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Turbidity and the suspended sediment load of the regulated River Tees.

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CONTENTS

SUMMARY

A discharge and turbidity record consisting of approximately 4000 paired data points, representative of an 11-year post-impoundment period, has been examined for the River Tees at Broken Scar, Darlington. A small amount of suspended sediment concentration data was also processed: these data are representative of both the pre-impoundment and post-impoundment sediment regime. Data were analysed (on a correlative basis) using structural and least-squares regression techniques, relating discharge, turbidity and suspended sediment concentration. The importance of sediment supply from upland areas in regulating suspended sediment at Broken Scar was considered, and the total annual load calculated. Finally, the statistical parameters of the suspended sediment distribution are related to the potential impact on salmonid fisheries. The following main conclusions were derived;

(1) Following the completion of Cow Green Reservoir the mean annual flood has been reduced by 14% and "bankful" discharge by 17%.

(2) Recurrence intervals for floods on the partial duration series have been approximately doubled.

(3) Suspended sediment data are log-normally distributed and values fall within the range 1.1 - 536 mg l^{-1} with a geometric mean of 5.1 mg 1^{-1}.

(4) Both sediment concentration and turbidity are positive functions of discharge raised to a power; the structural exponents being 1.17 and 1.05 respectively.

(5) Rating sub-divisions based on rising and falling hydrograph sub-sets did not improve the level of explanation given by considering the combined data. Seasonal subdivisions were only marginally more successful. There were no consistent rating shifts over the 11 year period.

(6) The influence of the 1975 drought was marked, reducing slope and intercept of seasonal ratings, except for the summer (June - August) period.

(7) Suspended sediment concentration is a negative exponential function of the one-day lag Soil Moisture Deficit. Soil Moisture Deficit is therefore a general index of sediment production in the upland catchment. Sediment is supply limited, at least up to an annual cumulative discharge of $6 \times 10^8 \ m^3 \ yr^{-1}$.

(8) Although pre- and post-impoundment sediment concentration discharge ratings were statistically significantly different, within 95% C.L. there was no significant change in the total annual suspended load following impoundment.

(9) Total suspended sediment discharge averaged over 11 years is 12957t yr^{-1} (15.83 $t \ km^{-2} \ yr^{-1}$) with no trend to reduced loads over the 11 year post-impoundment period.

(10) Spate events which occur less than 6% of the time are responsible for the transport of some 50% of the total load.

(11) The recorded levels of suspended sediment concentration are not likely to be detrimental to adult salmonids. However, the river bed is likely to be silted, and flushed only infrequently by flows with a return period of 2.2 yr. Thus potentially, silting could be detrimental to the survival of the young stages of salmonids in the R. Tees.

Notation

		S.I. Units
API	Antecedent Precipitation Index	mm
C.L.	Confidence Limits	-
C_s	Concentration of calibration suspension	$mg\ l^{-1}$
FTU	Formazin Turbidity Unit	$mg\ l^{-1}$
HER	Hydrologically Effective Rainfall	mm
No.	Number	-
Q	Instantaneous discharge	m^3s^{-1}
Q_s	Sediment discharge	$t\ d^{-1}$
Q_{tot}	Cumulative total annual discharge	$m^3\ yr^{-1}$
SMD	Soil Moisture Deficit	mm
SSC	Suspended Sediment Concentration in the river	$mg\ l^{-1}$
SSC_Q	Discharge weighted SSC	$mg\ l^{-1}$
T	Return period	yr
a	Regression constant	
b	Regression coefficient	
b_f	Best estimate of structural regression coefficient	
d.f.	degrees of freedom	
f	function	
p	probability level	
r^2	coefficient of determination	
s.e.	standard error	
$\bar{x}$	arithmetic mean	
x_g	geometric mean	
x_m	median, i.e. 50 percentile	
σ	standard deviation	
σ_g	geometric standard deviation	

Real number subscripts = Return period (T) in years. Integer subscrips = No. of lag days.

INTRODUCTION

The physical effects of river regulation in the U.K. by impoundments have attracted most attention from hydrologists and engineers concerned with predicting and maintaining discharge regimes for water supply. Recently additional interest has been focused on the consequent effects of flow manipulation (Armitage, 1980); for example, on temperature (Lavis & Smith, 1972), river channel morphology (Gregory & Park, 1974) and on the biota (Brooker, 1981). In addition Grimshaw & Lewin (1980), examining the effect of regulation on sediment yields, noted the paucity of data.

Data are needed because changes in suspended sediment load [1], both in terms of quality and quantity, may profoundly influence channel morphology and biota downstream of impoundments (Petts, 1979; Armitage, 1982). Usually the total load is reduced by a reservoir acting as an upstream sediment trap (Soltero et al., 1973) but the river may compensate by eroding the driver banks and bed downstream of the impoundment (Buma & Day, 1977). Where suspended sediment concentrations (SSC) are generally low and variable however (as is the case in most upland U.K. areas) the demonstration of a reduction in sediment discharge of less than an order of magnitude may be expensive and difficult to demonstrate statistically (Rice et al., 1975, quoted in Brown, 1980).

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(1) **This report considers only suspended load. Dissolved and bedload are not examined. References in the text to total load or sediment load refer only to suspended sediment loads.**

Grimshaw & Lewin (1980) suggested two basic methods to investigate the effects of regulation on suspended sediment discharge:

(i) Compare the river load before and after reservoir construction, and

(ii) adopt a paired catchment approach.

The former method assumes stationarity of process in the natural system. The latter method, involving selecting two adjacent catchments of similar physical attributes, one regulated and one unregulated, assumes constancy of process spatially.

In this report both approaches are adopted to examine the turbidity and suspended sediment concentration regime of the regulated River Tees. Neither approach is entirely satisfactory in the present case as will be detailed below.

One purpose of this exercise is to summarise divers suspended sediment concentration and turbidity data for a regulated river. Further, the data are used in regression analysis to isolate temporal changes in river load. Sediment supply and total annual load are considered and the likely effect of the sediment regime on fisheries discussed. A companion report (Carling & Douglas, in prep) deals with periodicities in the turbidity and discharge record isolated using spectrum analysis.

The Regulated River Tees and Suspended Sediment Data

Two major tributaties of the River Tees in Northern England (Fig. 1) were regulated by direct supply reservoirs at the turn of the century, but there are few reliable data concerning their sediment loads. The largest impoundment however, Cow Green reservoir, regulating flow in the main-stem river was completed in 1970. In the latter case there are some suspended sediment data available. Together these reservoirs (Table 1) control flow from 22% of the catchment area above an abstraction point 64.5 km below Cow Green at Broken Scar, Darlington.

A small amount of SSC data are available for the N.W.A. gauging station at Broken Scar for both the immediate period prior to 1970 and intermittently since that date. In addition, it is possible, with caution, to compare the sediment discharge of the regulated Tees with the sediment regime of the physically similar River Tyne, examined between 1959 and 1961 (Hall, 1964; 1967), which remained unregulated until 1982. However, the basis of the present analysis rests on the existence of over eleven years daily turbidity readings which could be correlated with SSC. These data have been used in regression analysis in an attempt to identify temporal consistencies in SSC loading, attributable to present-day climate, discharge regime and land use. Any long-term trend might, for example, be a lag effect resultant from the construction of Cow Green reservoir limiting SSC supply.

Such an analysis is timely; water transfers via a tunnel connecting the Tyne, Wear and Tees may commence in the 1980's, further complicating the discharge regime of the Tees (Burston & Coates, 1975). In addition, interest in the effect of SSC on the aquatic biota of the Tees, has resulted in speculation as to the suspended sediment load in the river (Armitage, 1977) and the quantity of sediment entrapped by the Cow Green reservoir (Crisp, 1977). Previous detailed investigations of SSC have been limited to streams affluent to the Tees (Crisp, 1966; Crisp & Robson, 1979; Carling, 1983; 1984a) or have been concerned with suspended sediment quality (Holmes & Whitton, 198la & b; Armitage, 1982).

Data collection and turbidity record

Turbidity readings of the river water at Broken Scar are taken daily at 0900 hrs GMT. A Hach light-scattering turbidity meter is used and the functional calibration (see Appendix A) is checked daily. Between 1971 and autumn 1973 the measurement was made in a bucket sample obtained from the river water surface. From 1973 until present a more satisfactory system has been used; a sample being piped to the laboratory from the abstraction main. The main, drawing at between 1.58 and 1.84 m^3 sec^{-1}, mixes the river water well. Despite the change in sampling method there was no noticeable difference in the mean or variance of the daily turbidity reading before or after the autumn of 1973. This implies that the suspended sediment is well mixed with depth and is of fine grain-size. In support of this observation Carling (1984a) found no noticeable depth differentiation in suspended silt concentration in a broad shallow Teesdale stream and Hall (1964) recorded minimal vertical and lateral concentration gradients in the River Tyne at Bywell.

Discharge values for 0900 hrs were abstracted from N.W.A. records; data being recorded at hourly intervals as stage on a compound Crump weir and converted to discharge (m^3 s^{-1}) by a modular rating curve.

The record analysed consists of a series of 4l62 daily paired observations of turbidity and discharge for the period 10 August 1970 to 31 December 1981. The record is unusually complete, only 85 turbidity values being missing and 37 discharge values. The longest continuous gap consisted of five turbidity values.

Summary statistics for the full record are given in Table 2. Discharge-related data are usually logarithmically distributed. Logarithmic transformation reduced but did not eliminate positive skewness.(Fig. 2).

RESULTS

Discharge regime

Cow Green reservoir was completed in 1970. Although over 80% of the discharge from the reservoir in the winter months may be over the spillway, regulation has substantially altered the river's flood regime. Discharges at Broken Scar < 0.1 times the median annual flow were eliminated (Fig. 3) whilst for discharges greater than 2.5 $m^3 s^{-1}$ the percentage exceedence time has been reduced by approximately 15-30%. The mean annual flood, $Q_{1.76}$ from the partial duration series, has been reduced from 390 $m^3 s^{-1}$ to 336 $m^3 s^{-1}$ whilst "bankful" discharge i.e. $Q_{0.9}$ has a value today of 291 $m^3 s^{-1}$ as opposed to 352 $m^3 s^{-1}$. Recurrence intervals for flood peaks have approximately doubled (Fig. 4). The maximum recorded flood before closure of Cow Green was 667 $m^3 s^{-1}$ with an estimated pre-impoundment recurrence interval of 35 years. The peak flood for the post-impoundment period of 591 $m^3 s^{-1}$ (T = 16 years) occurred in January 1982. The highest sampled peak discharge for the period of turbidity records examined occurred in March 1979, with a discharge of 371 $m^3 s^{-1}$ (T = 3 years). Of the discharges sampled, six came close to (>90%) or exceeded the post-impoundment "bankful", whilst 17 exceeded 70% "bankful". Only one flood exceeded the pre-impoundment $Q_{0.9}$.

