the restriction of spawning salmonids to those spawning areas below the dam; further, regulation will have some effect upon the flow rates and water levels over the spawning riffles as well as potentially resulting in changes in channel hydraulic geometry, and hence riffle morphology, that may be beneficial or deleterious to the spawning success of Atlantic salmon (Salmo salar L.).

1.1 Project design

The primary aim was to assess the available spawning area under differing flow conditions; i.e., velocity, depth as related to the bathymetry, discharge and the suitability of the gravels for spawning.

Although detailed quantitative information is recorded, the assessment is in some degree subjective, this is due to the generally insufficient published information on the spawning requirements of Atlantic salmon. Because of this shortcoming the assessment is related to conclusions drawn with respect to generalized requirements that are common to most salmon genera (Fraser 1975).

Specifically, seven main aims can be identified, these are:-

(i) Characterize the suitability of the spawning gravels in the River North Tyne for selected spawning riffles.

(ii) Relate monitored flow velocities and available spawning gravel to Northumbrian Water Authority data for discharge through the River North Tyne at Tarset foot-bridge gauging station, in order that predictions may be made from gauging records as to the hydraulic climate experienced over a spawning riffle for a given discharge.

(iii) Record the present pre-impoundment distribution of gravel sizes in a 42 km. reach of the River North Tyne below the dam site, in order to compare changes in gravel size and composition following impoundment, within the river generally and more specifically within spawning riffles.

(iv) Record typical cross-sections of spawning riffles to compare changes in riffle geometry following any adjustments of the fluvial hydraulic geometry following impoundment.

(v) Predict possible gravel movement under given discharges for management following impoundment.

(vi) 'Compare' qualitative biological assessment (by experienced N.W.A. personnel) to the monitored quantitative physical assessments of riffle quality achieved in the present investigation.

(vii) Suggest limiting discharges that might be favourably utilized by the N.W.A. at the time of salmon spawning to enhance spawning success.

This survey should be repeated some years after impoundment in order to record changes in the characteristics of spawning riffles and to check the validity of the present conclusions. The results of this investigation should yield information relevant to the management of further impoundment schemes on rivers frequented by spawning salmonids.

2.0 Methodology

2.1 Bathymetric survey

Four spawning riffles were surveyed by levelling along transects normal to the main stream line in order to obtain detailed bathymetric information at these stations. Details are appended (Appendix 1).

2.2 Gravel sampling

A total of sixty-three gravel samples were obtained for granulometric analysis. The mean sample weight was 15.77 kg. (standard deviation 4.51 kg.). Samples were obtained using an open ended steel cylinder, 56 cm. in diameter and 43 cm. high, placed on the river bed so that the upper end of the cylinder was clear of the water surface. This produced a stilling basin within the cylinder allowing more effective sampling of the finer materials of the bed which tend to be washed away during sampling in a stream flow. Samples were dug out to a depth of 30 cm. Effective sampling could be achieved in water depths of 20 cm. with stream flows of 1.0 m sec^{-1}, or greater depths up to 35 cm. in areas of reduced flow. Samples were dried and split, through a standard set of frames, into the fractions $x > 150$ mm; 150 mm $< x >$ 25 mm; 25 mm $< x >$ 1 mm; $x < 1$ mm. Judicious choice of these intervals was made following a literature search for information with regard to generally suitable and unsuitable gravel mixes for salmon spawning (e.g. Burner, 1951; McNeil and Ahnell, 1964; Cooper, 1965; Burns, 1970). This information has recently been reviewed and summarized (Fraser, 1975) and supports earlier conclusions (Warner, 1953).

Selected samples representative of the average grain size distribution for individual riffles were split into a series of fractions at 1/3 ϕ ($\phi = -\log_2$ diam.) intervals up to 25 mm. Material coarser than 25 mm was sized by measuring the intermediate axes (Krumbein, 1941) with calipers and weighing individual clasts.

2.3 Stream flow velocities

Stream flow velocities at varying discharges were recorded using a hand-held Ott current meter. Readings were obtained in the main stream line on each occasion, and therefore are representative of the 'maximum' flow velocities achieved at individual stations. A series of readings were obtained in the vertical at 0.40 ('Surface') and 0.80 ('Near-bed') of the non-dimensional depth, and averaged for each depth.

3.0 Results

Table 1 summarizes the qualitative assessment of ten spawning riffles (in the 42 km. reach of the River North Tyne below the dam site at Yarrow Moor and above Bellingham town), for the years 1974 to 1977. This information was supplied by the Northumbrian Water Authority. The number of pairs of salmon known, or estimated, to have spawned at each riffle are indicated and a qualitative categorisation made dividing riffles into a series, 'Poor', 'Moderate', 'Good', and 'Very good' based upon the assessment by the local water bailiff.

Within the time and cost restraints of the survey four riffles were selected for detailed examination. These are Falstone Ford, Ridley Stokoe, Newton and Charlton riffles (Table 1), covering the range of spawning riffles 'Moderate' to 'Very good'. On the basis of discussions with the N.W.A. water bailiff, Newton riffle is perhaps the best spawning riffle within the 42 km. reach of the River North Tyne, whilst Falstone Ford is utilized irregularly. Throughout this report these riffles are referred to by their riffle number (see Table 1).

3.1 Spawning Gravels

Tables 2 to 5 reproduce the summary grain size data for individual riffles. In each case with reference to the summary conclusions presented by Fraser (1975) (Table 6), it would appear that each riffle, in terms of grading of the spawning gravel, may be regarded as 'Good' in Fraser's tripartite division. It is noticeable, however, that riffle 8, categorized as 'Very good' in the N.W.A. scheme has a reduced proportion of fines less than 1 mm in size (by weight) and a proportionately greater weight of material in the range 25 mm to 150 mm. These gravels are presumably marginally better for spawning.

Riffle 8 is unique amongst the riffles surveyed, in that there is an immediate source of gravel other than the movement of gravel into the reach from upstream. Bank erosion is only evident at riffle 8, where river gravel (scroll-bar) deposits are being reworked on the left bank. Rip-rap has been placed here to prevent erosion but is breached in several places.

Fig. 1 reproduces histograms of grain size distributions for riffle 8. Included is a representative sample from the river bank deposits (Fig. 1a); a typical grain size distribution for the bed material within the riffle (Fig. 1b) and an example of the grain size distribution of the 'armour' layer (Fig. 1c); the latter develops at the surface of the riffle deposits and consists of poorly imbricated, larger than average, clasts. It is clear from Fig. 1 that the material constituting the spawning bed environment (Fig. 1b) is very similar in size distribution to the immediate source material (bank deposits), except that finer materials have been winnowed out. The 'armour' layer (Fig. 1c) although consisting of somewhat larger clasts is poorly developed, indicative of a spawning bed environment which is fairly frequently reworked. This explains the relatively small percentage weight frequency of fines found in riffle 8.

In contrast, for example, riffle 1 which is only a 'Moderate' spawning riffle has a more developed armour layer (Fig. 2b) which indicates that the gravel in the beds is less frequently reworked and that surface clasts tend to be larger than average, which may be a factor in reducing the spawning utilization of this particular riffle.

Qualitative observations at other riffles tend to confirm the general principles outlined above. In 'Very Good' riffles there is no well developed armour layer and gravels are not compacted. In the 'Poor' to 'Moderate' riffles, gravels tend to be compacted and exhibit a degree of armouring by larger bed elements.

This may be a factor in the choice of spawning sites by salmon. Obviously other factors such as discharge through the reach and the associated velocities and depths may be controlling spawning requirements by their direct influence on the hydraulic climate, or indirectly by affecting gravel mobility and composition.

3.2 Stream flow velocities

Data for maximum averaged flow velocities (Table 7) are recorded for each of the selected riffles for a range of discharges[1], (Table 8) (as recorded by the N.W.A.), from 50 $m^3 sec^{-1}$ to 4 $m^3 sec^{-1}$.

The regression for the relationship between discharge (Q) and the average velocity (U) has been reproduced for data from each riffle (Fig. 3). The fit in the case of riffle 1 is not good but the general trend is indicated. Deviations from the regression lines tend to be obtained at lower discharges and are related to complex reaction of the flow field to a relatively changing bathymetry, during falling discharges. As discharges increase above 40 $m^3 sec^{-1}$ velocities tend to be progressively reduced at riffles 1 and 3. Alternative or more complex design equations would be necessary to predict relationships for discharges in excess of 40 $m^3 sec^{-1}$. Consequently the regression equation for riffle 3 is not fitted to the data point at $Q = 41.85$ $m^3 sec^{-1}$ and should not be used to extrapolate to discharges in excess of 35 $m^3 sec^{-1}$. Further data would be required before any predictions might

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1. Maximum discharge during the investigation corresponded to the approximate condition whereby water surface width equals the channel width. Further increase in discharge is achieved by increases in depth and velocity until bankful discharge is obtained approximately 100 $m^3 sec^{-1}$.

be made as to velocity-discharge relationships above this value.

The excellent coefficients of determination (r^2 values, Fig. 3) for the regression lines for riffles 8 and 9 suggest that velocities tend to be maintained and alter steadily throughout the range of discharges examined. A one-way analysis of variance (Freund, 1962) indicated that for the limited amount of data available there is no statistically significant difference in the relationships of one data set to another. However, if the statistical relationships do represent a real phenomenon then preferential selection of riffles 8 and 9 by spawning salmon possibly may be related to steady flow velocities maintained at varying discharges. Further data would be necessary to verify or reject this hypothesis. The diagram does, however, allow estimation of the flow velocities experienced at the selected riffles under given discharge values obtained from the N.W.A. continuous monitoring scheme. Velocities experienced, fall in the range 0.52 m sec^{-1} to 1.80 m sec^{-1} (Fig. 3). Details of the velocities recorded at each station are shown in Table 7. It is evident that near-bed velocities are frequently much reduced compared to the surface velocities, indicating considerable shear flow which may be related to drag over the rough boundary. Near-bed velocities occasionally exceed those under which salmon have commonly been observed to spawn. Fraser (1975) summarising earlier work indicated that minimum average velocities are typically of the order of 0.33 m sec^{-1}, and 0.79 m sec^{-1} is an average maximum. Average near-bed velocities in excess of 0.79 m sec^{-1} were recorded for discharges of 41.85 and 33.86 $m^3 sec^{-1}$ at riffles 1 and 3 and for discharges of 50.08 and 41.88 m^3 sec^{-1} for riffle 9. Within riffle 8 maximum velocities in excess of 0.79 m sec^{-1} were recorded for discharges as little as 9.31 $m^3 sec^{-1}$.

Clearly flow velocities may be excessive under the highest discharges observed, e.g. greater than 30 to 40 $m^3 sec^{-1}$. Under lower discharges, although velocities may be locally excessive in the main stream line they are unlikely to be a limiting factor in these spawning riffles as suitable areas of acceptable flow velocities exist laterally away from the main stream line.

