THE EFFECTS OF KIELDER RESERVOIR ON THE ECOLOGY OF THE RIVER N TYNE

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3.6 SUMMARY AND RECOMMENDATIONS

3.6.1 THE RESERVOIR

Construction of the Kielder scheme commenced in 1976, and impoundment of water behind the dam started inn 1980 forming by 1982 an 11 km long reservoir covering an area of 1086 hectares with a maximum depth of 52 m.

Between 1981 and 1983 two hydro-electric power turbines were installed at the base of the dam. One is designed to operate on Compensation Water discharges of 1.3 m^3/s, the second is a bigger machine designed to operate at a maximum discharge of about 14.1 m^3/s. Releases from the reservoir into the river North Tyne downstream are now designed to maxmise income from the sale of Hydro Electric power, (HEP). Generally HEP discharge releases through the turbines vary each day from Compensation Water values, up to a maximum flow of 15.4 m^3/s, except when the reservoir is nearly full to overflowing, when the discharge is continuous. To obtain maximum efficiency, draw-off from the reservoir is at several levels, but about 70% is through the scour valve at the bottom of the reservoir.

Water quality in the reservoir is related to quality of inflows and also bed deposits; within the reservoir water quality varies with depth especially during periods when the reservoir is stratified thermally. In winter the water stored in the reservoir is usually well oxygenated due to circulation through the action of wind, but as ambient temperatures increase in summer the reservoir becomes thermally stratified. Stratification begins in early May and increases until natural overturn in September or October.

3.6.2 THE RIVER NORTH TYNE

The North Tyne has an established migratory fishery, and the upper reaches of the river and its tributaries provide extensive fish spawning areas. To mitigate the loss of spawning grounds due to the flooding of the upper valley, over 160,000 hatchery reared juvenile salmon are introduced in the North Tyne every year.

Recent improvements to the quality of the Tyne estuary, by the construction of the Tyne interceptor sewerage scheme, has substantially improved conditions for fish migration and will enhance the fishery and influence other biota in the long term. It is therefore of particular importance that discharge from Kielder be managed in a way which does not hinder enhancement of the salmonid fishery.

3.6.3 Invertebrates

During investigations invertebrate samples were collected monthly from seven sites on the North Tyne and two on the nearby river Rede, which was used as a control.

Both the North Tyne and the Rede were found to have a generally rich and diverse fauna. However, there was a marked reduction in both species diversity and in abundance immediately below the dam, in particular at Yarrow, a site only 0.2 km below the stilling basin. Further downstream the invertebrate communities are much improved, and at Newton, a site some 14 km from the dam fauna showed great species richness and diversity, on a level with that found in other clean northern rivers. Furthermore the biotic scores obtained at sites greater than 3 km from the dam have steadily improved since impoundment.

3.6.4 Salmonids

The research programme was designed to investigate the environmental impact of the operation of Kielder dam on each stage in the life history of the salmonid population; the stages of spawning, swim-up and early development, and adult fish.

Changes in the adult population have for many years been monitored by electro-fishing surveys of the North Tyne, South Tyne and river Rede, and by the collation of detailed rod returns from anglers. Research programme surveys showed that populations of 0+ and yearling salmon and sea trout are greatly reduced immediately below the dam, but population rapidly improve downstream, in a way which reflect the results of the invertebrate surveys. Rod returns show a significant improvement in the status of the North Tyne salmon fishery.

Annual redd counts by water bailiffs indicate continued spawning at all known sites below the dam, including Yarrow. Comparative data have been gathered from the rest of the North Tyne and its tributaries, revealing the general abundance of redds now found in the North Tyne.

Since it has been established that there is ample evidence of spawning below the dam, but a sparcity of young salmonids, fish study was concentrated on determining at which point in the life cycle of fish disruption in recruitment occurs.

Experiments on the survival of both green and eyed salmon ova in Harris boxes, planted at several sites on the river showed percentage survival to be good, with over 75% of ova surviving to the swim up stage even at Yarrow, immediately below the dam.

Further experiments in Freshwater Biological Association's experimental emergence boxes at Lartington have shown that alevins did not appear to have problems emerging from gravel covered with the same deposit that is widespread below the dam and which covered the gravel surface to a depth similar to that typically found in the field.

3.6.5 CAUSES OF ECOLOGICAL IMPACT

Analyses of water quality river discharge and water temperature data have suggested that three phenomena, associated with operation of the Kielder scheme, may be responsible for the changes and variations in both fish and invertebrate populations below the dam.