Turbidity-discharge rating curves

The turbidity-discharge paired data are plotted in Fig. 5. The data are very scattered but show a positive relationship with discharge. A least-squares regression equation,

$$FTU = 1.23 \quad Q^{0.46} \quad r^2 = 0.40 \qquad p < 0.001 \qquad (1)$$

poorly represents high values of discharge when most sediment is transported. The functional relationship equation 4A (Appendix A), anticipated from the preliminary calibration analysis, is visually a good fit to the high data values.

Rating sub-divisions using various base-flow thresholds to isolate (i) rising and (ii) falling hydrograph data sets did not substantially reduce the variance. Lagging the data sets to allow for turbidity peaks occurring before or after the hydrograph peak was also unsuccessful. Only slightly more satisfactory was the use of seasonal ratings which resulted in increased values of r^2 for individual seasons, although data overlap generally resulted in negligible separation of the data sets with the exception of summer 1975 (p. 7). Examples are given in Figs. 6 and 7. The seasons were defined as Autumn: September to November inclusive; Winter: December to February; Spring: March to May, and Summer: June to August. Other sub-divisions such as Hall's (1967) Winter: November to March; and Summer: April to October were singularly unsuccessful. There was no evidence of consistent rating shifts over the eleven year period.

Summer ratings however did tend to give higher turbidities than other seasonal ratings especially at low discharges, whilst winter ratings tended to be slightly steeper indicating a more rapid system response.

The best defined rating curve separation occurred in 1975, the first year of the drought (Fig. 7). The summer rating increased turbidities by 31% at baseflow (3 m^3 s^{-1}) compared with the rating for 1974, while for the peak 1975 discharge, 96 m^3 s^{-1} the hypothetical increase was 313%. Rating intercepts for the other three seasons were depressed by 13% and slopes by 21% compared with average values for the other ten years. The generally higher values of turbidity in summer 1975 presumably reflect the reduction in vegetation cover and the increase in river bank dry ravel coupled with moderate runoff. The summer rating curve fell below pre-drought level in 1976 as the drought intensified. This may be related to reduced rainfall in summer 1976 compared with 1975, i-e. 75 mm total as opposed to 226 mm, as well as reduced runoff, 26 mm compared with 38 mm in 1975. Mean daily discharges in 1976 remained at compensation level for over 3 months whilst in summer 1975 several small freshets had occurred. Consequently, little sediment was delivered to the river system by surface runoff in the summer of 1976. Ratings readjusted to the pre-drought levels in 1977.

Suspended sediment - discharge rating curves

Data are available for 1966 to 1970 and 1978 to 1981 (Fig. 8). In addition six SSC values were recorded at Broken Scar following a catastrophic landslide of peat into the headwaters of the Tees in 1963 (Crisp *et al*., 1964).

No seasonal rating sub-divisions were attempted because the data sets were small. Excluding the catastrophic event from consideration, although there was a statistically significant change in the ratings from the pre-impoundment (1966) to the post-impoundment periods (1970 and 1978-I98I; comparison of slopes using the t-test and 95% C.L.) there was no significant difference in annual discharge-weighted loads (Anova and F-test, 95% C.L. see p. 12).

Suspended sediment and effect of soil moisture deficit

The changes in sediment rating curves in 1975 and 1976 were interpreted as owing to variable sediment supply. At its simplest, the SSC at Broken Scar may be seen as the result of a supply control and sediment transport capacity which may be written;

$$\underline{S}SC = f\ (\text{capacity}) + f\ (\text{sediment production})$$

Discharge is the obvious control on SSC capacity but an index of potential sediment production is required. Many factors may combine to influence sediment supply rate. However, the purpose of the exercise was to demonstrate a link between SSC and sediment production in the uplands, where, it has been argued, most load is generated (Hall, 1967; Grimshaw & Lewin, 1980), rather than exhaustively seek a variance minimisation and prediction model. Hall (1967) reported a positive relationship between an Antecedent Precipitation Index and SSC for a given discharge in the R. Tyne. However, API can be difficult to interpret in dynamic terms (Weyman, 1975, P. 39). In this study the daily Soil Moisture Deficit (SMD, as calculated by the Met. Office for the Widdybank Fell Meteorological Station, Fig. l) was selected as a sediment production index. One can hypothesise that no sediment loaded runoff will occur if the SMD is positive, as rainfall will infiltrate the soil and replenish the soil moisture reservoir. Negative Values of SMD, Hydrologically Effective Rainfall (i.e. potential runoff) should correlate negatively with SSC. Of course this is an over-simplification. Infiltration rates in upper Teesdale are low (Adamson, 1970) and runoff can occur during high-intensity rainfall before SMD is reduced to field capacity. However, except for occasional summer thunderstorms, rainfall intensities generally are low, and Hall (1968) found no relationship between SSC and rainfall intensity in the Tyne basin.

The calibration data for SSC were regressed against progressively lagged SMD data up to a maximum lag of 14 days. The SMD value for the previous day is therefore SMD_1, and the two day lag SMD_2 etc. Significant correlations are given in Table 3 for an exponential model fitted by least squares. At the 95% C.L. the system has a five day memory. The best correlation is with the 1 and 2 day lags (Fig. 9) as might be expected from previous evidence of time-of-travel (Northumbrian Water Authority, 1977).

The r^2 value (Table 3) demonstrates the significance of sediment production, as indexed by SMD_1 in an upland regulated catchment.

Data were combined in a multiple regression equation relating SSC as the dependent variable with discharge and SMD_1;

$$\ln SSC = 0.6892 \ln Q - 0.0180 \; SMD_1 - 0.1658 \qquad (2)$$

The percentage of variance explained, compared with a power function relating SSC and Q (Fig. 2A) was only increased by 1% ($r^2 = 0.49$, df = 113, $p < 0.02$). Consequently equation (2) has little increased predictive power but serves to demonstrate the form of the functional relationship between the variables.

Post-impoundment load

Daily total load (Q_s) was calculated taking each daily 0900 hr discharge value and FTU value as representative of the daily 24 hr mean discharge. With reference to equation 3A the daily sediment discharge in tonnes may be expressed as;

$$Q_s = 0.0864 \quad Qe^{1.1704} \quad + \quad 0.0877 \qquad (3)$$

Q values were summed to yield the annual sediment discharge. In addition, the weighted sediment discharge was calculated as;

$$\Sigma_1^{365} \; (SSC) \; Q / \Sigma_1^{365} \; Q \qquad (4)$$

Discharge weighted values and total load are presented in Table 4. Weighted values were used to detect any trends in sediment production in the catchment, which could not be attributed to changes in discharge regime following the closure of the Cow Green impoundment. When weighted sediment load was plotted as a linear function of time there was no significant trend in sediment production over the 11 year period (i.e. regression slope not significantly different from zero at 99% confidence level).

Total sediment production is on average 12957t yr^{-1} within 95% confidence limits of 8221 to 1769t yr^{-1}. Sediment discharge per kilometre square of catchment averaged 15.83t km^{-2} yr^{-1} (95% C.L. 10.05 to 21.6lt km yr^{-1}) ranging between 39 tonnes in the wet year 1979 to only 5 tonnes in the drought of 1976.

Solution of equations 3A, 4A and 3 for the dominant effective discharge, $Q_{0.9}$ = 352 m^3 s^{-1} yielded a concentration ($C_{0.9}$) of 377 mg 1^{-1} and critical load of 132 kg s^{-1}.

The mean discharge-weighted concentration (Table 4) is 2.52×10^{-5} t m^{-3} or 25.2 mg 1^{-1}. From Fig.10 it is evident that concentrations greater than 25 mg 1^{-1} only occur less than 6% of the time and are associated with discharges in excess of 39 m^3 s^{-1} which also occur less than 6% of the time. These higher magnitude events therefore do most of the work in transporting the annual load.

The discharge-weighted load expressed as mg 1^{-1} falls as the annual discharge increases to about 6×10^8 m^3 yr^{-1}. This implies that sediment is supply-limited rather than transport limited. There are only two points for discharges in excess of 6×10^8 m^3 yr^{-1}, but these indicate a much higher sediment throughput, consequently one can cautiously imply the presence of a sediment production threshold occurring between 6.03 and

6.09×10^8 m^3 yr^{-1}. The single point circled in Fig. 11 is the sediment concentration during the drought year 1976 when little sediment was delivered to the river. The curve is an hypothetical response function drawn by eye. The descending data points fit the function $SSC_Q = 617.82 - 29.87 \ln Q_{tot}$

which describes the sediment depletion until the threshold is attained. The point at 2.2×10^8 m^3 yr^{-1} represents the baseflow discharge at Broken Scar and the associated average SSC value at Cow Green, 6 mg l^{-1} (Northumbrian Water Authority, 1977). This locus is the effective minimum discharge-concentration point under the present operational regime

The effects of discharge modification on sediment load are poorly known and are dependent on basin characteristics for example, so that the response of individual catchments may be highly variable (e.g. Rango, 1970). Understanding of inbalance in natural systems is inadequate (Coates & Vitek, 1980) so although the general shape of the curve in Fig. 11 is believed to be correct, the loci of maxima and the exact form of the curve at high discharges are unknown. The presence of an apparent sediment production threshold within a range of commonly occurring discharges, however, is salutary to our appreciation of basin sediment dynamics.

Pre-impoundment load

There are data available to estimate SSC retention by the Teesdale reservoirs (Table 5). Armitage (1977) estimated that 91% of SSC was retained by Cow Green reservoir, a figure subsequently revised to 95% (Edwards & Crisp, 1982). Crisp (1977) calculated the annual deposition rate for Cow Green reservoir as 66.67 t km^{-2} yr^{-1}. Of the available estimates for reservoir deposition in Teesdale, Crisp's is the most reliable, based on the sediment load of a stream affluent to Cow Green (Crisp, 1966; see also Crisp & Robson, 1980). Winter's (1950) method of calculation was extremely crude by today's standards. The data for Blackton reservoir for example, yield an infilling rate corrected for catchment area three times the value for Cow Green, a value not readily supported by observation.

Accepting Crisp's value of 66.67 t km^{-2} yr^{-1} as a best estimate of sediment production in the headwaters of the regulated catchment the load for the total impounded catchment is 12115.27 t yr^{-1}, most of which is deposited in the reservoirs. Assuming the lowland and unregulated uplands have contributed sediment at the same average annual rate before and after reservoir construction an estimate of the pre- Cow Green total load at Broken Scar is 66.67 t multiplied by the catchment area (60 km^2) plus the present average sediment discharge, i.e. a total of 16957 t yr^{-1}. This assumes negligible deposition in the 64.5 km from Cow Green to Broken Scar. Despite the large data set used to estimate the present load it is clear that within 95% C.L. there is no evidence that the load at Broken Scar has been reduced substantially by Cow Green reservoir.