3.3 Available spawning area

The potential available spawning area was calculated by considering the bathymetric data (Appendix 1 and Figs. 5 & 6) and the water depths associated with particular discharges for the four selected riffles. Areas of vegetated islands within cross-sections were discounted. Similarly areas of gravel inundated to a depth of less than 0.12 m or having depths in excess of 1.08 m were disregarded in the analysis as these are generally unsuitable for spawning (Fraser, 1975).

Fig. 4 records the available spawning area (A_s) under differing discharges (Q) for each riffle. Riffle 1 shows the least conservative retention of spawning area for falling discharges and this is related to its situation in a river bend with a well developed point bar on the right bank. Slight changes in discharge over a very low gradient bathymetry (Fig. 5) lead to rapid changes in the available spawning area. The irregular use by salmon of an otherwise acceptable riffle may reflect this 'instability' in the spawning environment.

It is interesting to note that riffles, 3, 8 and 9 occur in association with well developed 'stable' mid-channel bars (Figs. 5 & 6). These bars have become heavily vegetated; under all discharges less than approximately 40 m^3 sec^{-1}, the flow is confined within the channels on either side of islands. Under falling discharge conditions one channel is sub-dominant to the other and there is a preferential channelling of flow into a narrow cross-sectional area. This is particularly evident at riffle 8 where the 'main' channel exists on the left bank and is relatively narrow.

As a result, at riffle 8, although the maximum potential spawning area is less than at riffle 1 or riffle 9 (i.e. 3438 m^2 compared with 4115 and

4625 m^2, Table 8) the steep curve in Fig. 4 indicates that reduction in spawning area is of a conservative nature so that even under low discharge conditions, i.e. 3.95 $m^3 sec^{-1}$ (Table 8) the potential spawning area at riffle 8 is 2699 m^2 compared with riffle 1, 1075 m^2 and riffle 9, 2458 m^2. It is probably the conservative retention of spawning area, velocities and depths over riffle 8 that results in it being the best spawning riffle within the 42 km reach of the River North Tyne studied. The absence of larger armouring bed elements must also be attractive to spawning salmon.

3.4 Downstream distribution of gravel sizes

The pre-impoundment distribution of gravels throughout the whole 42 km reach was recorded, so that any changes following impoundment may be compared to the pre-impoundment conditions.

Fig. 7 details the modal and mean grain sizes of gravel samples collected at locations throughout the 42 km reach (Table 9) (only the bed elements coarser than 25 mm were considered in the analysis). There is no distinct change in the grain size distribution downstream until some 26 km below the dam site where the modal diameter of the clasts (and to some degree the mean grain size) decreases (Fig. 7). This is concommitant with a general increase in the channel bed width below Tyne bridge (NGR 783856). The visual characteristics of the bed are distinctive in the reaches above and below Tyne bridge. Upstream, large bed elements up to 60 cm (intermediate axis) are common, downstream gravels become better graded and this is reflected in the convergence of the values of the mean and modal grain sizes at a distance greater than 26 km (Fig. 7).

3.5 Critical tractive force

Neil (1967) reported on the incipient motion of large bed elements in streams and provided the following equation for motion:-

$$\frac{\rho \bar{U}_c^2}{g(\gamma_s^1 - \gamma)d} = 2.5 \left(\frac{h}{d} \right)^{0.20} \qquad (1)$$

which is related to a mean (cross-sectional) flow velocity. Baker and Ritter (1975) have similarly reviewed empirical data concerning the initiation of coarse bedload transport and related published information to the shear stress (kg m^{-2}) exerted on the bed by the stream flow. The latter parameter has been successfully used in sediment transport investigations (Graf, 1971), but in terms of general management policy it is expedient to relate initiation of gravel movement to a critical discharge. Virmani et al. (1973) related Neil's equation to a critical discharge, viz:-

$$\bar{Q}_c = 11.6Wh^{1.1} d^{0.40} \qquad (2)$$

and it is this relationship in conjunction with equation (1) which is utilized in this investigation.

The essentially well sorted gravel throughout the 43 km (Fig. 7) permits the choice of a modal grain diameter ($\bar{d}$) representative of the whole reach, i.e. 0.037 m. Table 10 records critical velocities, calculated from equation (1), necessary to entrain the modal bedsize material for varying flow depths. No allowance has been made for bed compaction and armouring. The latter, for example, may occur following incipient motion of particles on the surface of the gravel bed so that the sediment surface rapidly restabilizes.

The limiting condition of a loose bed is inherent in most models of initiation of gravel transport (Church 1972), and is a reasonable assumption in the case of the better quality spawning beds of interest here (see pp. 6). The values in Table 10, may be related to critical discharges, for example at riffle 1 at Falstone. This is the spawning riffle immediately below the dam site. Utilizing equation (2) the maximum discharge observed at riffle 1 during the survey (i.e. 41.85 $m^3 sec^{-1}$ 28.2.78) is considered as an example.

Values of W and h in equation (2) are respectively 37 m and 1.11 m. Under these limiting conditions general bed motion would not be expected until a discharge of 128.77 m^3sec^{-1} was achieved. The artificial control of W and h require increased velocities to move gravel, at high discharges. Low discharge flow may be shallow and rapid. In these conditions Bernoulli effects are maximized. Equation (2) does not contain any terms allowing for these, and cannot be regarded as accurate for discharges on the Tyne of less than approximately 10 m^3sec^{-1}. Under low discharge conditions limited gravel transport may be expected at relatively low values of bed shear stress. This should, however, be spatially and temporally restricted.

Even by allowing each parameter to adjust in an iterative manner to simulate the quasi-interdependence of parameters in the real environment it is clear that extensive gravel transport is an unlikely event within the range of discharges experienced in this investigation, and would occur most frequently under natural conditions with over-bank flood flows or sudden high velocity flood wave discharges contained within the channel course.

Extensive removal of gravel by regulated discharges following impoundment would therefore seem improbable. However, the occasional flood discharge, which at present may be responsible for reworking the spawning riffles, removing fines from the interstices of the modal lattice-work gravel population and preventing compaction and armouring, will be a rare event.

For example, reference to unpublished N.W.A. rating table data for discharges past the gauging station at Tarset suggests that limited scour might be expected for discharges exceeding 100 m^3sec^{-1} which would be over-bank flow conditions in restricted localities on the North Tyne. Daily discharge frequencies for the natural flow regime of the Tyne indicate that discharges equal to 100 m^3sec^{-1} only occur at present with a frequency of 0.06; following regulation this would be halved.

At present flood discharges of 140 m^3sec^{-1} have a return period of 3 months. It might be desirable to maintain discharges and return periods of this order following regulation in order to rework spawning gravels if siltation became a problem.

Spawning environments therefore might benefit from occasional artificial 'freshet' discharges in conjunction with other users' requirements; although it is unlikely that discharges of a magnitude sufficient to rework spawning beds are acceptable for other aspects of river management.

3.6 Qualitative versus quantitative assessment

In terms of the qualitative assessment of the four riffles surveyed in the course of investigation, the quantitative evidence would support the conclusions drawn by the N.W.A. water bailiff. Riffle 8 would seem to be the best spawning riffle from consideration of the monitored physical parameters. In this respect concerted qualitative assessments of riffle quality by equally experienced personnel would seem to be meaningful in terms of identifying critical reaches of the River North Tyne which should have special consideration, in terms of salmon spawning, in the event of any engineering works or other changes to the physical environment of the river, being promoted.

However, quantitative scientific investigations into physical characteristics of the spawning environment are still required to optimize management decisions.

4.0 Summary Conclusions

Conclusions are drawn with respect to the seven main aims identified above (pp. 1).

(i) The gravels within the spawning riffles examined in this investigation (Tables 2 - 5) are within the 'Good' category of Fraser (1975). The small percentage of fine material (< 1 mm) within each gravel bed is notable and may be related to flushing experienced in riffle areas where cross-sectional areas are restricted and gradients steepen.

(ii) Flow velocities are maintained at the four salmon spawning riffles examined, for a wide range of discharges (Fig. 3). Potential spawning areas are maintained in those riffles with mid-channel bars i.e. riffles, 3, 8 and 9, in comparison to the riffle examined on a channel bend, riffle 1 (Fig. 4). Riffle 8 exhibits the most conservative retention of spawning area during conditions of falling discharge, which may explain the large numbers of spawners which utilize the riffle annually (Table 1).

(iii) No progressive change in bed material mean or modal grain size occurs, at present, within a distance of 26 km below the dam site at Yarrow Moor. Below 26 km (i.e. Tyne bridge) there is a progressive reduction in the modal grain size and an improvement in sorting (Fig. 7).

(iv) Typical pre-impoundment cross-sections of the channel of the River North Tyne are shown for the four selected riffles (Figs. 5 & 6), further detailed bathymetric data are appended for reference (Appendix 1).

(v) It is not anticipated that gravel beds within the River North Tyne will achieve mobility under less than bankfull discharge except in conditions of artificial 'freshet' releases. If siltation became a problem, the form that the hydrograph of these freshets should take to rework gravels in the spawning beds, and the frequency of discharges of this nature would need to be further evaluated within the management policy of the Kielder reservoir.

(vi) Qualitative assessments, by experienced personnel, of salmon spawning riffles are adequate for general management decisions, but should be supplemented by detailed quantitative scientific investigations.

(vii) At spawning time a discharge greater than 30 to 40 $m^3 sec^{-1}$ would be disadvantageous in terms of excessive velocities and depths for successful spawning. Low discharges only become limiting in terms of greatly reducing available spawning area below 10 $m^3 sec^{-1}$. Within these constraints no adverse effects are anticipated on the spawning ability of salmon in the 42 km study reach under regulated conditions. It is recommended that during the spawning season a 'maintenance' discharge of 10 m^3sec^{-1} would be desirable and spawning 'enhancement' discharge of 10 - 20 m^3sec^{-1} preferable.

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References cited

(1) Baker, V.R., & Ritter, D.F., 1975. Geol. Soc. Amer. Bull., 86 : 975 - 978. 'Competence of rivers to transport coarse bedload material'.

(2) Burner, C.J., 1951. Fisheries Bull., Fish Wildl. Serv., Fisheries No. 61. 'Characteristics of spawning nests of Columbia River salmon'.

(3) Burns, J.W., 1970. Calif. Fish and Game, 56 (4) : 253 - 270. 'Spawning bed sedimentation studies in N. California'.

(4) Church, M., 1972. Canada Geol. Survey Bull. 216, 208 pp. Baffin Island sandurs : A study of arctic fluvial processes.

(5) Cooper, A.C., 1965. Int. Pac. Salmon Comm. Bull. 18 : 1 - 71. 'The effect of transported stream sediments on the survival of sockeye and pink salmon eggs and alevin'.

(6) Fraser, J.C., 1975. F.A.O. Fisheries Tech Paper No. 143. 'Determining discharges for fluvial resources'.

(7) Freund, J.E., 1962. Mathematical Statistics. Prentice Hall.

(8) Graf, W.H., 1971. Hydraulics of sediment transport. McGraw Hill.

(9) Krumbein, W.C., 1941. Jour. Sed. Petrology, 11 : 64 - 72. 'Measurement and geological significance of shape and roundness of sedimentary particles'.