3.6.6 River Deposits

Below the dam, and at several sites downstream, an unusual deposit was observed to cover the surface of the river bed. When analysed this deposit was found to be around 40% organic in nature and is composed of very find silt held together by a matrix of algae. It has a considerable metal content, (5% Iron, 5% Aluminium and 1% Manganese by dry weight) which are believed to originate from the anoxic hypolimnetic water at the bottom of the reservoir. It was also shown that the metal levels in the streams feeding Kielder reservoir are generally higher than those found in the river system downstream; this may be a consequence of afforestation.

During periods of low discharge in summer months, the deposits were found to be up to 2 cm thick, and could therefore have a blanketing and smothering effect on much of the invertebrate community. During periods of compensation level discharge only, the deposit was particularly widespread. It was noticeable that organisms normally occurring on clean surface of stones, (e.g. Simuliids and Heptagenid Mayfly) were invariably absent at Yarrow, where the deposit was most prolific.

As already described the deposit was shown by experiment to affect successful emergence of young salmonids from the gravel. It is also likely to cause clogging of the gravel at Yarrow and thus to impair the passage of oxygen. It may even affect the functioning of the fish gills. It is possible that high metal content of the deposit may cause problems of toxicity.
When HEP generation is taking place the deposits frequently appeared to be moved downstream; they were found periodically at other sites along the river.

Deposits of a similar nature have been reported downstream of other reservoirs elsewhere.

3.6.7 Temperature Changes

Results showed winter temperatures in the river immediately below the dam to be significantly warmer than ambient conditions. For example, during a winter week 1.5°C above the dam at Butteryhaugh, compared with 4.5°C immediately below the dam at Yarrow and 2.5°C at Chollerford 35 km downstream. In contrast, in June, the temperature below the dam was still only 7°C when at Chollerford it had reached 15°C. These values represent changes in the natural thermal regime of the river. It is believed that they may have a disruptive effect upon several stages in the life cycle of both salmonids and invertebrates, many aspects of which are triggered by thermal "cues".

Warm winter temperatures below the dam seem to cause an increase in the rate of salmonid egg development, which if followed by cooler releases in early summer due to reservoir stratification, could result in a considerable time-lag before a critical water temperature of 7°C is reached. It is at this temperature that the young fish begin to feed. This time-lag could cause newly emerged fry to starve to death. The study showed that in the winter 1986/87 there was a gap of several weeks between the emergence of young fish from the gravel and the first day when river temperature reached 7°C. In the winter 1987/88 no such lag occurred.

Another cause for concern is that young fish, developing more slowly in cooler summer water temperatures found below the dam, will reach a smolting stage relatively late in the year. A water temperature of 11°C is required to induce smoltification. The smolts would have to pass through the Tyne estuary in the warmest part of the year when any pollutants in the tidal waters would have maximum impact by reducing oxygen levels.

3.6.8 Fluctuating Flows

The full or potential influences of fluctuating discharges and velocities in the river downstream of the dam are still being analysed. Nevertheless fluctuating flows of the type associated with hydro-electric power generation are normally believed to be harmful to invertebrate fauna of a stream, since very few organisms are adapted to sudden changes in water velocity. Effects upon fish population below a dam can be equally harmful. The flow fluctuations may cause displacement of fry or failure to attract upstream migrants.

The latter of these two perceptions did not seem to occur at Kielder, where adult fish were observed to spawn below the dam successfully. It is possible that riffle-pool seqences may be disrupted by sudden releases from the dam; this is still under investigation.

Since the impoundment, constituency of sediments in the North Tyne has coarsened as far downstream as Bellingham and "armouring" of the bed has taken place. This "armouring" makes it more difficult for the salmon to dig their spawning redds. Evidence of "armouring" was found at Newton. Also during periods of tributary floods, sediments may be washed into the North Tyne system, these may build up unless accompanied by adequate releases from the reservoir, and spawning beds may silt up.

The fluctuating flows, and therefore changes in wetted areas at the stream margin, will cause exposure of eggs to dual hazards of dessication or freezing. Redds were found below the dam having been completely exposed during periods of Compensation flow but mild conditions during observations precluded observation of the influence of freezing temperatures.

3.6.9 CONCLUSIONS

The three-year programme has served to reveal why and to what extent Kielder Water, and releases to generate hydro-electric power, are influencing ecology of the river North Tyne. Study of invertebrate and fish populations have, in particular, led to the general conclusion that there is presently ecological impact for at least 14 km downstream of the dam. It is not yet determined whether the impact will remain constant and within this limit.

Reasons for impact have been detected, or are believed, to include

- dislocation of reproductive cycle caused by deposit of an alluvial/algal/metals matrix on the river bed,
- seasonal change in thermal regime of river flow,
- disturbance of breeding grounds caused by bed armouring, and
- more frequent variation in velocities of flow and river discharge due to hydro-electric power generation.