Turbidity and Fisheries

The effects of chemically-inert suspended sediments on fisheries have been studied extensively both in the laboratory and in the field. Although the main emphasis has been on the level of concentration of solids, there is evidence that particle size gradation, angularity and physical composition are also of importance (e.g. O'Connor et al., 1977); these latter aspects have been little researched.

Alabaster & Lloyd (1980) recently reviewed the literature concerning concentration effects on river biota within an European context. Their conclusions are broadly similar to summary observations for North America (e.g. Phillips, 1970) and reiterate the recommendations drawn in the EIFAC (1964) report. Concentration data for the Tees are interpreted here with reference to Alabaster & Lloyd's (1980) conclusions.

Turbidity values ranged from less than 1 to 200, with an arithmetic mean of 5.02. As the distribution is logarithmic, the geometric mean gives a good measure of central tendency and has a value of 3.74. These data as they relate to the turbidity distribution are shown in Fig.10. With reference to equation 3A the turbidity values correspond to SSC values as follows: range ~1.1 - 536 mg 1^{-1}, geometric mean 5.1 mg 1^{-1} and the 50 and 95% percentiles are 2.7 and 25.7 mg 1^{-1} respectively.

Although no definitive limits can be specified for water quality (Alabaster & Lloyd, 1980) it is useful to compare the Tees data with other U.K. studies.

Salmonids can withstand concentrations of 10^3 mg 1^{-1} for short durations, but sustained concentrations greater than 200 mg 1^{-1} will lead to increased mortality or loss of condition in adult fish (e.g. Scullion & Edwards, 1980). Herbert et al. (1961) observed a normal trout population in a river with a SSC of 60 mg 1^{-1} and Alabaster & Lloyd (1980) report two good trout fisheries with mean and maximum concentrations of 18 and 412 mg 1^{-1}, and 24 and 100 mg 1^{-1} respectively. It is concluded that adult trout in the R. Tees are unlikely to be affected adversely by the maximum observed turbidities because these levels are not maintained for more than a day or two. The question of the effect on the food supply of fish is largely related to the effect of settling solids on stream benthos. This aspect is not examined here. Nevertheless, concentrations are less than are commonly reported as deleterious to benthos and are typical of unregulated upland streams in Teesdale (Carling, 1983).

Few trout spawn in the main-stem Tees and salmon and sea trout are presently scarce, although historically good runs occurred. Potential spawning gravels should be kept as clean as possible (Alabaster & Lloyd, 1980) but experimental evidence (Carling, 1984b) suggests that clean river gravels rapidly become silted by low concentrations of suspended solids under a variety of hydraulic conditions. Quite small freshets may resuspend fine silt from a surface gravel layer, approximately one mean grain diameter thick (Carling, 1982). For example, the initial plateau peak discharge in the N.W.A. experimental release in 1976 (Northumbrian Water Authority, 1977) which resuspended fine bed materials at Broken Scar corresponds to a discharge of 0.15 m^3 s^{-1} per metre bed width. This value agrees fairly well with a minimum peak discharge of 0.113 m^3 m^1 s^{-1} required to promote limited scour from at least 50% of the bed area of an upland stream (Carling, 1982). However, substantial cleansing of gravel to depth cannot be expected unless discharges exceed an "effective" value for general bed movement.

Hey (1975) and Charlton (1977) discuss effective discharges with reference to British gravel-bed rivers and Charlton et al. (1978) conclude that, in lieu of detailed data on bed mobility, bankful discharge should be used. A reasonable value, therefore at Broken Scar would be the pre-impoundment $Q_{0.9}$, obtained from the partial duration series (Fig. 4), of 352 m^3 s^{-1} which following regulation now has a recurrence interval of about 2.2 yrs. Milhous (1982) suggests that a discharge half the effective value will flush fines from the surface layer but this is unlikely to benefit spawning salmonids.

Consequently, although some winnowing of superficial sediments will occur annually, thorough and widespread cleansing of surface gravels will not occur frequently. Gravels immediately below the surface layer may remain silted and compacted for a number of years.

DISCUSSION

The discharge modifications resulting from regulation are typical of discharge regimes below U.K. water-supply reservoirs (e.g. Petts & Lewin, 1979). Although these modifications can lead to changes in gravel-bed channel morphology, notably localised deposition or scour (Petts, 1979), no significant changes have been noted in the R. Tees. Mid-channel bars appears to be more stable and are often heavily vegetated. In some cases secondary channels are vegetated and silted. Previously, vegetation was removed frequently by high flows. Tributaries downstream of Cow Green have had a negligible effect on stream channel morphology at confluences, and bank erosion is negligible.

The range of SSC values is typical of undisturbed upland streams although the response in SSC level for increments in discharge is small (as indexed by the regression exponents, Figs. 7 and 2A). The response is certainly sluggish in comparison with the unregulated R. Tyne at Bywell (Hall, 1967), where the exponent was of the order of 2.3. Large values of b have been tentatively described as typical of upland catchments draining resistant rocks (Walling & Webb, 1981) and it is therefore attractive to ascribe the low coefficient for the Tees to impoundment effects. This is not satisfactory however. The SSC has not been reduced following impoundment and the pre-impoundment regression exponents were also low. In addition, exponents in two of the undisturbed tributary streams to the Tees are less than one, i.e. 0.81 and 0.99 (Carling, unpubl.). The poor response of the Tees system reflects the generally undisturbed nature of the catchment and the supply limited fine sediment load. Where locally peat erosion in the Tees basin is prominent, as on the Rough Sike catchment, the exponent is larger, i.e. b = 2.1 (Crisp & Robson, 1979). It is possible therefore that steep regression slopes are associated with catchments where sediment load is not supply limited; contrary to Walling & Webb's (1981) assertion.

It is tempting to ascribe the steep regression slope for the ft. Tyne sediment rating to the disturbance of thick peat deposits by forestry operations noted by Hall (l967), as it is known that ditching operations on peat increase the slope of the sediment rating curve at least in the short-term (Robinson, 1980). However, the catchment of the Tyne at Bywell is some 2159 km^2 in area, larger than the Tees at Broken Scar (826 km^2), and includes lowland reaches of eroding river banks. Hall (1967) measured the rate of bank retreat and estimated that erosion attributable to this source was of the same order as the annual total sediment load. If this is the case, the uplands are not a major source of sediment in the R. Tyne at Bywell and it is not realistic to compare extant data for the Tyne and Tees despite the fact that the catchments are comparable in other respects.

The upland catchment of the Tees is an important source area for SSC as demonstrated by the SMD analysis. Although Broken Scar is over 64 km from the source areas, a proportion of the load is generated by direct runoff to unregulated tributaries. Nevertheless, under normal runoff conditions the sediment supply is progressively depleted. The memory in the system, as noted in the correlation of SSC with the one day lag SMD, agrees broadly with the time-of-travel estimates made during 1976 (Northumbrian Water Authority, 1977). In addition, also demonstrated is a longer term persistence of up to five days. This naturally leads to consideration of phase differences in sediment load and discharge. These aspects are considered by Carling & Douglas (in prep.).

The average total load of 16 t km^{-2} yr^{-1} is low compared with other upland sites (Table 5 and Walling & Webb, 1981) and yet the small load cannot be ascribed to the effects of regulation. Other unregulated streams within the Tees basin, where peat erosion is minimal, also have low annual yield (Carling, 1983). Further the variability in total load from year to year is readily demonstrated (Table 4), indicating the necessity for long-term estimates in order to make confident comparisons between catchments.

Grimshaw & Lewin (1980), in a seminal study of the effects of the Cwm Rheidol impoundment, noted a considerable reduction in downstream sediment yield. The monitoring station on the Afon Rheidol however was only some 16 km downstream of the dam compared with 64 km in this study. Clearly the effect of impoundment will decrease downstream and the location of the sampling stations is critical in assessing the effects of impoundments.

Further study is required on the downstream extent and nature of physical and biotic adjustments, before critical evaluations of the impact of reservoirs on the total river system can be formulated.

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FIGURE CAPTIONS

Fig. 1 Location of R. Tees in Northern England and sites mentioned in the text. (l) Rough Sike, (2) Widdybank Fell Meteorological Station, (3) Great Eggleshope Beck, (4) Carl Beck, (5) Lunedale and Baldersdale reservoirs.

Fig. 2 Percentage frequency histograms of logarithmically transformed data (a) 0900 GMT discharge (b) 0900 GMT turbidity.

Fig. 3 Flow duration curves for turbidity sampling station. (l) Post-impoundment regulated discharge 1970-1976. (2) Reconstructed post-impoundment "natural" discharge 1970-1976. (3) Pre-impoundment unregulated discharge.

Fig. 4 Partial duration series for R. Tees at Broken Scar. Closed symbols - Pre-impoundment; Open symbols - Post-impoundment.

Fig. 5 Scattergram of turbidity and associated discharge where N is 3937. Low gradient curve is fitted by least squares (1n FTU = 0.2063 + 0.45821nQ, $r^2 = 0.40$). Steep gradient curve is equation 4A, p. ii.

Fig. 6 Representative seasonal rating scatter plots of turbidity versus discharge. (a) Autumn 72, (b) Winter 72/73, (c) Spring 73, (d) Summer 73, (e) Autumn 73 (f) Winter 73/74.

Fig. 7 Seasonal FTU rating curves for the drought years 1975 and 1976, in relation to the previous and subsequent years. Sp = Spring, S = Summer, A = Autumn, W = Winter.

Fig. 8 Pre-impoundment suspended sediment concentration data for Broken Scar. 0 - catastrophic peat landslide (Crisp, 1966), o - 1966, • - 1967, • - 1968, • - 1969, x - 1970. Also shown is the least-squares post-impoundment regression line (see Fig. 2A).

Fig. 9 Relationship between the suspended sediment concentration and the Soil Moisture Deficit at day lag one. Hydrologically Effective Rainfall (HER) is plotted as negative values of SMD. The relationship vis a vis saturation is clarified by the vertical line at zero SMD. The exponential equation for the regression line is given in Table 3.

Fig. 10 Cumulative percentage distribution of turbidity data. The straight line is a least squares log-normal best fit with x equal to the linear plotting position, (r^2 = 0.98). Hachured dividers delimit approximate zones of trout fishery quality (Alabaster & Lloyd, 1980) in relation to values of SSC. The turbidity statistics, x = mean, x_g = geometric mean, x_m = median and σ_g = geometric standard deviation all fall within the good fishery category.

Fig. 11 Discharge weighted suspended sediment concentration in relation to the annual total water discharge. The curve is a hypothetical response function drawn by eye, except for the portion between Q_{tot} = 3-6 which was fitted by least-squares.