(10) McNeil, W.J., & Ahnell, W.H., 1964. Spec. Scient. Rept. U.S. Fish Wildl. Serv., Fisheries No. 469. "Success of pink salmon spawning related to the size of spawning bed material'.

(11) Neil, C.R., 1967. 12th Congress Internat. Assoc. for Hyd. Res., Fort Collins : 46 - 54. 'Mean velocity criterion for scour of coarse uniform bed-material'.

(12) Virmani, Peterson & Watters, 1973. Proc. 21st Annual Hydraulics Div. Speciality conf., Montana, University, Bozeman Aug. 1973 : 73 - 84. 'Discharge, slope, bed element relations in streams'.

(13) Warner, G.H., 1953. Adm. Rept. Calif. Dept. Fish and Game : 5 pp 'The relationship between flow and available salmon spawning gravel on the Feather River below Nimbus Dam'.

Table 1

The number of Spawning Salmon Utilizing Spawning Riffles Annually

1977

	NGR (Sheets NY78/88)	Riffle No.	No. of Spawners	Qualitative Riffle Assessment*
Falstone Ford	722876	1	3 pairs?	Moderate
Stannersburn	727866	2	None	Poor
Ridley Stokoe	744858	3	6 pairs	Very good
Lynne Stream	756858	4	8 pairs?	Very good
Tarset Bridge	783856	5	None	Poor
Snabdaugh	789850	6	10 pairs?	Good
Carriteth	791845	7	6 pairs?	Good
Newton	799843	8	12 pairs	Very good
Charlton	806844	9	5 pairs	Good
Hesleyside	827835	10	4 pairs	Good

1976

	Riffle No.	No. of Spawners	Qualitative Riffle Assessment*
Falstone Ford	1	1 pair	Moderate
Stannersburn	2	None	Poor
Ridley Stokoe	3	4 pairs	Very good
Lynne Stream	4	5 pairs	Very good
Tarset Bridge	5	None	Poor
Snabdaugh	6	6 pairs	Good
Carriteth	7	1 pair	Good
Newton	8	8 pairs	Very good
Charlton	9	5 pairs	Good
Hesleyside	10	4 pairs	Good

* N.W.A. Water Bailiff's assessment.

Table 1 (continued)

No. of spawners annually

1975

	Riffle No.	No. of Spawners	Qualitative Riffle Assessment*
Falstone Ford	1	8 pairs	Moderate
Stannersburn	2	None	Poor
Ridley Stokoe	3	10 pairs	Very good
Lynne Stream	4	14 pairs	Very good
Tarset Bridge	5	None	Poor
Snabdaugh	6	13 pairs	Good
Carriteth	7	7 pairs	Good
Newton	8	18 pairs	Very good
Charlton	9	7 pairs	Good
Hesleyside	10	5 pairs	Good

1974

Falstone Ford	1	1 pair	Moderate
Stannersburn	2	None	Poor
Ridley Stokoe	3	5 pairs	Very good
Lynne Stream	4	3 pairs	Very good
Tarset Bridge	5	None	Poor
Snabdaugh	6	None	Good
Carriteth	7	1 pair	Good
Newton	8	5 pairs	Very good
Charlton	9	7 pairs	Good
Hesleyside	10	2 pairs	Good

* N.W.A. Water Bailiff's assessment.

Table 2

Gravel composition in spawning riffle

Size composition of gravel by weight (kg)

Riffle 1

Sample No.	Total wt (kg)	150 mm (kg)*	25 mm (kg)	1 mm (kg)	< 1 mm (kg)
1.1	21.79	-	16.31	4.83	0.65
1.2	16.32	-	16.12	2.99	0.21
1.3	14.57	-	10.58	3.46	0.53
1.4	16.54	-	12.72	3.24	0.58
1.5	18.23	-	14.86	2.78	0.59
1.6	19.00	-	15.74	2.70	0.56
1.7	20.56	10.43	7.53	2.13	0.47
1.8	20.78	4.56	11.44	4.23	0.55
1.9	22.16	-	17.96	3.85	0.35
$\bar{x}$ =	18.88	1.67	13.70	3.47	0.50
σ =	2.51	-	3.17	0.80	0.13
Percentage contribution of individual fractions		9%	71%	18%	3% Σ 100%

* Minimum grain size in each class interval. Minimum in each case is also the maximum of the next smaller size class.

Table 3

Gravel composition in spawning riffle

Size composition of gravel by weight (kg)

Riffle 3

Sample No.	Total wt (kg)	150 mm (kg)*	25 mm (kg)	1 mm (kg)	< 1 mm (kg)
3.1	19.44	-	17.38	1.97	0.09
3.2	21.66	-	18.07	3.41	0.18
3.3	15.91	-	14.50	1.41	0.00
3.4	20.33	-	16.76	3.48	0.09
3.5	20.47	-	17.65	2.67	0.15
3.6	14.27	-	12.49	1.76	0.02
3.7	15.44	3.60	10.04	1.75	0.05
3.8	10.97	-	8.82	1.99	0.16
3.9	17.45	-	12.87	4.34	0.24
3.10	19.15	3.32	13.19	2.52	0.12
3.11	17.13	-	13.16	3.68	0.29
3.12	20.47	-	15.71	4.41	0.35
3.13	10.17	-	8.55	1.57	0.05
3.14	10.78	-	9.81	0.96	0.01
3.15	10.87	-	8.39	2.33	0.15
$\bar{x}$ =	16.30	0.46	13.16	2.55	0.13
σ =	3.92		3.00	1.04	0.10
Percentage contribution of individual fractions		3%	81%	16%	0.8% Σ 100%

* Minimum grain size in each class interval. Minimum in each case is the maximum of the next smaller size class.

Table 4

Gravel composition in spawning riffle

Size composition of gravel by weight (kg)

Riffle 8

Sample No.	Total wt (kg)	150 mm (kg)*	25 mm (kg)	1 mm (kg)	<1 mm (kg)	
8A	13.7	-	13.52	0.15	0.10	
8B	15.07	-	14.05	1.02	0.00	
8.1	10.19	-	7.10	2.95	0.14	
8.2	13.69	-	11.87	1.67	0.15	
8.3	11.09	-	9.46	1.54	0.09	
8.4	9.13	-	8.01	1.10	0.02	
8.5	13.03	-	11.37	1.62	0.04	
8.6	11.64	-	10.18	1.44	0.02	
8.7	12.41	-	9.81	2.60	0.00	
8.8	20.30	-	17.76	2.43	0.11	
8.9	16.61	-	15.61	0.98	0.02	
8.10	15.17	-	14.04	1.09	0.04	
8.11	13.91	3.34	9.51	1.04	0.02	
$\bar{x}$ =	13.54	0.26	11.71	1.51	0.06	
σ =	2.81	-	3.00	0.74	0.05	
Percentage contribution of individual fractions		2%	87%	11%	0.4%	Σ 100%
Bank material sample	21.020	-	10.560	8.050	2.410	
		0%	50%	38%	11%	Σ 100%

* Minimum grain size in each class interval. Minimum in each case is the maximum of the next smaller size class.

Table 5

Gravel composition in spawning riffle

Size composition of gravel by weight (kg)

Riffle 9

Sample No.	Total wt (kg)	150 mm (kg)*	125 mm (kg)	1 mm (kg)	< 1 mm (kg)
9A	14.44	4.34	8.53	1.45	0.12
9.1	12.98	-	9.81	3.17	0.00
9.2	13.80	-	12.54	1.22	0.04
9.3	12.59	-	10.48	2.02	0.09
9.4	13.55	-	13.22	0.32	0.01
9.5	14.00	-	12.42	1.55	0.03
9.6	16.78	-	11.00	5.77	0.01
9.7	12.15	-	9.87	2.25	0.03
9.8	18.76	11.55	7.11	0.14	0.01
9.9	16.19	1.88	12.94	1.29	0.08
9.10	13.33	-	11.55	1.74	0.04
9.11	13.19	2.93	8.69	1.57	0.00
9.12	11.63	-	10.03	1.59	0.01
	$\bar{x}$ = 14.11	1.59	10.63	1.730	0.040
	σ = 1.93	-	1.8	1.40	0.40
		11%	76%	12%	0.29% Σ 100%

* Minimum grain size in each class interval. Minimum in each case is also the maximum of the next smaller size class.

Table 6

Suitability of gravel mixes for salmon spawning (adapted from Fraser 1975)

Gravel size (cm)		Good	Fair	Poor
Large	30 > x > 15	30% or less (by weight)	31 - 39	40% or more
Medium	15 > x > 7	40% or more " "	21 - 39	20% or less
Small	7 > x > 2	50% or less " "	51 - 79	80% or more
Fine	2 > x > 0.1	20% or less " "	21 - 39	40% or more
Sand + silts	x < 0.1	10% or less " "	11 - 19	20% or more

Table 7

Stream flow velocities (m s^{-1})

Time GMT	1015	0830	0830
Riffle No. 1	28/2/78	1/3/78	2/3/78
Surface	-	1.20	1.18
	0.97	1.34	1.09
	0.82	1.24	1.18
Bottom	0.89	0.93	0.62
	0.81	0.70	0.67
	-	0.70	0.60

Time GMT	0945	1000	1035
Riffle No. 3	28/2/78	28/2/78	1/3/78
Surface	0.70	1.24	1.96
	0.92	1.30	1.96
	0.73	1.20	1.90
Bottom	0.75	0.64	0.83
	0.78	0.70	0.94
	0.95	-	0.87

0845	0930	0830		0830	0815
3/3/78	4/3/78	5/3/78		6/3/78	7/3/78
0.94	0.86	0.87		0.92	0.93
1.08	0.94	0.89		0.94	1.02
1.04	0.91	0.87		0.95	0.97
0.39	0.38	0.31		0.59	0.33
0.48	0.37	0.29		0.54	0.20
0.45	0.35	0.32		0.58	0.44

0850	0905	0915	0900	0830	0830
2/3/78	3/3/78	4/3/78	5/3/78	6/3/78	7/3/78
1.30	1.32	1.09	0.86	0.67	0.64
1.34	1.26	1.04	0.88	0.71	0.63
1.36	1.29	1.00	0.88	0.69	0.68
0.89	0.68	0.61	0.46	0.57	0.35
1.00	0.83	0.55	0.45	0.55	0.42
1.01	0.73	0.63	0.53	0.56	0.38

Table 7 (Continued)

Time GMT		1315	1000	1500
Riffle No. 8		28/2/78	1/3/78	2/3/78
	)	1.82	1.96	1.61
Surface	)	1.76	2.06	1.79
	)	1.82	2.02	1.79
	)	1.35	0.95	0.58
Bottom	)	1.66	0.93	0.71
	)	-	0.95	0.51

Time GMT		1445	0940	1435
Riffle No. 9		28/2/78	1/3/78	2/3/78
	)	2.00	1.86	1.04
Surface	)	1.99	1.85	1.00
	)	1.96	1.82	1.05
	)	1.50	1.00	0.52
Bottom	)	1.50	1.15	0.40
	)	-	0.98	0.52

Stream flow velocities

1355	1600	0945	1200	0915
3/3/78	4/3/78	5/3/78	6/3/78	7/3/78
1.52	1.26	1.04	0.97	0.93
1.39	1.19	1.12	0.85	0.97
1.48	1.25	1.04	0.96	0.89
1.01	0.39	0.33	0.37	0.44
0.99	0.46	0.35	0.35	0.42
0.97	0.51	0.44	0.40	0.50

1530	1930	1145	0900
4/3/78	5/3/78	6/3/78	7/3/78
0.70	0.92	1.15	0.83
0.67	0.95	1.17	0.82
0.68	0.98	1.20	0.86
0.45	0.79	0.68	0.40
0.42	0.76	0.72	0.31
0.45	0.75	0.71	0.33

Table 8 Discharge[1]/spawning area relationships. Riffles 8 and 9 1978.