Analyses of these and other features are currently being carried out for full appraisal and final report in April 1989.

3.6.10 RECOMMENDATIONS

Although in advance of full and final report IT IS RECOMMENDED that discussions should take place within Northumbria Water on a range of operational criteria which are currently believed to bear upon future ecological impact. These should include the following:

(i) Releases from Kielder during summer months should be designed to avoid protracted periods of Compensation Water only, to prevent downstream deposits of silt/algae matrix.

(ii) Consideration should be given to providing releases which in the autumn will encourage upstream migration of spawning fish.

(iii) Since downstream bed matrix deposits with high metal deposits are believed to be the result of releases from oxygen-poor waters of the reservoir's hypolimnium, consideration should be given to:

- prevention of stratification, and/or
- releases from the reservoir primarily not from scour valve levels especially during sensitive times of a year.

(iv) A proven computer simulation model allows reliable forecast of river temperatures downstream of the dam when reservoir temperatures are known. This consequently permits forecast of critical temperatures influencing survival of biota. Consideration should be given as to how this model might be used in conjunction with reservoir water temperature monitoring to best manage releases to minimise ecological impact.

(v) Consideration should be given to the possibility of using controlled release freshets which might have the benefit of reducing the extent of armouring and also the build up of sediments and harmful silts deposited by tributarial inflows downstream of the dam.

CHAPTER FIVE : SEDIMENT STUDIES

by D Sear

3) rates of adjustment and degree of change will be unique to the conditions within the post-regulation channel.

Petts (1979, 1980) identified three major adjustments to a river subsequent to regulation: 1) degradation 2) aggradation 3) channel metamorphosis. Included within these basic categories of adjustment are the four dimensions of channel change, 1) vertical, 2) lateral, 3) longitudinal and 4) temporal (Knighton A D 1984). The mechanisms of these changes involve some alteration of width, depth, capacity, slope, topography, hydraulics and sediment characteristics through time (Petts' Model of Change Through Time, Hey 1975).

Carling (1988) further emphasised the importance of aggradation within regulated channels, and reiterated the conclusions of Petter (1979, 84, 87) on the importance of the role of unregulated tributary sources of sediment and floods.

The following discussions of suspected environmental impacts associated with channel and sediment changes subsequent to regulation are based on studies to date with specific reference to gravel bed rivers.

Channel Degradation

Channel degradation occurs where competent flows occur in the absence of sediment supply. Degradation was until recently, seen to be the dominant and primary affect of regulation associated with proximity to the dam and seen as a migrating erosional front controlled by slope, roughness and the degree of bed armouring. Degradation is maximum between the dam tailwater and 69 channel widths, downstream. Petts (1984, Petts & Thoms 1987) identified increases in depth where channels were narrowed by aggradational episodes but the process of degradation is different being a function of increased sediment supply in relation to reduced flow competence rather than reduced sediment supply and maintained flow competence. Petts (1979) makes the point that in gravel bed rivers no degradation is likely owing to the armoured status of the channel prior to regulation. This point is emphasised by Kellerhalls (1982) who points to the sand bed nature of all degradation documentations below high dams and the lack of degradation found below four major dams on active gravel bed rivers. These situations reflect the relative importance of flow incompetence over reduced sediment supply. Degradation is possible at riffle sites experiencing flows competent to remove particles under the higher velocities but incompetent to transport particles from upstream pools. This process would again by controlled by armouring and slope could be important following armour loosening floods or overloosening by salmon redding.

Aggradation

Aggradation occurs when sediment supply exceeds flow competence. Kellerhalls (1982) suggests that flow competence can be reduced considerably by only a small flow reduction.

Consequently a reduction in flood peaks coupled with a continuing sediment supply will lead to aggradation. These conditions occur most rapidly and to greatest extent at the inflow of irregulated tributaries (Petts, 1979, 84, 87; Carling 88, Kellerhalls 82, Milhous 82). The extent of aggradation is conditioned by the balance between sediment supply and frequency of competence flows. The rate of adjustment is related to the effectiveness of tributary floods; and the degree of tributary rejuvenation due to reduced base levels, one flood being capable of supplying enough sediment to reduce channel capacity on the river Rheidd by 60% (Petts 1984); and also the tributary catchment land use (Newson 1980, Petts 1984). Petts & Thoms (1987) proposed a model whereby continued supply of sediment from an irregulated tributary coupled with increased flow competence in the narrowed mainstream will effectively allow downstream migration of sediment and hence the aggradational front resulting in the build up of depositional channel side berms and a reduced channel capacity. The downstream extent of aggradation from tributaries range from 50 m to > 8 km (Kellerhall R (1982).