FIG 1

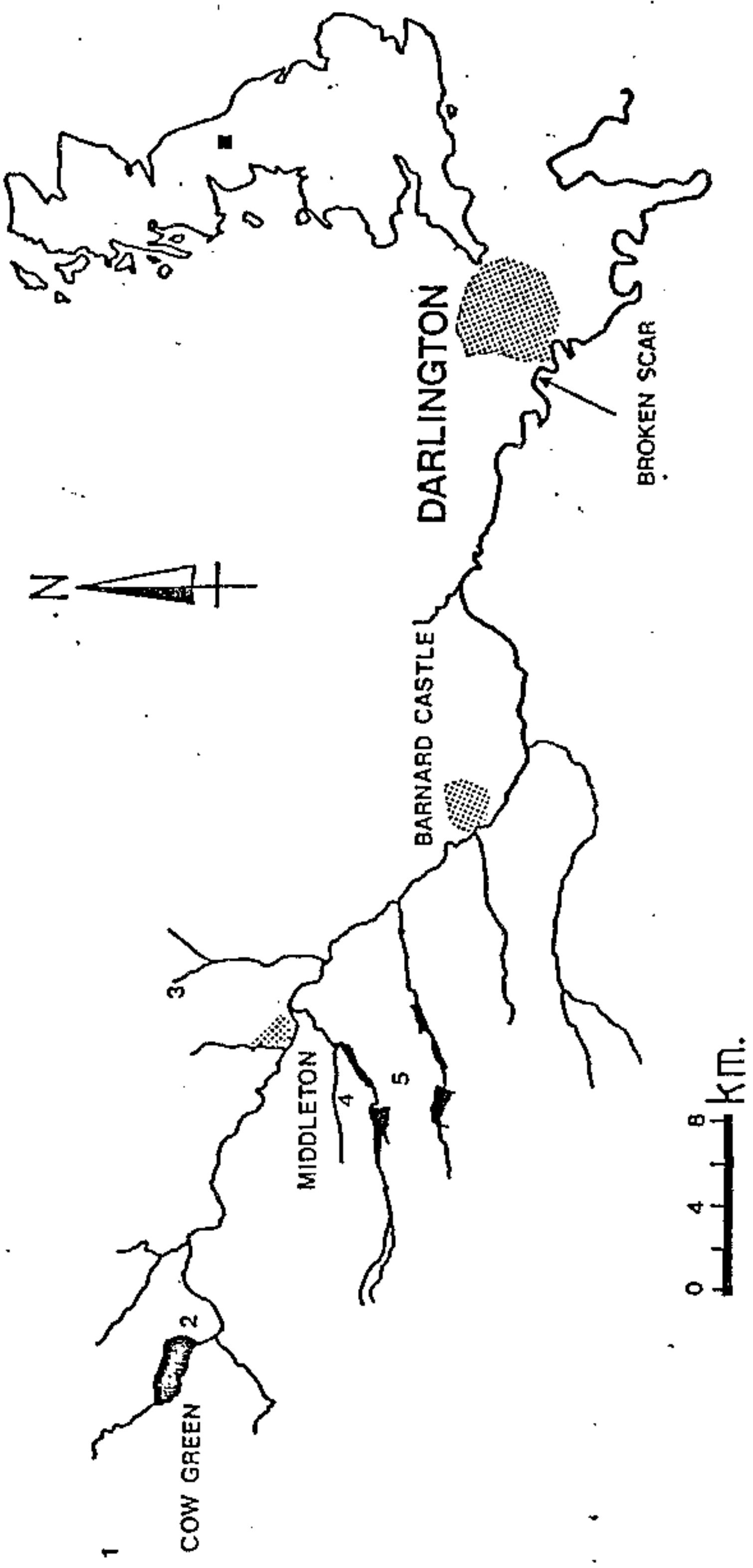

COW GREEN
1
2
3
MIDDLETON
4
5
BARNARD CASTLE
N
DARLINGTON
BROKEN SCAR
0
4
8
km.

FIG 2

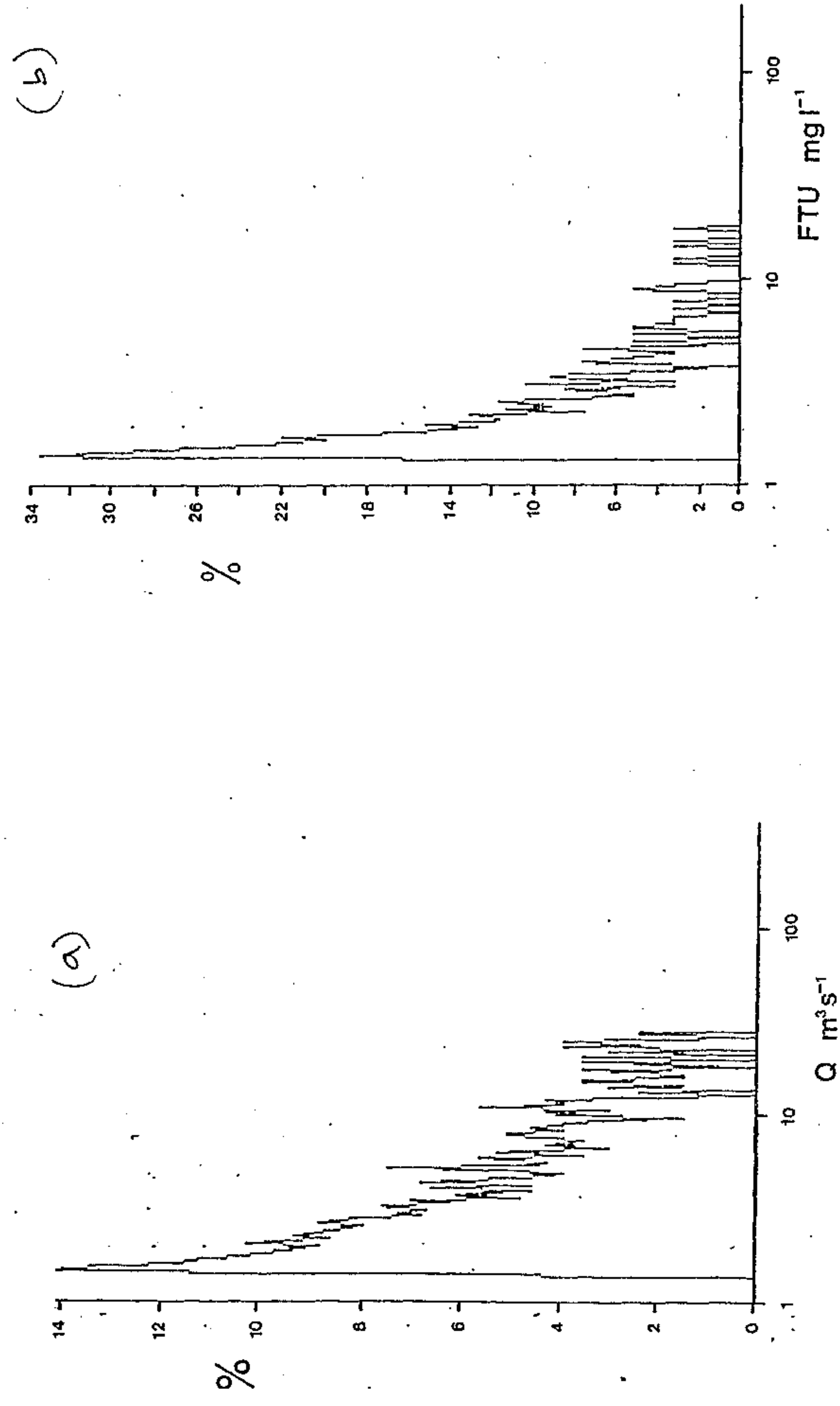
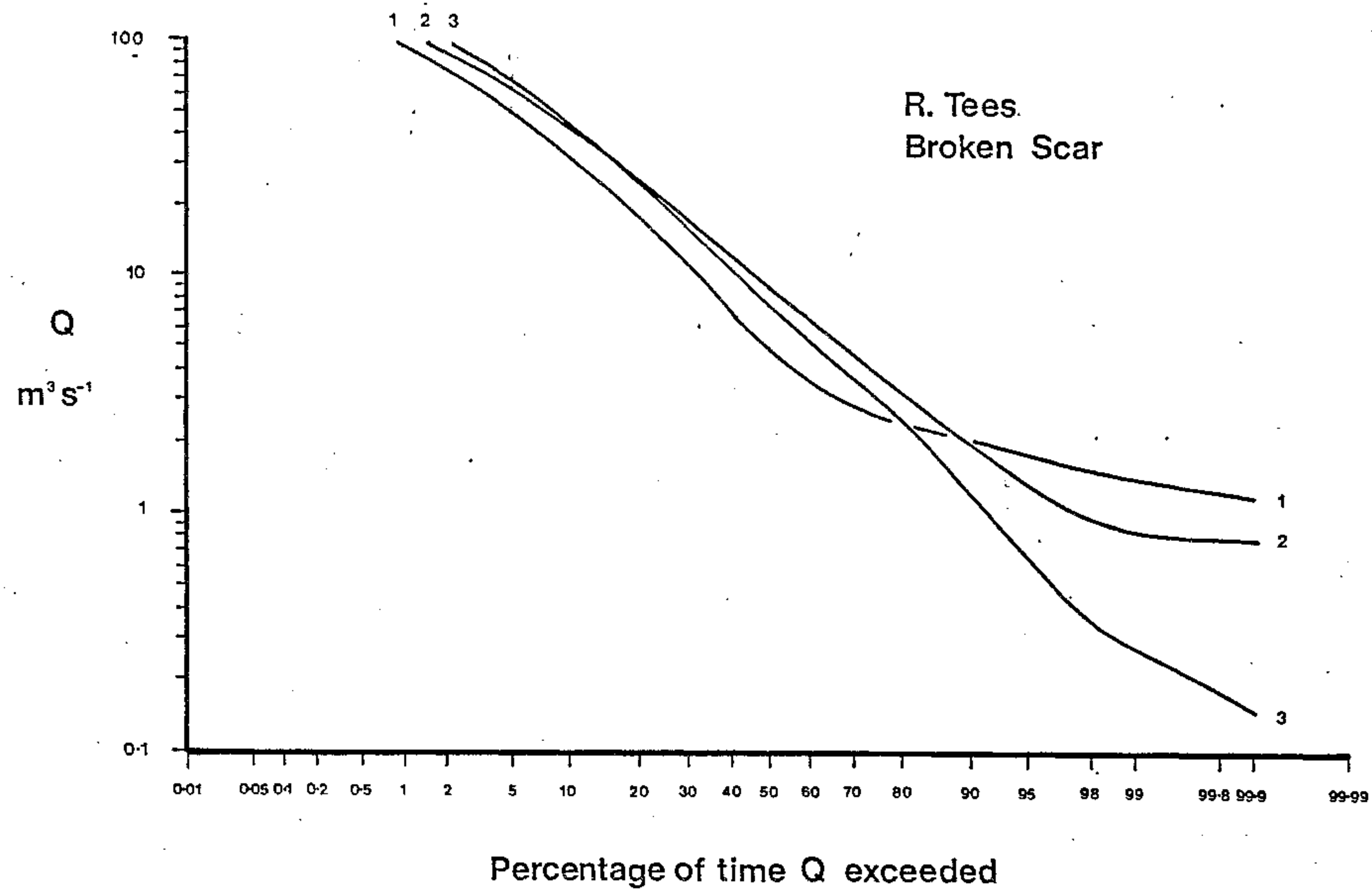
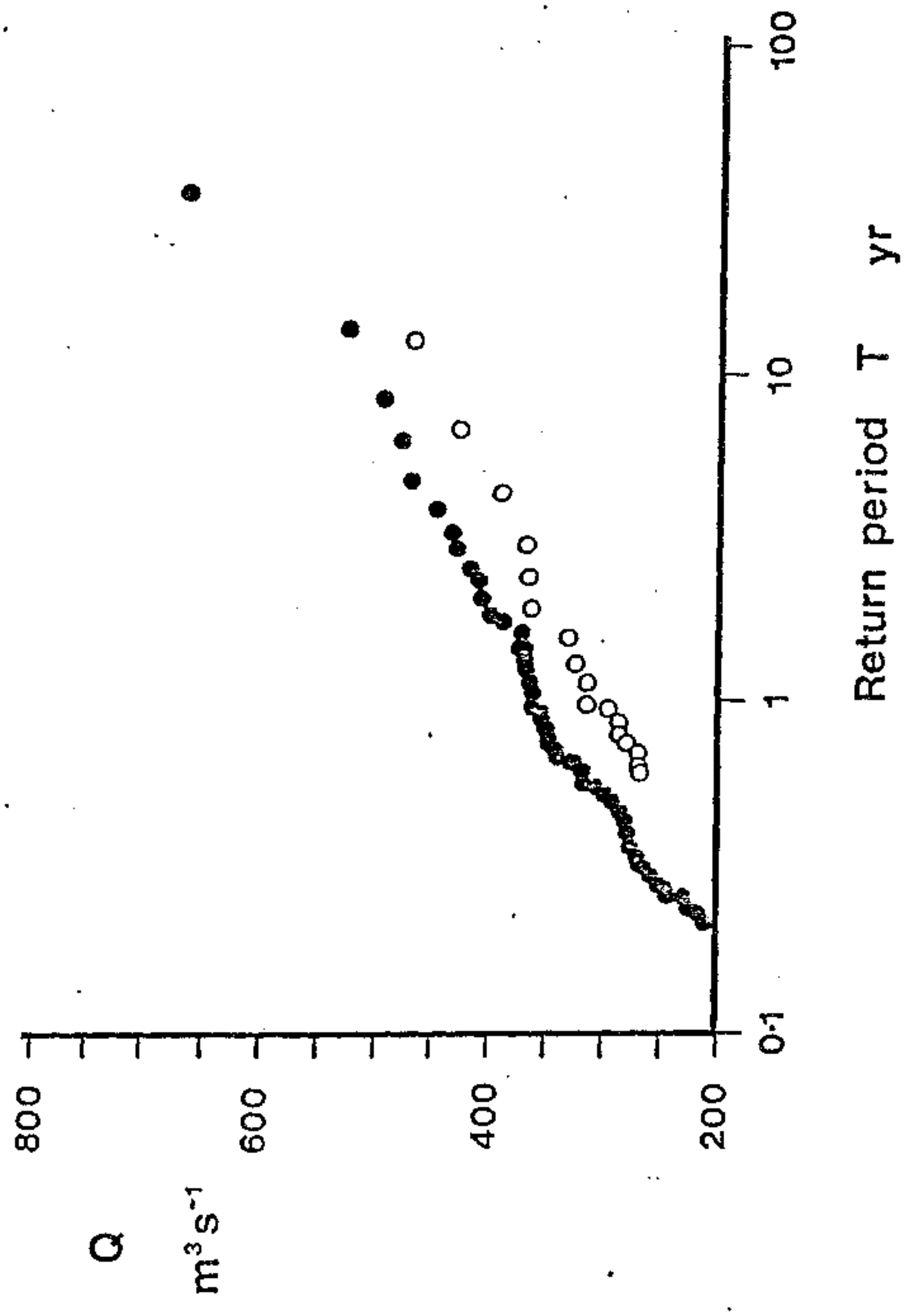