Date	Discharge (at 0900) $Q(m^3 sec^{-1})$	Spawning area available As (m^2)	
		Riffle 8	Riffle 9
28th February	50.08	3439	4625
1st March	41.88	3355	4328
2nd March	13.22	2991	3036
3rd March	11.44	2843	3000
4th March	8.93	2741	2906
5th March	6.48	2700	2633
6th March	4.92	2552	2327
7th March	4.94	2699	2458

Discharge[1]/spawning area relationships. Riffles 1 and 3 1978

Date	Discharge (at 0900) $Q(m^3 sec^{-1})$	Spawning area available As (m^2)	
		Riffle 1	Riffle 3
28th February	41.85	4115	2134
1st March	33.86	3840	1798
2nd March	18.59	2956	1412
3rd March	9.31	2205	970
4th March	7.15	1971	887
5th March	5.36	1788	804
6th March	3.98	1311	721
7th March	3.95	1075	591

1. Discharge records for estimating spawning areas (or velocities) at Riffles 1 and 2 are obtained from the neighbouring N.W.A. gauging station at Tarset (N. Tyne). Discharge records for estimates made for Riffles 8 and 9 are obtained by summing discharge records at Tarset (N. Tyne) and N.W.A. discharge records at Greenhaugh (Tarset Burn) the only major tributary between the Tarset gauging station and Riffles 8 and 9.

Table 9

GRAVEL SAMPLING POINTS   KIELDER SURVEY   MARCH 78

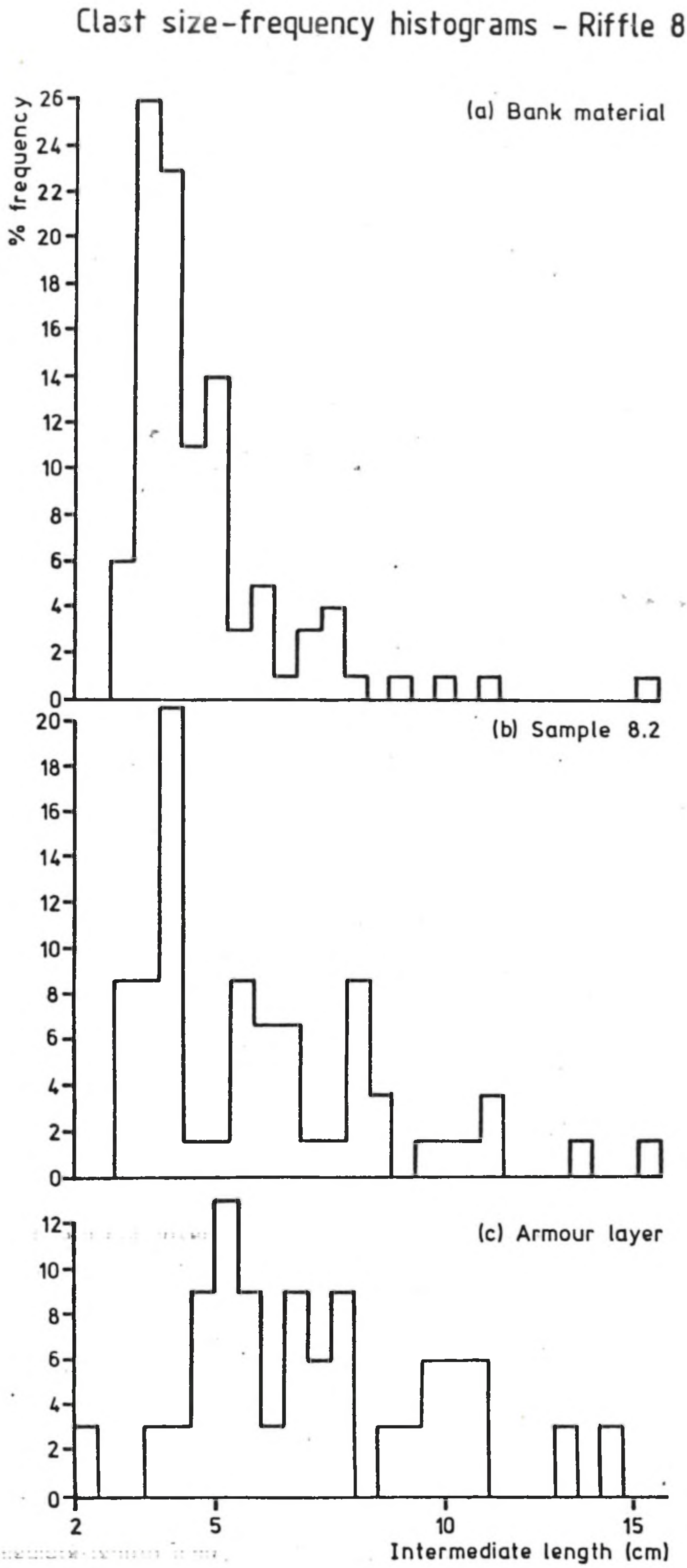
Name of sampling point	NGR	Distance downstream of dam (km)
Yarrow Moor	713878	1.6
Ugly Dub	717876	3.6
Falstone (Riffle 1)	722876	4.8
Falstone Bridge	723871	7.0
Smales Mouth Confluence	732859	10.5
Ridley Stokoe (Riffle 3)	744858	14.0
Llyne (Riffle 4)	756858	16.9
Tarset Foot Bridge	776862	18.9
Tyne Bridge (Riffle 5)	783856	26.2
Snabdaugh (Riffle 6)	789850	28.4
Carriteth (Riffle 7)	791845	29.8
Newton (Riffle 8)	797843	31.8
Charlton (Riffle 9)	806844	34.9
Hesleyside (Riffle 10)	821836	39.7
Dunterley (Riffle 11)	827835	41.4

Table 10

Critical tractive velocities for gravel of modal size 0.037 m in flows of differing depths

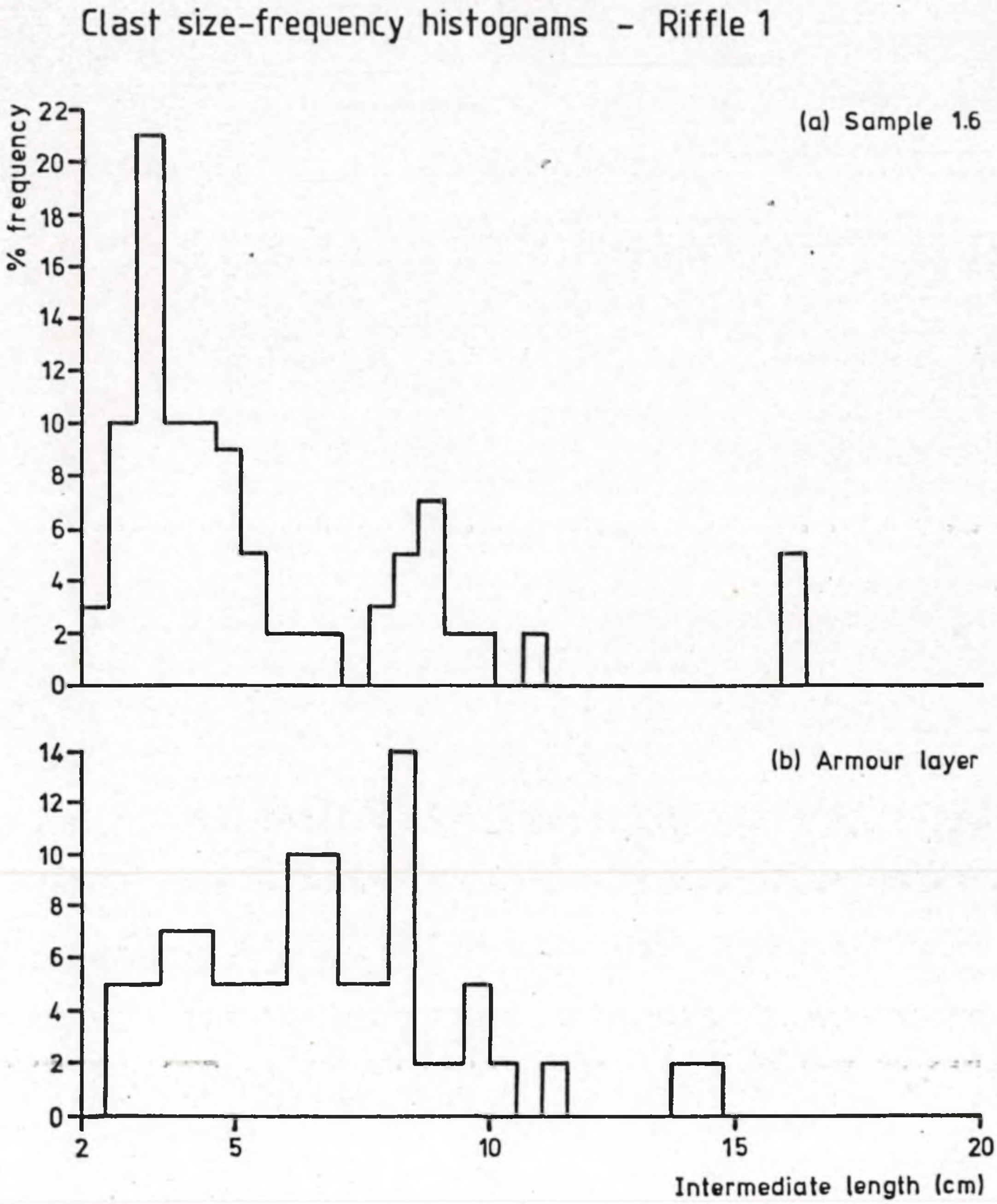
Depth ($\bar{h}$)	Velocity (U_c m sec^{-1})
0.20	1.45
0.50	1.60
1.00	1.72
1.50	1.77
2.00	1.82
2.50	1.86

Fig. 1.



Clast size-frequency histograms - Riffle 8
% frequency
(a) Bank material
0
2
4
6
8
10
12
14
16
18
20
22
24
26
(b) Sample 8.2
0
2
4
6
8
10
12
14
16
18
20
(c) Armour layer
0
2
4
6
8
10
12
2
5
10
15
Intermediate length (cm)

Fig. 2.