The growth of tributary bars can in some instances increase the flood hazard upstream due to ponding of flow similarly the increase in water depth due to ponding reduces the upstream sediment supply and velocities encouraging the possibility of aggradation upstream and downstream of tributary confluences.

Aggradation also occurs due to redistribution of channel sediment where flows remain competent but sediment supply is reduced. The possibility of riffle degradation could result in a corresponding pool aggradation, effectively unifying channel slope. Petts (1983) mentions the plastering of fines on the bank of channels leading to a positive feed back mechanism with vegetation colonisation. Stabilisation of bars by vegetation leads to increased trapping of fines and subsequent aggradation. The growth of new depositional bars and islands can be encouraged by vegetated colonisation in the main channel (Northrop 1965). Back aggradation can be effected by bank collapse (Petts 1978).

Armouring

The armouring of a gravel bed river is a well documented phenomenon and is a typical situation for non-regulated gravel bed streams (Carling & Reader 1982, Church et al 1985, Bray & Church 1980, Petts 1979). Within regulated streams the size and compaction of the armouring of a channel can be increased in the absence of sediment supply and the maintenance of flow competence events. In extreme cases the bed could become paved (Bray & Church 1980). The preferential removal of finer particles, hydraulic winnowing, can be maintained and riffle sites under regulated flows, this situation can be deleterious to salmonid spawning (Milhous R T 1982). Armouring is also a feature of degradation below dams, but this is confined mainly to sand dominated channels although riffles nearest to dams may be armoured due to reduced sediment supply. Localised armouring at channel confluences can be achieved by the increase in velocities through a reach constricted by an aggrading confluence bar. The effectiveness of the armouring process will be conditioned by the reduction of the frequency of competent flows and the reduction of fine sediment transport (Walters W H 1982).

Siltation

Siltation involves the infiltration of fine sediment (<1 mm) into the voids within a gravel bed. This process can be deleterious to salmonid egg survival and can effect changes in the structure of benthic invertebrate populations if excess siltation occurs. Carling & Crisp (1989) suggest that salmonids tend to select gravels with <20% (by weight) material </mm and means for gravels selected by such fish species rarely exceeded 12%. Milhous (1982) concludes that salmonids use fairly narrow size ranges for spawning with <11% material <6.3 mm size being typical for spawning grounds. Maximum siltation rates occur for events with high sediment loads and maximum bed parasite conditions satisfied on receding flows of the first flood after a long period of low flows (Milhous 1982). Carling (1987) concluded that siltation of salmonid pedds could take as little as 2-3 days under conditions of maximum siltation. The sediment supply aspect involved with siltation, would seem to infer a maximum siltation potential at tributary confluences and a minimum at near dam spawning sites (Milhous 1982). Frostick et al (1984) suggested that void filling is incomplete when a coarse armour exists, this is primarily due to the ingress of coarser particles into the bed whilst finer particles are winnowed out.

The reduction in frequency of armour disrupting flows after regulation may well increase the siltation potential of spawning grounds given a source of sediment. A change in land use, such as forestry can accentuate the siltation rates by increasing sediment supply, a potential problem when considering the common association of regulation schemes with afforestation (Newson 1980, 1986, 1988; Milhous 1982; Petts 1984). A feature of some uplaid gravel bed regulated streams appears to be the formation and growth of a dense periphyton layer made up of silt clays and algae communities (Gilvear 1987). This organic deposit is found in unregulated streams, but appears to be accentuated under regulated flows.

Timescales

In discussions of channel changes due to regulation a minor point to recall is the uniqueness of an individual system response and the complexity of variable interrelationship that conditions the response. Rates of adjustment to river regulation have been related to the frequency of competent discharges sediment supply and rapidity of colonisation by riparian vegetation. Using these conditions Petts (1980) derived a model for channel change through time. Whilst this model identifies the potentially rapid response of a system to regulation (reaction time) and the larger relaxation time to effect a new equilibrium, no values for time are included. In an earlier model (Petts 1979) that showed the sequence of changes leading to reduced channel capacity, Petts included the time dimension. This model emphasises the initial rapid response downstream of tributary inputs and occurring within 10 years after impondment. Subsequently most of the river, up to a point where regulation effects are minimal, adjusts within 100 years.