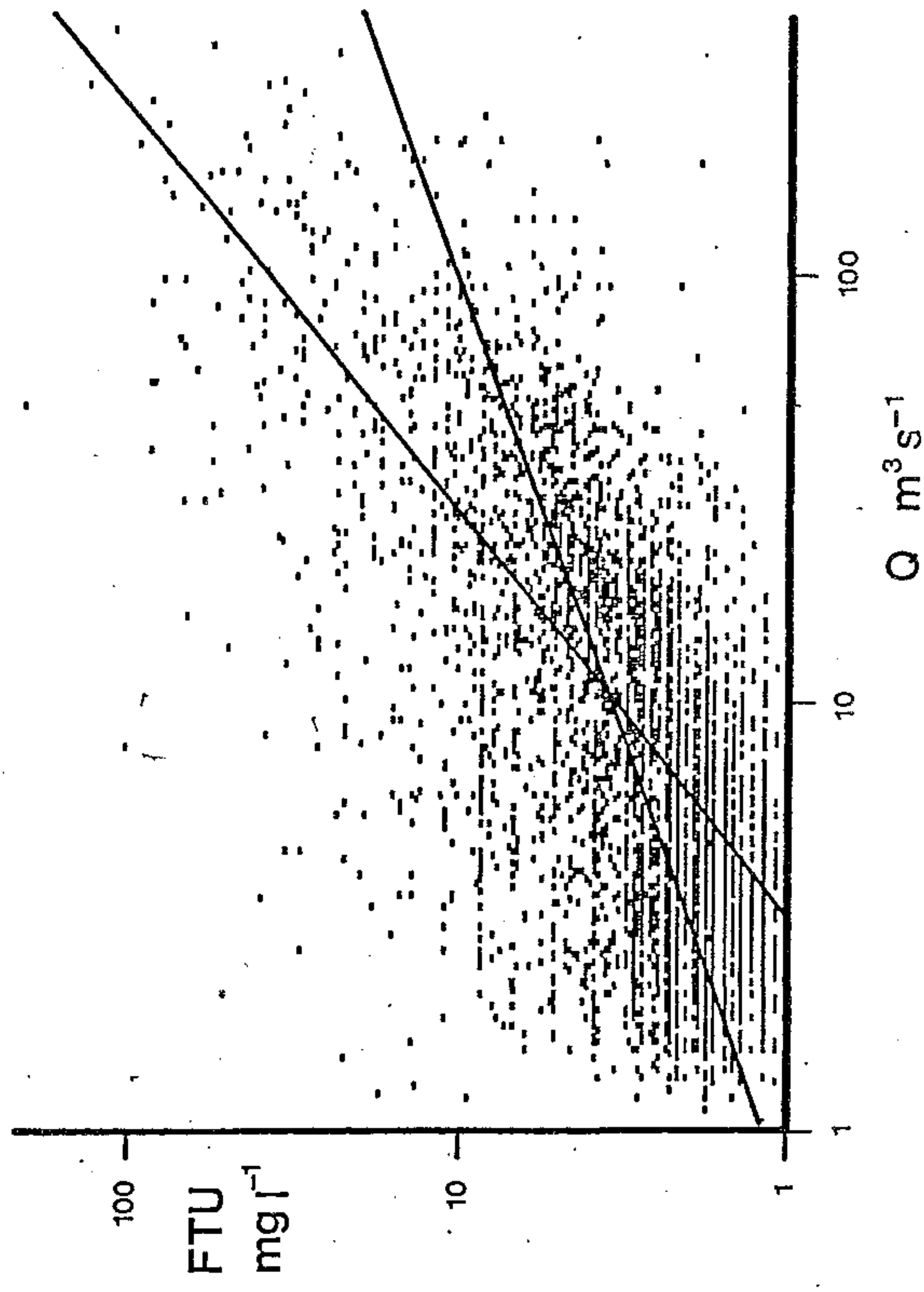
FIG 3

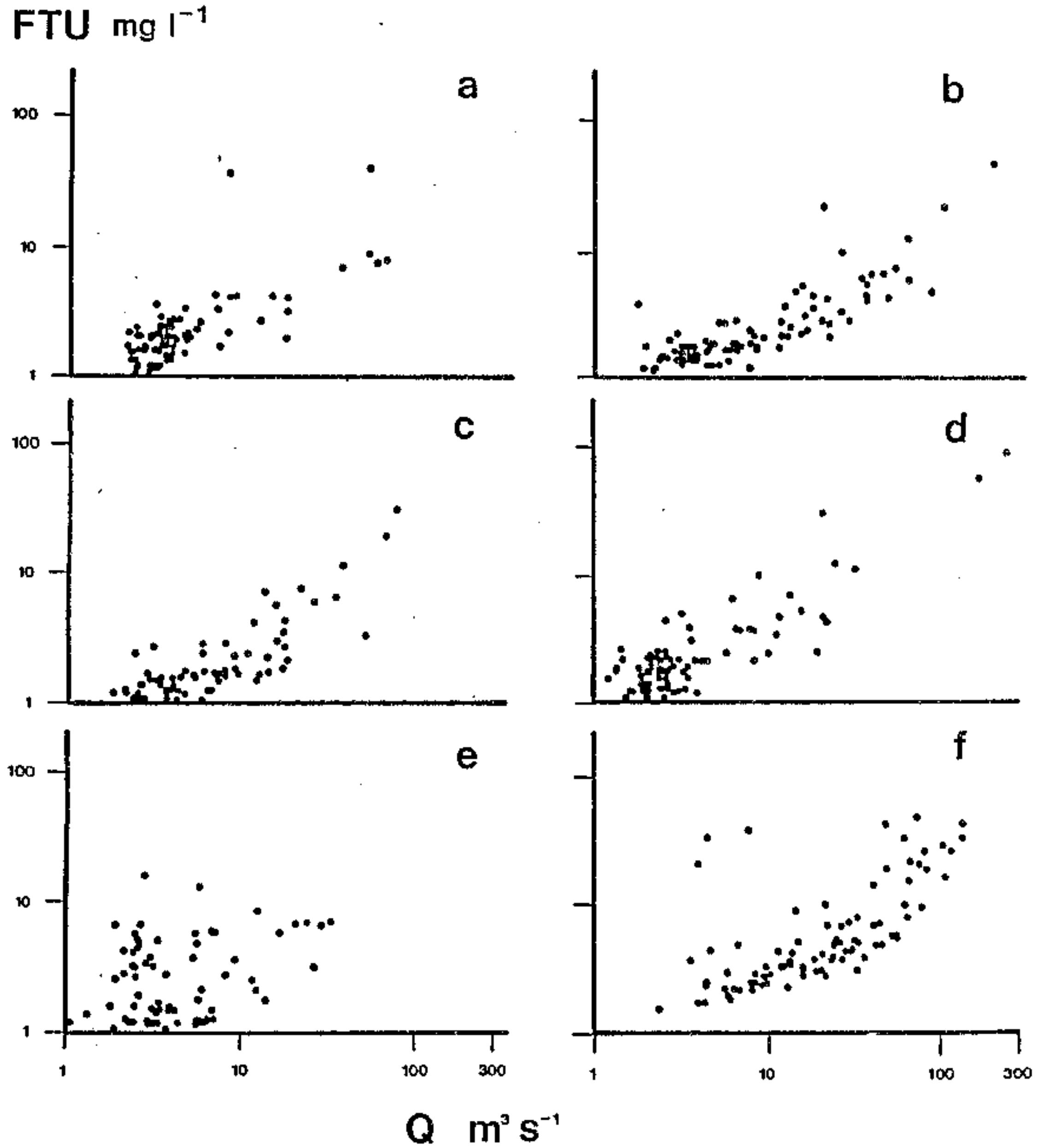


R. Tees.
Broken Scar
Q
m³s⁻¹
100
10
1
0·1
1
2
3
0·01
0·05
0·1
0·2
0·5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99·8
99·9
99·99
Percentage of time Q exceeded