Clast size-frequency histograms - Riffle 1
(a) Sample 1.6
(b) Armour layer
% frequency
0
2
4
6
8
10
12
14
16
18
20
22
2
5
10
15
20
Intermediate length (cm)

FIG. 3. Kielder 3-78 Velocity - Discharge relationships for Riffles 1,3,8,9

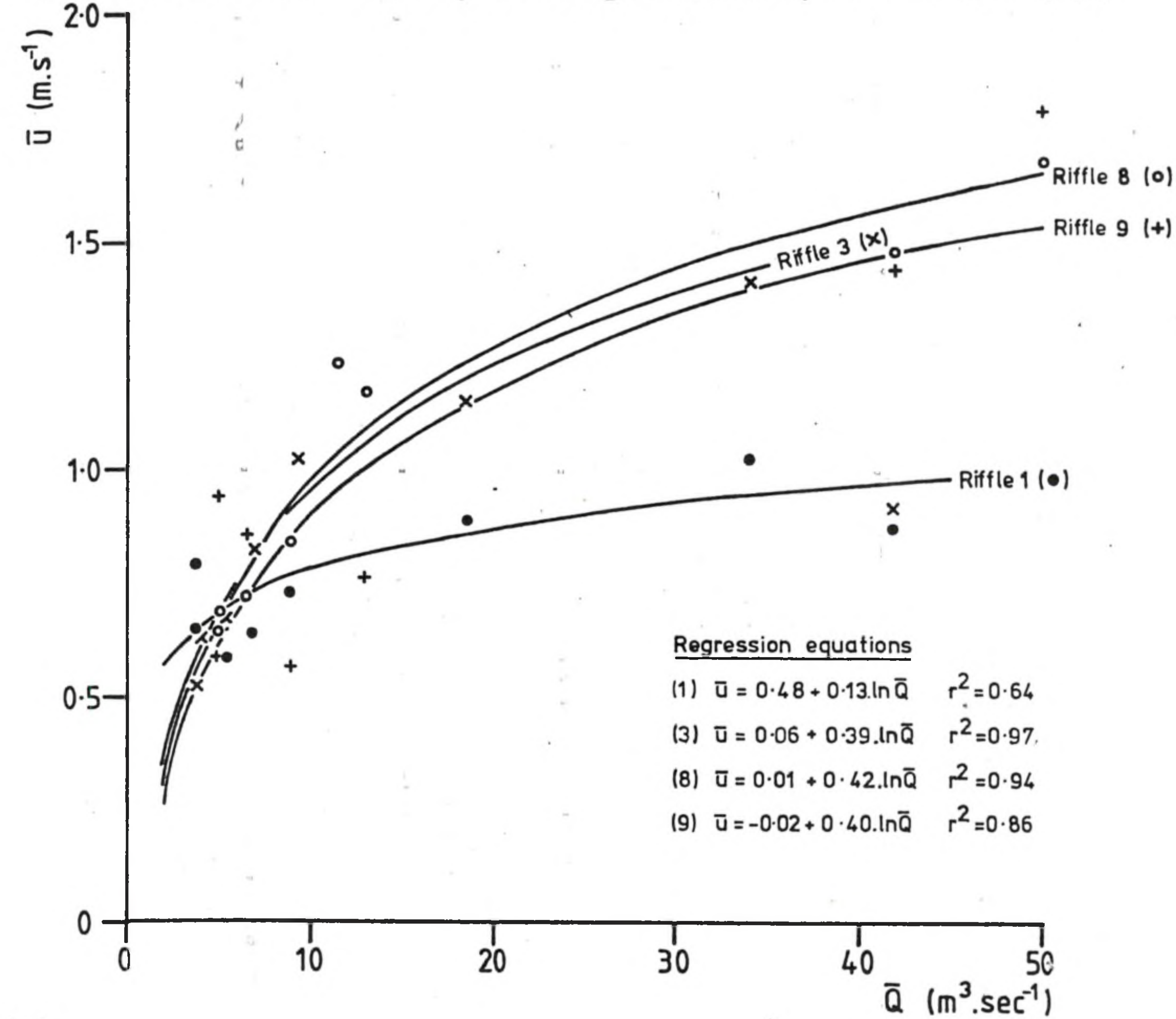
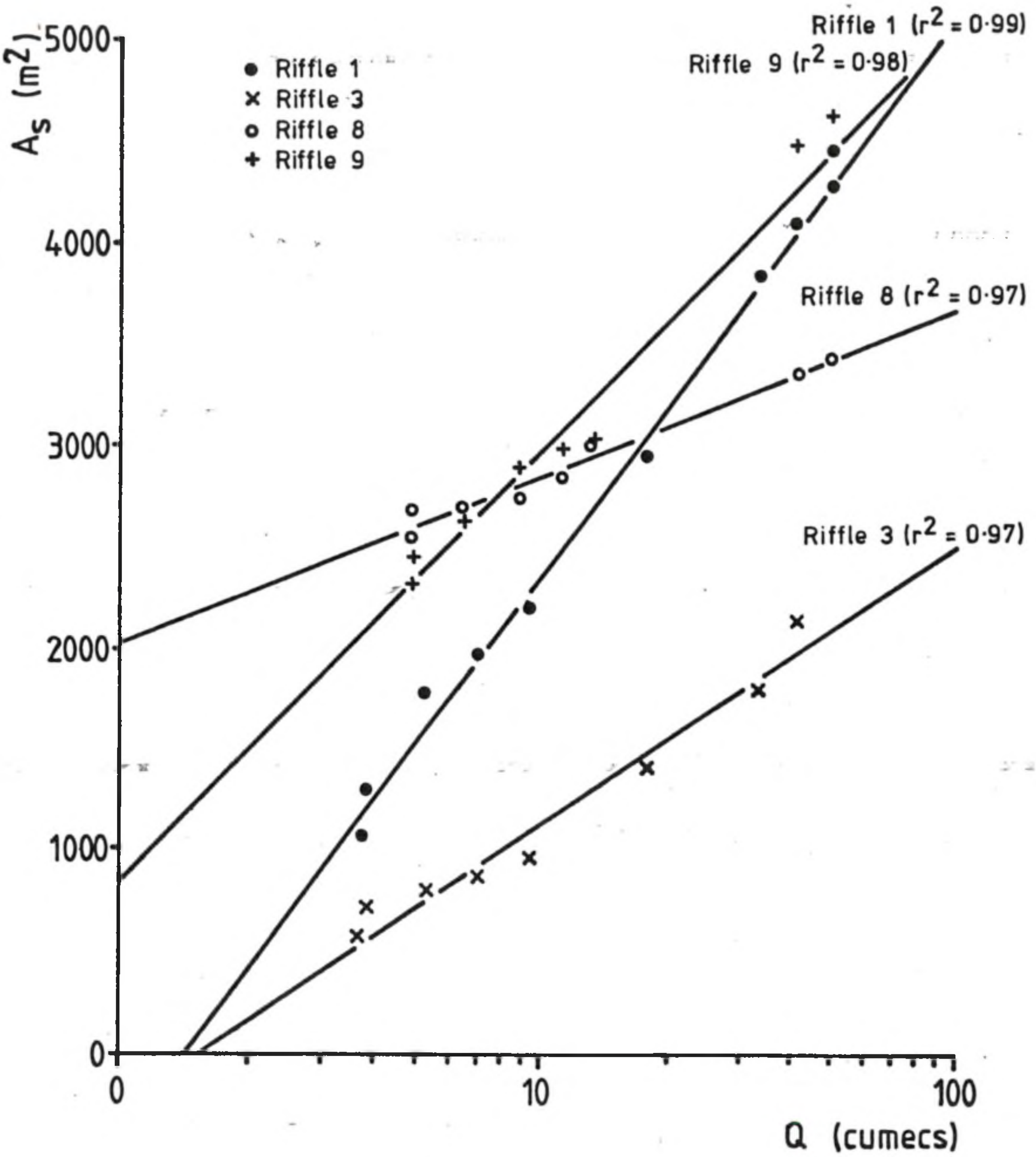


Fig. 3.

Fig. 4.