FIG 4

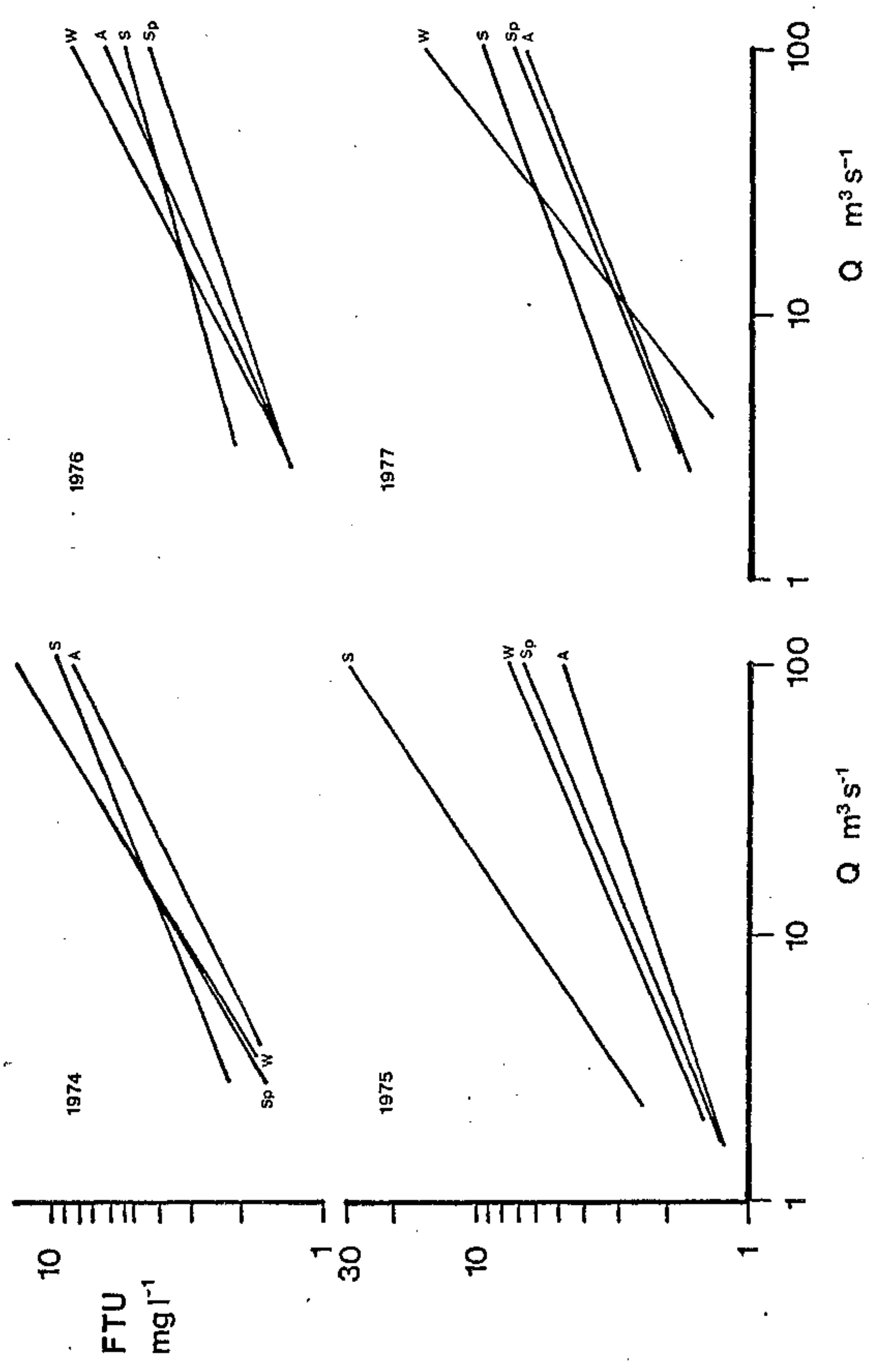



FTU
mg l-1
100
10
1
Q m3s-1
1
10
100



FTU mg l⁻¹
a
b
c
d
e
f
100
10
1
1
10
100
300
Q m³ s⁻¹

FIG 7



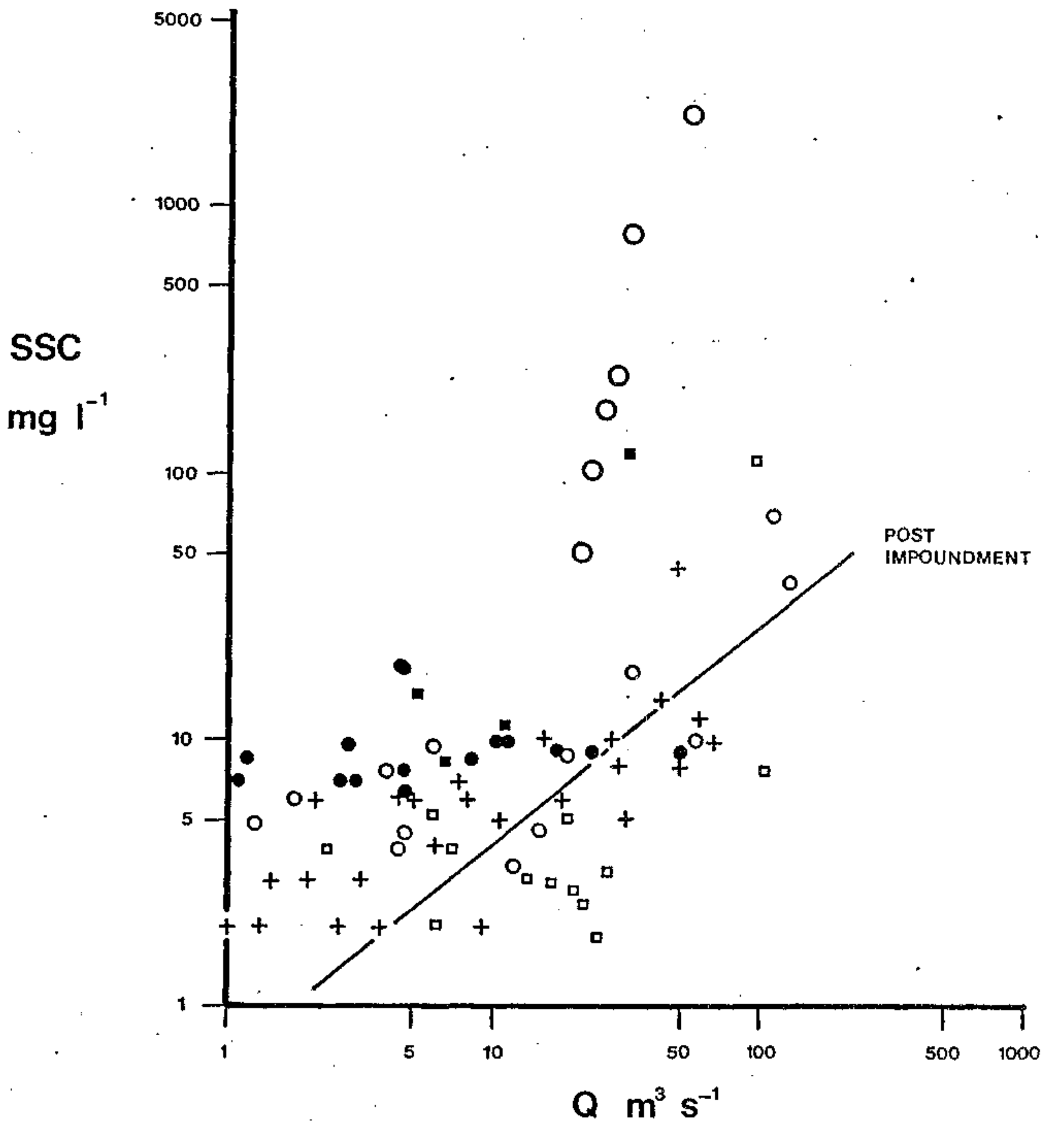

SSC
mg l⁻¹
5000
1000
500
100
50
10
5
1
1
5
10
50
100
500
1000
Q m³ s⁻¹
POST
IMPOUNDMENT