Kielder 3-78

Discharge-spawning area relationships for Riffles 1,3,8 & 9



Kielder 3-78 Bathymetric survey Representative cross-sections

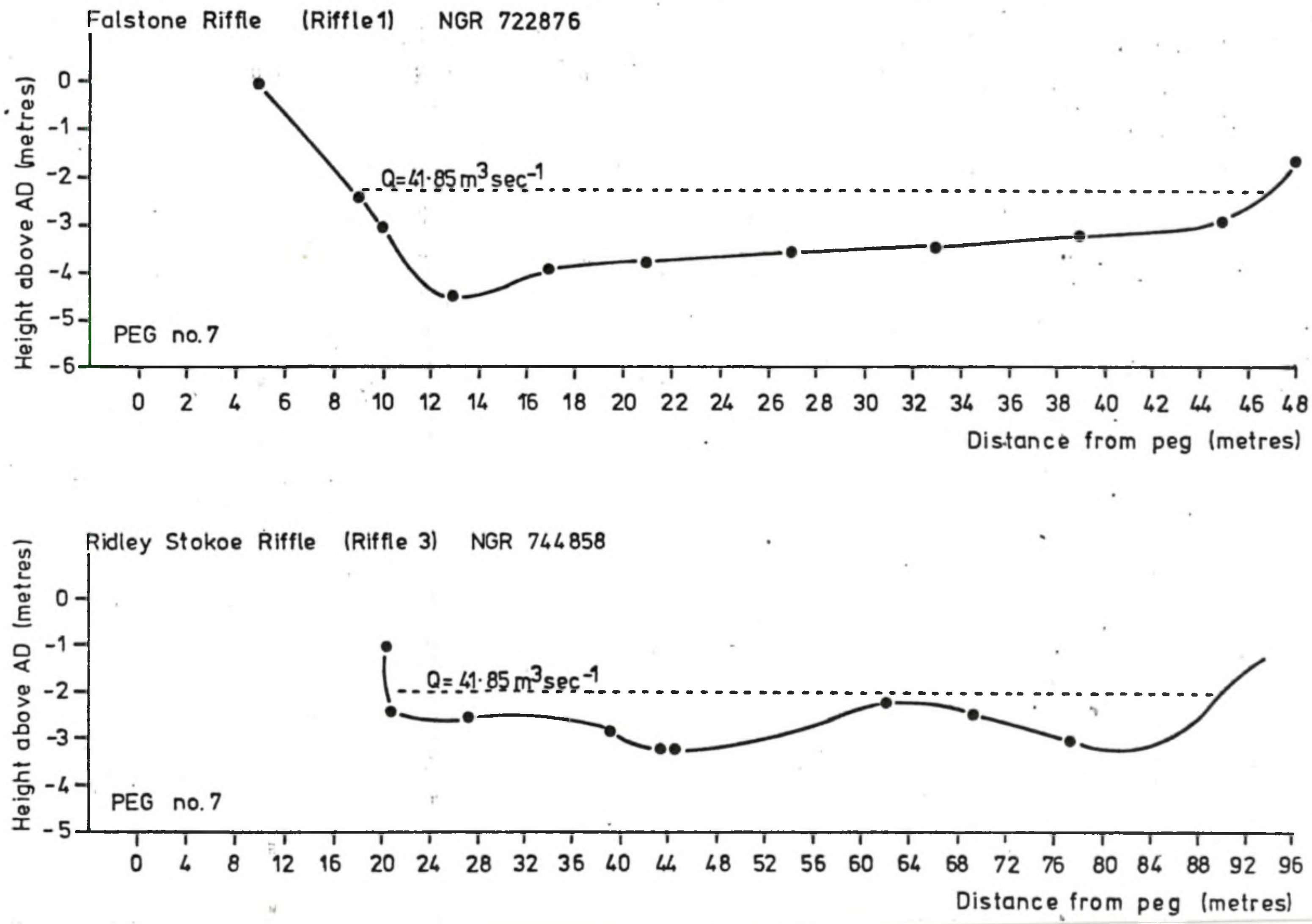


Fig.5

Kielder 3-78 Bathymetric survey Representative cross-sections

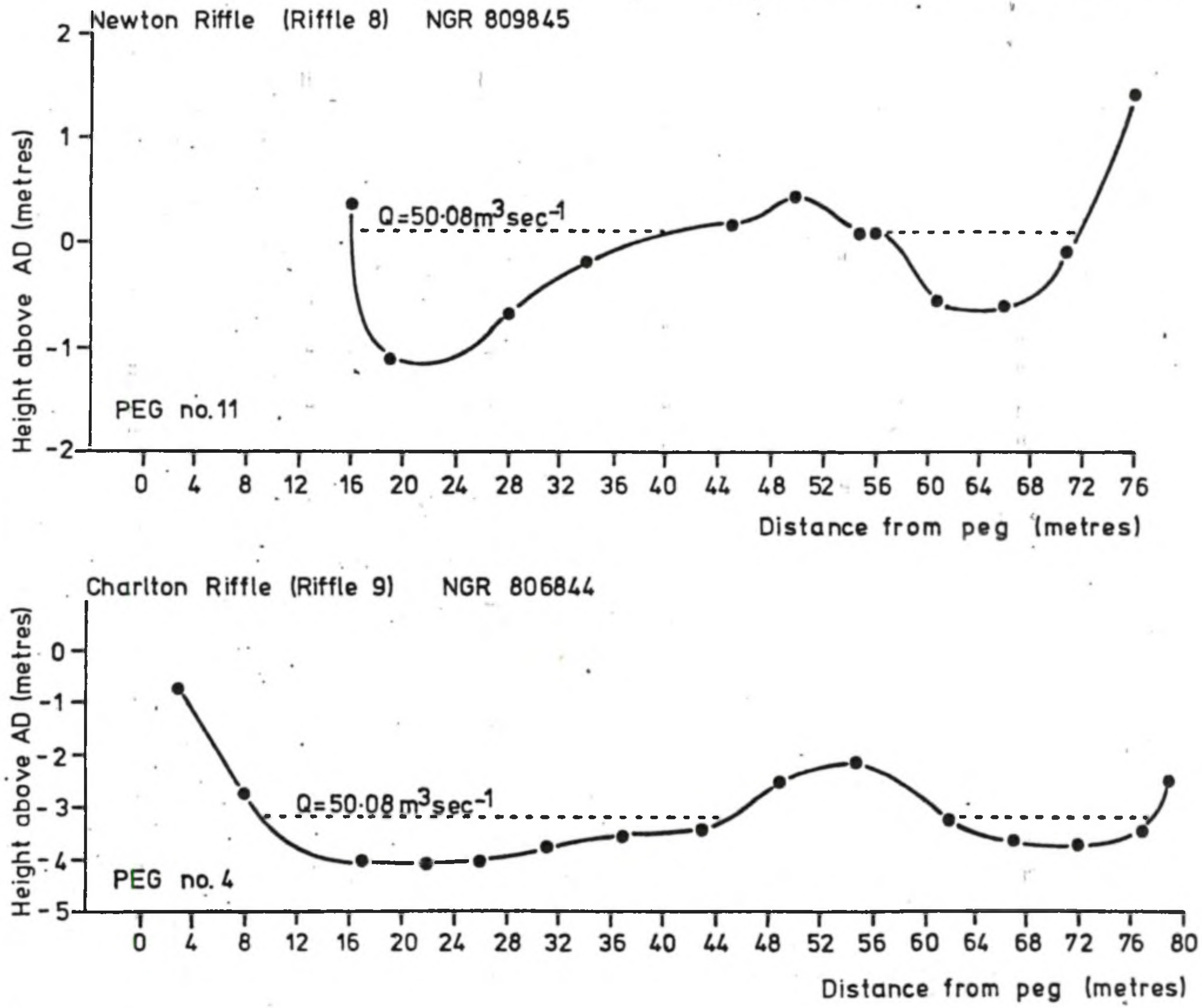


Fig.6

Kielder 3-78 Cobbles >25mm Averages & modal values of intermediate lengths

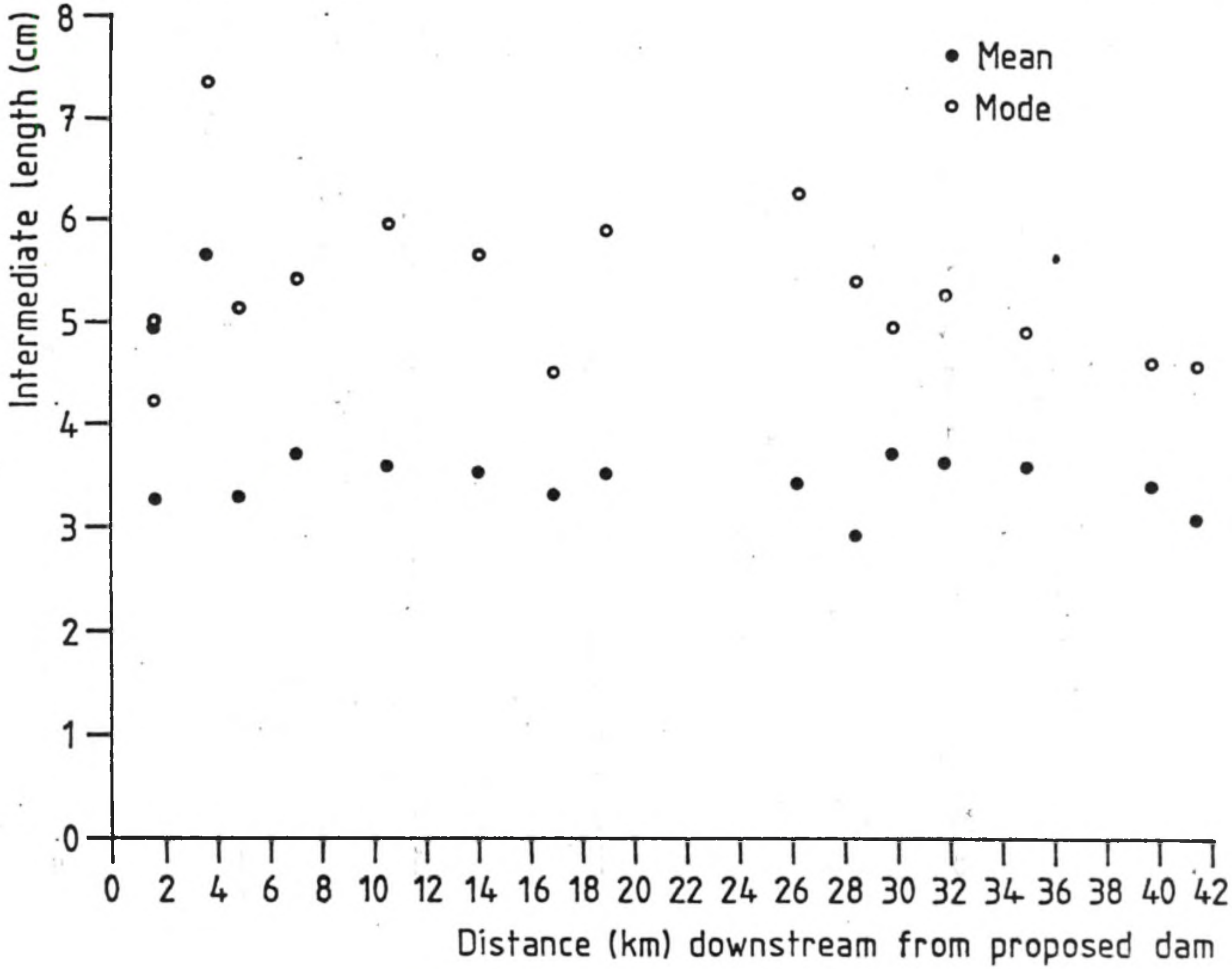


Fig.7

Appendix 1

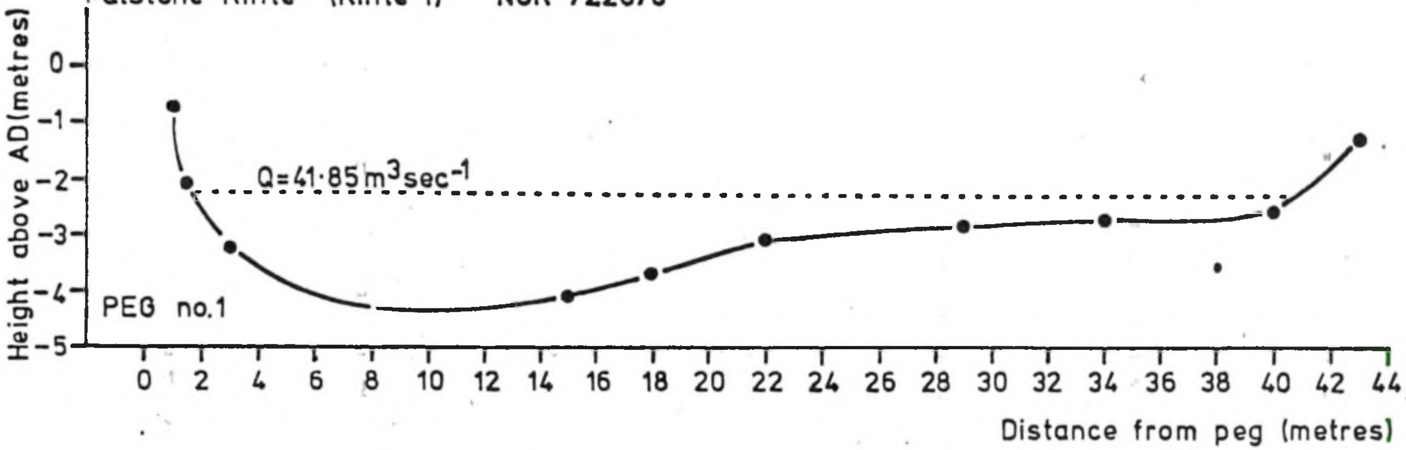
Bathymetric Survey

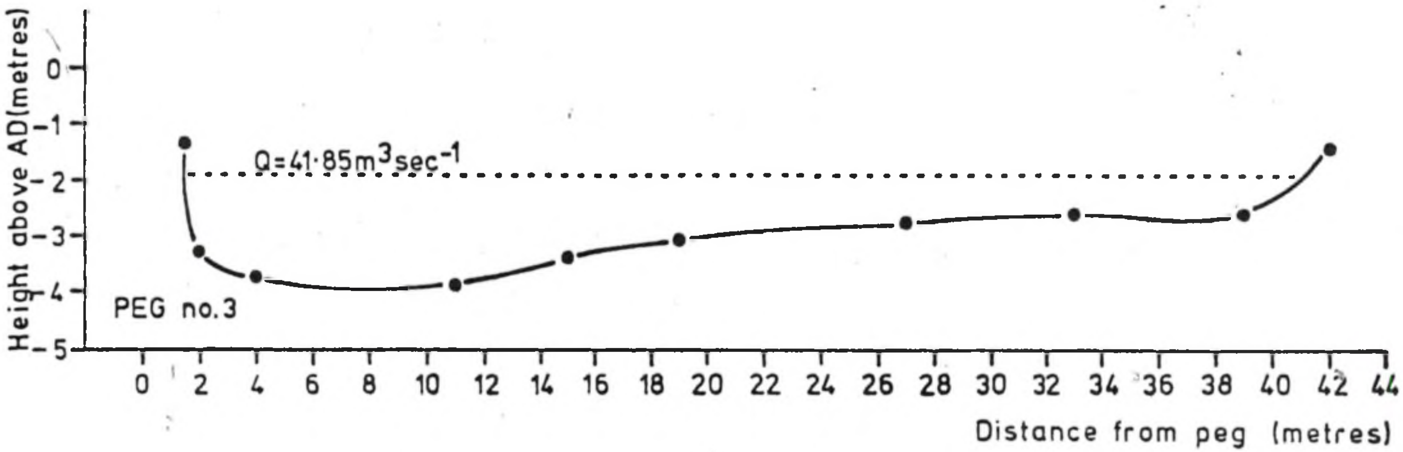
National Grid References	O.S. Sheets NY 78/88
Falstone riffle (Riffle 1)	NGR 722876
Ridley Stokoe riffle (Riffle 3)	NGR 744858
Newton riffle (Riffle 8)	NGR 797843
Charlton riffle (Riffle 9)	NGR 806844

A selection of representative transects across riffles are presented below. In each case the true left bank is on the left of the diagram.

Kielder 3-78 Bathymetric survey Representative cross-sections

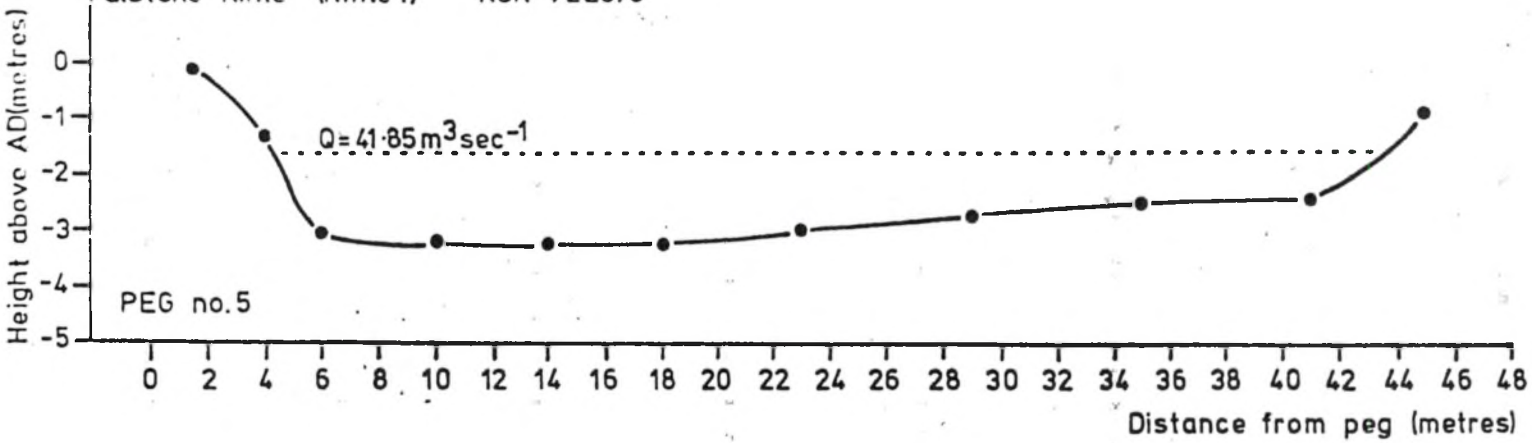
Falstone Riffle (Riffle 1) NGR 722876

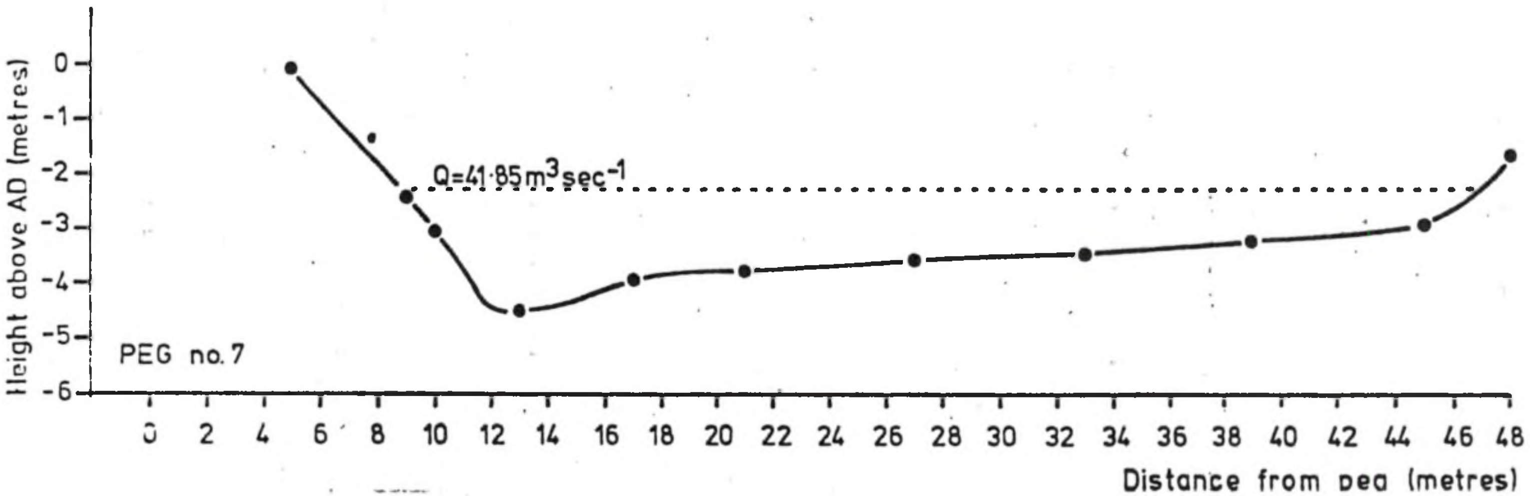




Kielder 3-78 Bathymetric survey Representative cross-sections

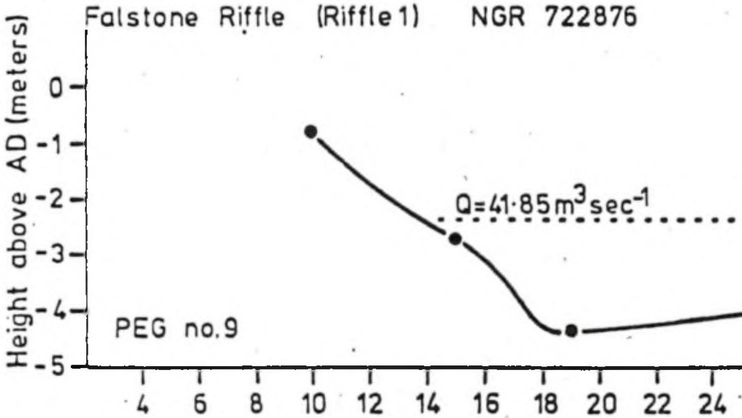
Falstone Riffle (Riffle 1) NGR 722876



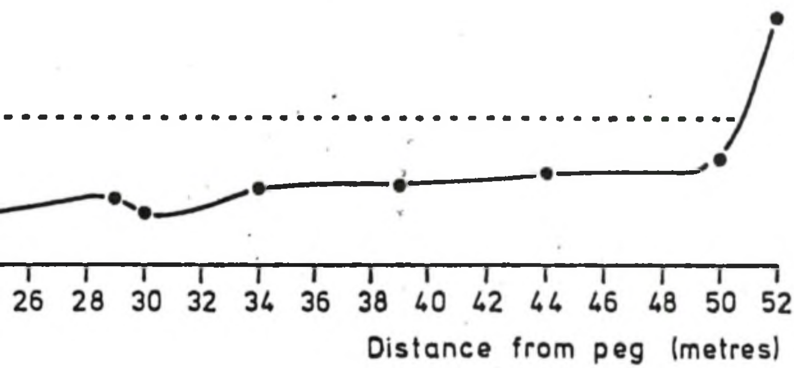


Kielder 3-78 Bathymetric survey

Falstone Riffle (Riffle 1) NGR 722876

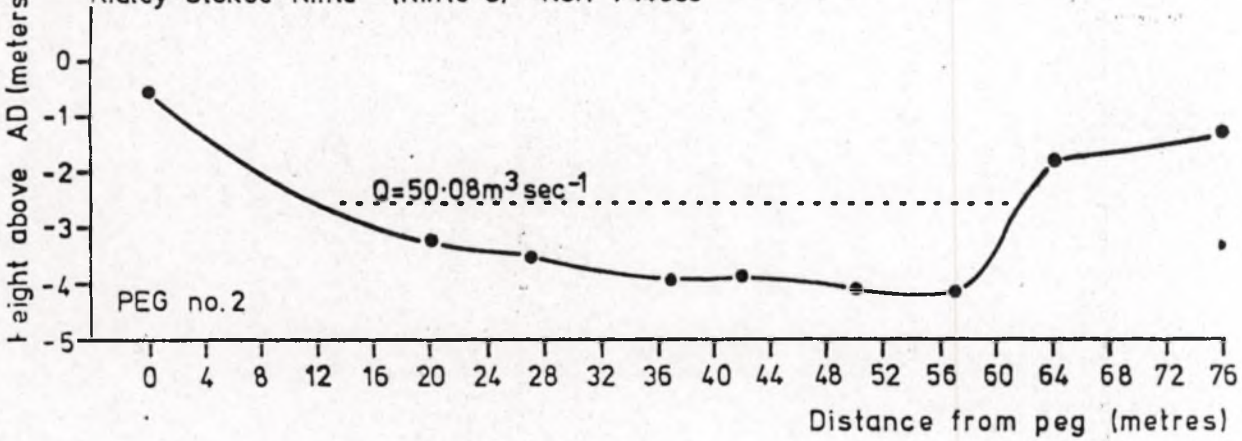


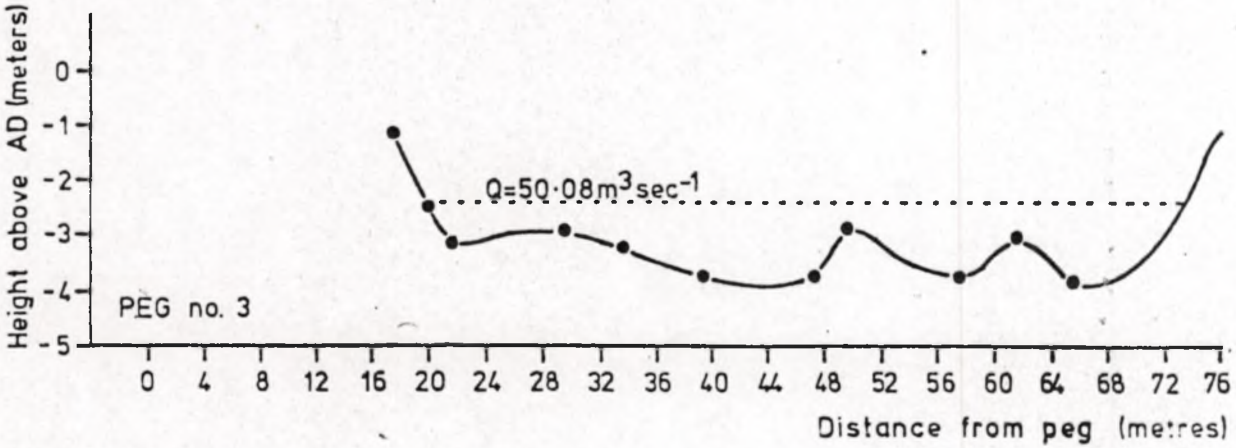
Representative cross-sections