FIG 9

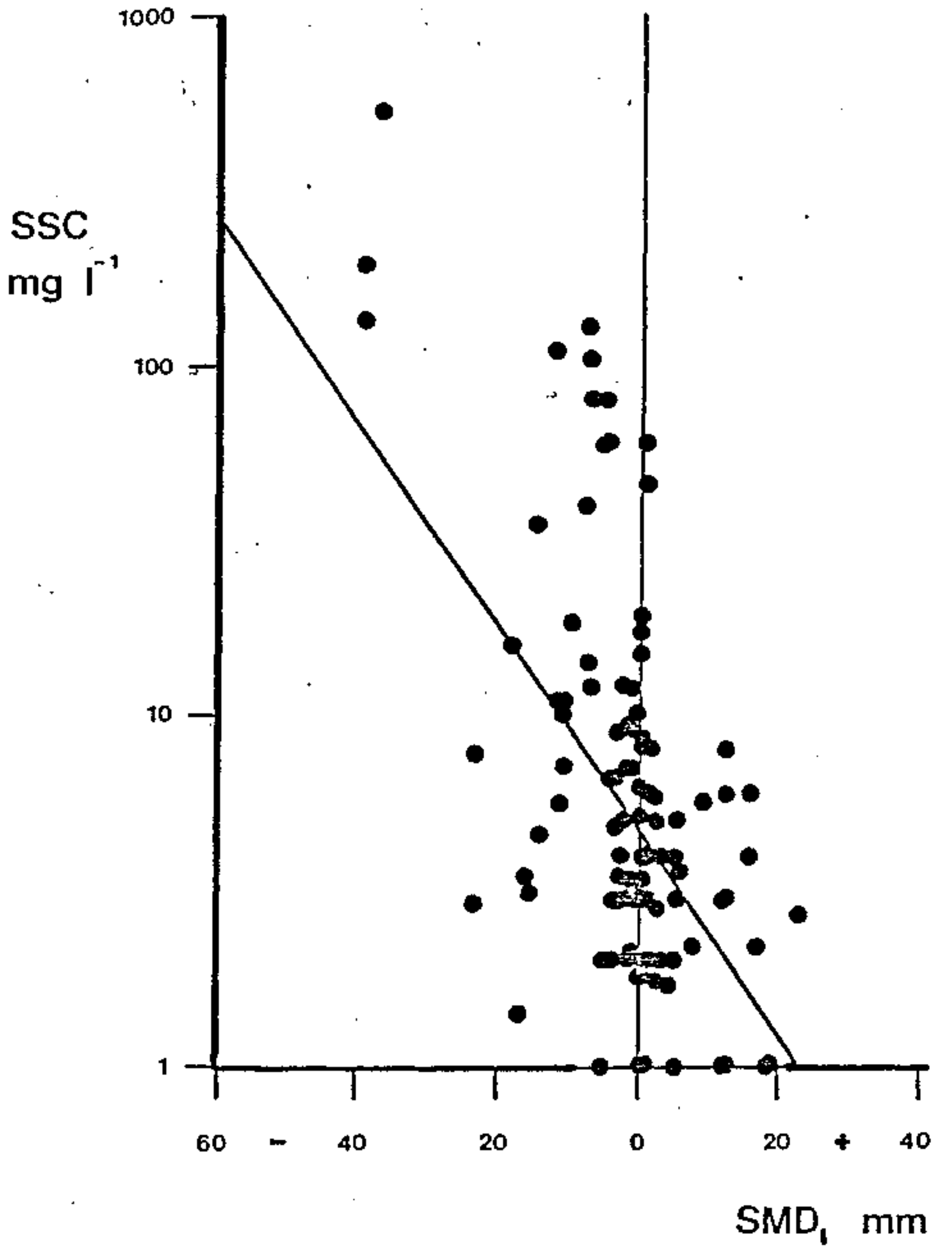


FIG 10

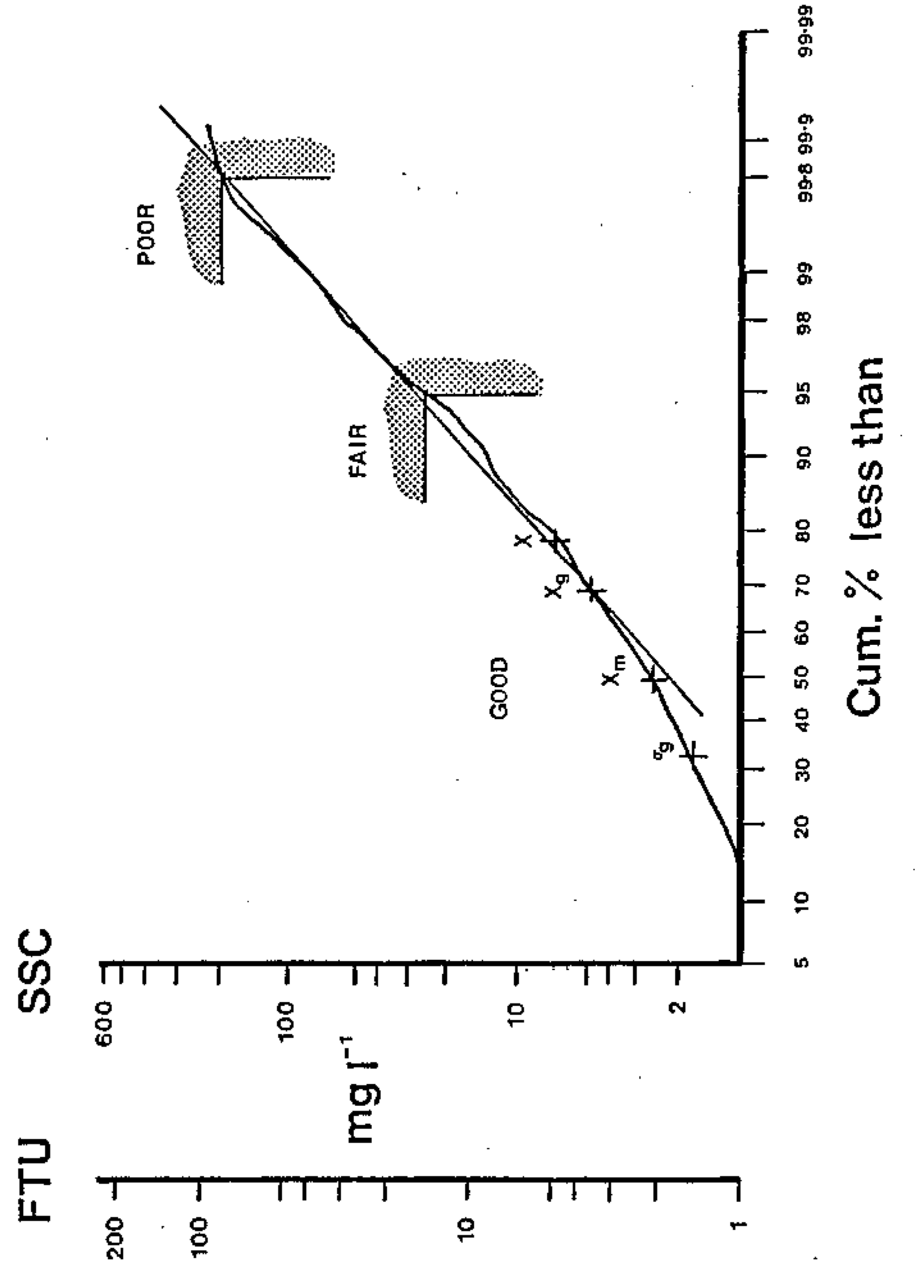

FTU
200
100
10
1
SSC
600
100
10
2
mg l⁻¹
POOR
FAIR
GOOD
X
Xg
Xm
σg
5
10
20
30
40
50
60
70
80
90
95
98
99
99·8
99·9
99·99
Cum. % less than

FIG 11

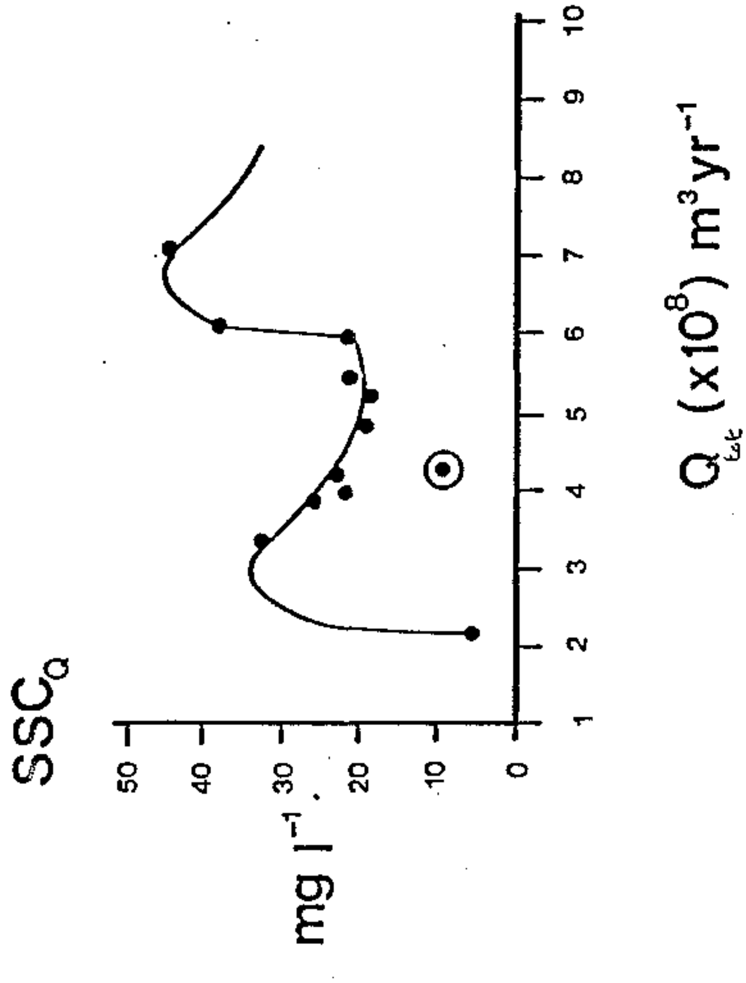


TABLE 1. Summary data for Regulatory Teesdale Reservoirs[1] (source N.W.A.)

	(1) Capacity ($m^3 x10^6$)	(2) Area (ha)	(3) Compensation ($m^3 x10^3 d^{-1}$)	(4)[2] Direct Supply ($m^3 x10^3 d^{-1}$)	(5)[2] Typical Retention Time (months)	(6)[2] Min. Retention Time (months)	(7) Total Impounded Catchment (km^2)
Cow Green	40.9	311.8	38.5	-	6.8	2.3	60.0
Grassholme	6.1	56.6	6.5	11.3	5.0	0.9	78.7
Hury	3.9	51.4	3.5	99.8	1.1	0.3	43.1

(1) The reservoirs at Balderhead, Selset and Blackton feed Grassholme and Hury and have no direct supply or discharge to the rivers.

(2) Values in columns 4, 5 & 6 are only approximate and will vary according to operational requirements.

TABLE 2. Summary Data, water years 1971-1981

	$\bar{x}$	$\bar{x}_g$	σ	min	max	s.e. of the mean	N
Discharge (m^3s^{-1})	15.95	8.66	26.90	0.74	370.66	0.42	4018
Turbidity ($mg\ l^{-1}$)	5.01	3.74	8.07	0.48	200.00	0.13	3937

TABLE 3. Relationship of SSC to Soil Moisture Deficit[1].

N = 115 for the regression equation ln SSC = lna-b SMD.