Kielder 3-78 Bathymetric survey Representative cross-sections

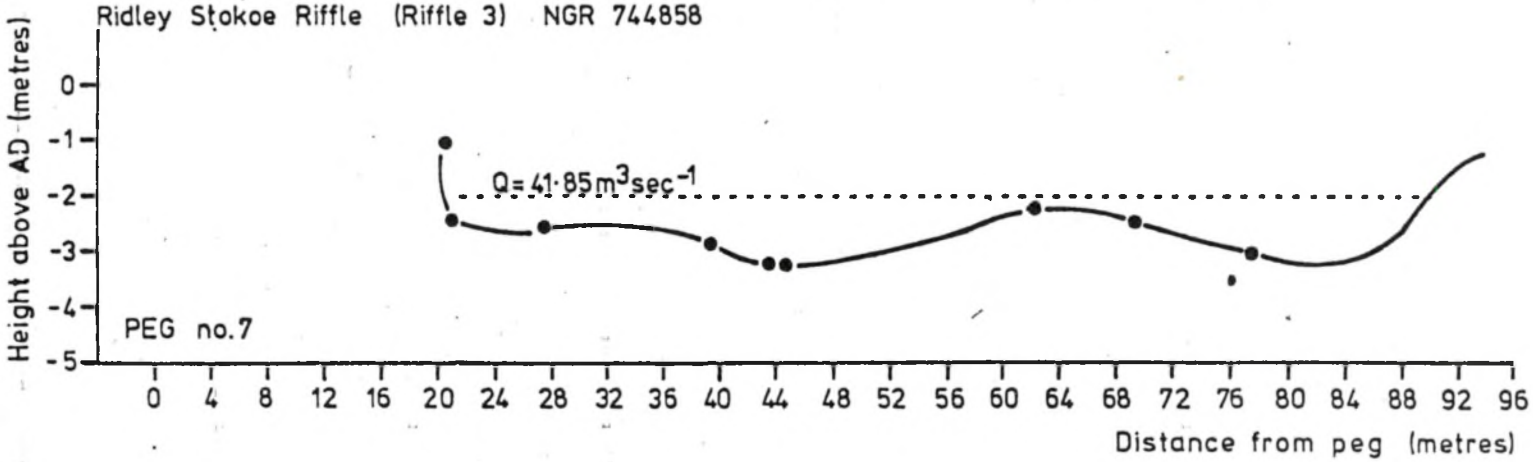
Ridley Stokoe Riffle (Riffle 3) NGR 744858

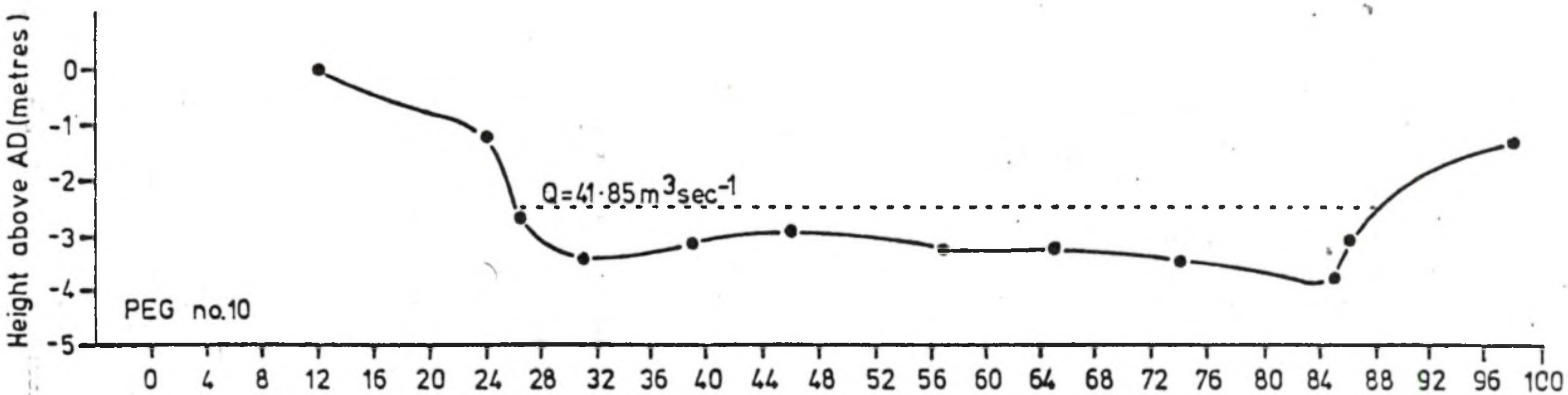




Kielder 3-78 Bathymetric survey Representative cross-sections

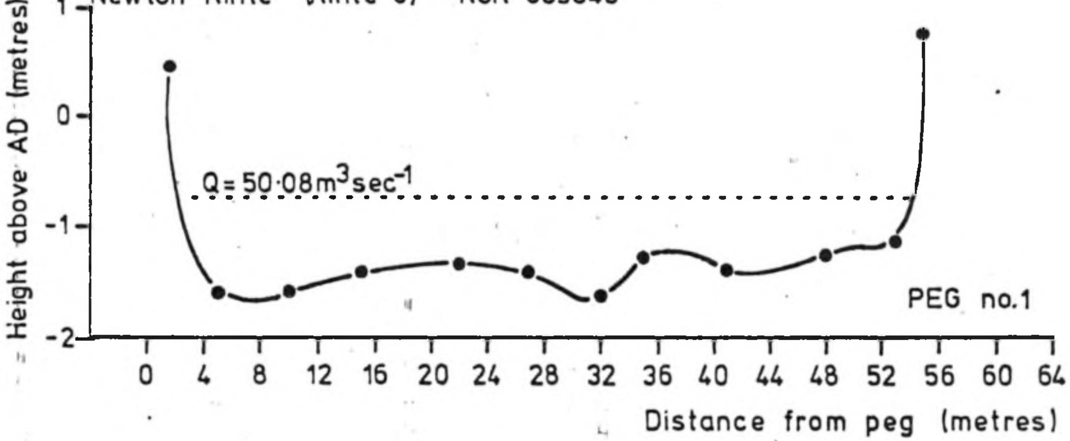
Ridley Stokoe Riffle (Riffle 3) NGR 744858

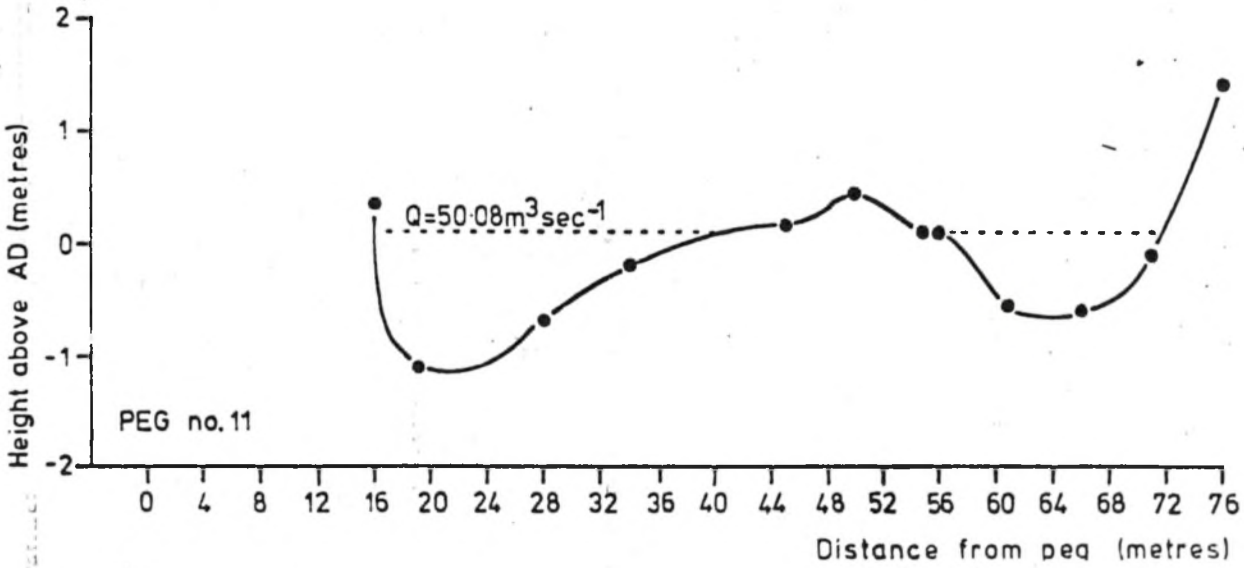




Kielder 3-78 Bathymetric survey Representative cross-sections

Newton Riffle (Riffle 8) NGR 809845





Kielder 3-78 Bathymetric survey Representative cross-sections

Charlton Riffle (Riffle 9) NGR 806844