Coefficients a	Coefficients b	r^2	p	Lag SMD (Days)
5.1501	0.0438	0.067	<0.01	0
4.6249	0.0668	0.303	<0.001	1
4.7425	0.0472	0.148	<0.001	2
4.8849	0.0422	0.087	<0.01	3
5.1316	0.0314	0.030	<0.10	4
5.0012	0.0254	0.041	<0.05	5

[1]Data from Widdybank Fell Meteorological Station (calculated by the Meteorological Office using the Penman-Monteith method for a root constant of 50 mm).

TABLE 4. Suspended load in R. Tees at Broken Scar

Water year	(1) tonnes yr^{-1}	(2) tonnes km^{-2} yr^{-1}	(3) tonnes m^{-3} ($\times 10^{-5}$)
1971	9898	12.09	2.56
1972	9675	11.82	2.30
1973	10913	13.33	3.27
1974	8488	10.37	2.13
1975	9773	11.94	1.87
1976	4101	5.01	0.95
1977	13105	16.01	2.17
1978	9385	11.47	1.93
1979	31961	39.05	4.49
1980	11843	14.47	2.16
1981	23391	28.58	3.84

Summary statistics for 11 years:

	$\bar{x}$	σ	s.e.	95% C.L. of $\bar{x}$
(1)	12957	7854	2368	3221 - 17693
(2)	15.83	9.60	2.89	10.05 - 21.61
(3)	2.52	0.99	0.30	1.92 - 3.12

TABLE 5. Summary suspended sediment production in upland basins

Source	Load $t\ km^{-2} yr^{-1}$	Catchment Area km^2	Location
Tees basin			
Crisp (1966)	112	0.83	Rough Sike
Crisp & Robson (1980)	128	0.83	Rough Sike
Conway & Millar (1960)	85	0.048	Burnt, eroded and drained heather.
Conway & Millar (1960)	21	0.038	Artificially drained heather moor.
Conway & Millar (1960)	0	0.055	Undisturbed heather/sphagnum moor.
Carling (1983)	25	2.18	Carl Beck
Carling (1983)	12	11.68	G. Eggleshope Beck
Winter (1950)	205	78.67	Grassholme Res. (R. Lune)
Winter (1950)	156	34.11	Blackton Res. (R. Balder)
Carling (unpubl.)	16	818.40	River Tees, Broken Scar
Tyne basin			
Hall (1967)	117	39.89	Catclough Res. (R. Rede)
Hall (1967)	62	2159.00	Tyne, Bywell
Tay basin			
Al-Jabbari *et al.* (1980)	15.7-183.4	175-3213	R. Earn (various stations)
Al-Ansari *et al.* (1978)	27.2- 90.4	176	R. Almond

APPENDIX A

Calibration

Laboratory calibration by N.W.A. staff of the turbidity meter against known concentrations of Formazin gave a precise functional relationship;

$$C_s = 2.5 \text{ (FTU)} \qquad (1A)$$

where C is the suspended $S_1 0_2$ concentration (mg 1^{-1}) and FTU is the Formazin Turbidity Unit.

Laboratory calibrations require verification or modification using data from the natural gauging site. Suspended sediment in the River Tees is not the only contributor to turbidity, for example, phytoplankton derived from the river bed (Holmes & Whitton, 198la) may possibly increase FTU readings at low to moderate discharges (Appendix B). At low discharges fine particulate matter, although contributing little to the total suspended sediment concentration (SSC) may maintain relatively high turbidities. Factors such as water colour (Vanoni, 1977, p. 428) may effect sensitivity whilst sampling, analytical errors and rating shifts from storm to storm may increase the variance of a field calibration (Beschta, 1980).

Field calibration data were collected at 0900 hrs on various dates, representative of all seasons, between August 1978 and July 1981. Because of the infrequent occurrence of high discharges there was a disproportionate number of low discharge readings, but the peak discharge for the 10 year period was sampled.

The field data were compared with equation (1) using functional or structural analysis (Mark & Church, 1977). The resultant equation,

$$SSC = 2.48\ (FTU) + 0.72 \qquad r^2 = 0.56 \qquad p<0.001 \qquad (2A)$$

is structurally equivalent to equation (1) with the term 0.72 mg 1^{-1} representing the threshold of effective SSC detection.

Although structurally correct, equation (2A) visually does not appear to represent well the many low FTU values (Fig. 1A). A power function frequently yields a better relationship between SSC and FTU for field data (Fig. 1A). Both SSC and FTU determinations are subject to error so again a structural relationship was sought,

$$SSC = 1.09 \quad (FTU)^{1.17} \qquad r^2 = 0.73 \qquad p<0.001 \qquad (3A)$$

The percentage variance explained is increased by 17% when compared with (2A) and consequently (3A) is preferred for its explanatory value.

Where SSC is the principal factor controlling turbidity levels the exponent in (3A) is less than or in the vicinity of 1.50 (Emmett, 1975). Steeper slopes might indicate the importance of other forcing functions in maintaining turbidity levels. Such a situation evidently does not apply to the River Tees.

The data relating SSC and discharge were scattered (Fig. 2A). Nevertheless, a power function with SSC as the dependent variable gave a structural exponent of 1.17, the same as equation 3A. The implication follows that FTU $Q^{1.0}$. In fact b_f was 1.05 in the latter case; the general level of turbidity being practically directly proportional to discharge throughout the range of discharges examined, i.e.

$$FTU = 0.3122 \qquad Q^{1.05} \qquad (4A)$$

APPENDIX B

Phytoplankton and Turbidity

Holmes & Whitton (l98la; 198lb) describe phytoplankton blooms in the River Tees and also noted a tendency for the number (No.) of individuals in the flow to increase with discharge. Partly on the evidence of a previous investigation (Butcher *et al.*, 1937), they concluded that the main source of phytoplankton drift was the river bed, material being suspended by scouring discharges. The contribution from reservoir releases was deemed negligible.

Holmes & Whitton (l98la, Table 4) give concentrations of live and dead planktonic diatoms for a station close to Broken Scar for each month in the water year 1977 for which there are corresponding turbidity data. As total concentrations of phytoplankton may exceed 3×10^9 No. m^{-3} it is of value to speculate as to whether or not phytoplankton density increases turbidity values. Both variables, however, are a partial function of discharge; which correlation needs to be removed before valid comparison of the variables may be made. Linear detrending of both series successfully removed the influence of discharge. There was no significant relationship between corrected values.

Despite the above result, no firm conclusions can be drawn. The data set was small and no phytoplankton density data were available for high discharges, so it is conceivable that a more extensive investigation could yield a conclusive result.

Fig. 1A Relationship between calibration suspended sediment concentration and turbidity. Curve (1) is equation 1A, Curve 2 is equation 2A and Curve 3 is equation 3A in text, p. i & ii.

Fig. 2A Relationship between calibration suspended sediment concentration and discharge. Low gradient curve is the least squares fit (1n SSC = 0.6396 + 0.8076 1n Q, r^2 = 0.48) and the steep curve is the structural relationship, (1n SSC = 0.3622 + 1.1704 1n Q, r^2 = 0.48).

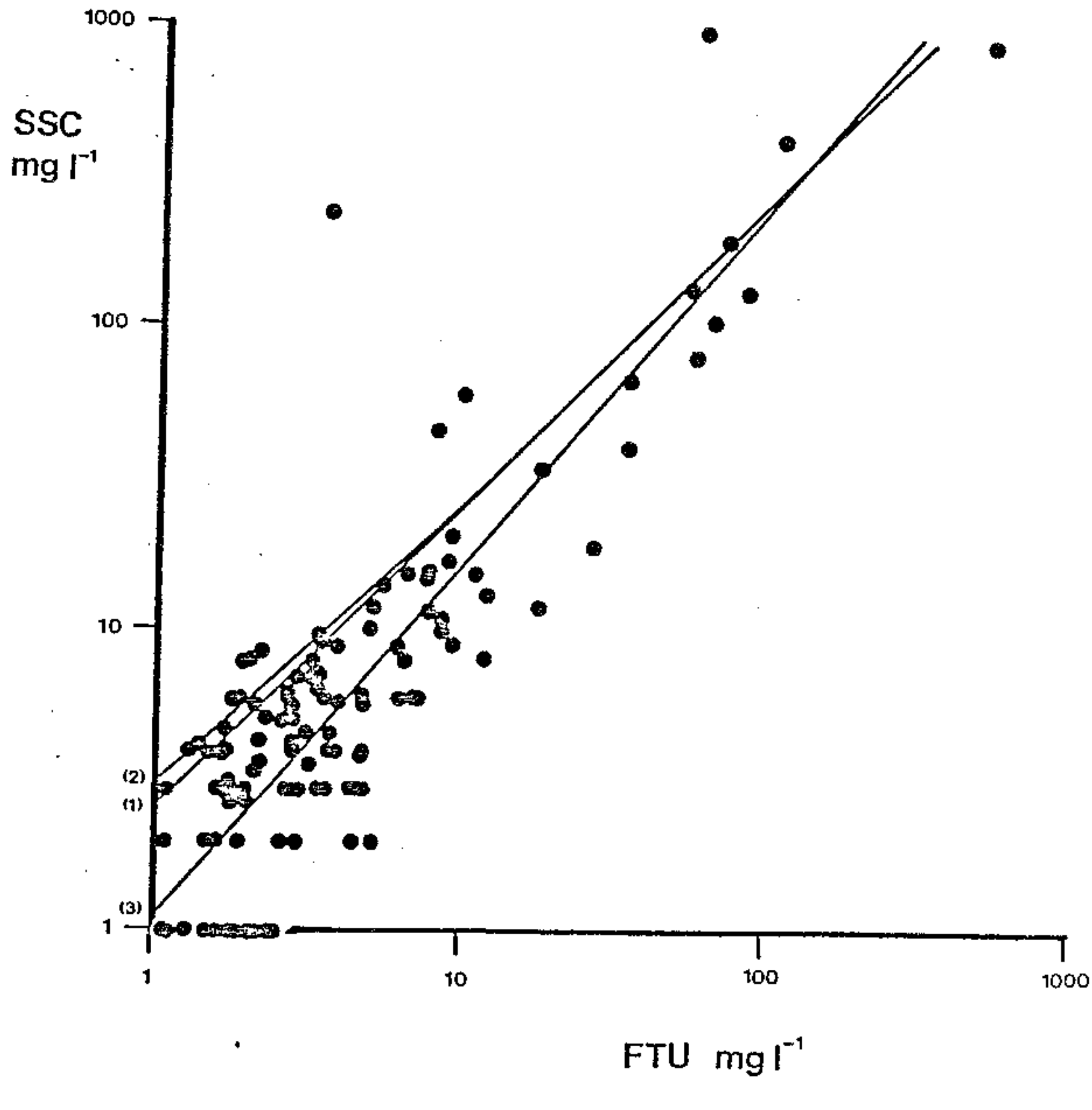

1000
100
10
1
SSC
mg l⁻¹
(2)
(1)
(3)
1
10
100
1000
FTU mg l⁻¹

FIG 2A