In gravel bed rivers the processes of change will be triggered by extreme events and the probability of these increase with time. The reaction time in this case is conditioned by flood frequency of a required competence to effect a change. The relaxation time can be considerably reduced by stabilisation of deposits by riparian vegetation (Petts 1980). Reference to table 1 identifies the rapidity of aggradational processes relative to degradation, and the importance of tributary sediment inputs.

ADJUSTMENT	TIMESCALE	SOURCE
DEGRADATION	Riffles destroyed after 26 years	Trinity scheme (Boles 1980)
	30 cm during 1 event	Cleweley Dam (Thorne 1982)
	0.3-3.9 cm yr^{-1} 9 years (nearest dam)	River Ter (Petts & Pratts 1983)
	0.3-3.2 cm yr 9 years (further from dam)	" " " " "
AGGRADATION	1.5 m yr^{-1} (Tributary source)	Peace River (Kellerhall 1982)
	1 m during one event (Tributry)	Colorado River (Dolan et al 1974
	7.2 cm yr^{-1} (Tributary event)	Rheidol (Petts 1984)
	4.2 cm yr^{-1} (Redistribution)	River Ter (Petts & Pratts 1983)
	12 cm yr^{-1} (Redistribution)	Bistinta River (Ichim Radoane 19
ARMOURING	34 years after dam - armouring of spawning riffles reduce fish stocks by 60%.	Sacramento River (Milhous 1982)
	Medium grainsize increased after 25 years regulation	Colorado Mustafa (1980)
SILTATION under regulated flows	(0.0152 kgm^{-2} day^{-1} below dam *	
	(0.1178 kgm^{-2} day^{-1} after significant *	N Tyne
	(tributary inputs	
	[All riffle sites]	
during baseflow	0.0157 kgm^{-2}day (pool riffle) * unregulated	Great Eggleshope Beck (Carling 1987)

(* TIME AVERAGED MEAN)

Rates of degradation will 'tail off' as armouring effects a balance between flow competence and sediment supply.

Aggradation occurs most rapidly at tributary confluences. Aggradation due to bank fines plastering occurs less rapidly, a reflection of sediment supply and calibre. Rates of armouring in regulated gravel bed rivers are difficult to determine and poorly represented in the literature. Table 1 refers to two cases in the United States, but as with many studies the channels have a high sand load. The adjustments do however occur within 35 years and therefore represent a rapid reaction time. In unregulated catchments pavement formation occurred within 2 - 3 months (Gomez 1983), and during discrete flood events (Milhous 1987). In regulated gravel bed rivers, a coarse armour layer is likely to exist prior to regulation. The rate of armouring will then depend upon the number of flow competent particles on the bed surface. Rates will vary with increased armouring likely on riffles where flows are fastest and shear stresses highest at low-medium flows. The degree of armouring may be slight, but compaction may be high due to a greater frquency of low-medium flows. Compaction can occur within periods of months (Frostick et al 1984) and may be deleterious to spawning salmonids.

Siltation rates fluctuate according to supply and event frequency. During freshets, rates can be up to 1000 times as high as during base flows (Carling 1984, Frostick et al 1984). Siltation is variable within a channel with maximum levels downstream of tributaries and within pools, and slack water zones. Carling (1987) estimates 2-3 day siltation of salmon spawning redds under maximum siltation rates in unregulated streams. Siltation is often increased during dam construction when large quantities of fine sediment may be released (Davey et al 1987). The impact of construction phase siltation will depend upon the 'flushing' capacity of post dam flows. Davey et al (1987) also noted distinct seasonality in rates of siltation with maximum siltation in the winter and spring and minimum siltation during autumn when mean flows were lowest. The peak in sediment siltation occurs nearest the damsite during construction phases (Davey et al 1987) when maximum sediment loads occur.

CHANNEL TOPOGRAPHY

Channel topography and sediment characteristics are necessary criterion by which to assess and predict river channel adjustments, both spatially and through time. The history of channel change and sediment distribution, coupled with patterns in past and present flow regimes, interact to condition with contemporary fluvial environment.

The river North Tyne drains a catchment area of 1118 km^2, consisting of carboniferous sandstones and limestones with a dominant East South East strike. The North Tyne valley follows the strike as far as the confluence with the Rede (20 km downstream of the Damsite) then abruptly alters course some 70 south.

The North Tyne is a low sinuosity (0.76) partially geologically confined cobble bed river (D50 = 59.8 mm). The channel exhibits a system of well defined, diagonally alternating riffles and pools, and remnant zones of sedimentation, (Church & Jones 1982, Church 1983, Macklin & Lewin 1989).

The river flows within a glacially modified valley, infilled with boulder clay, but with areas of fluvial sands and gravels forming a floodplain up to 1 km wide. Multiple sets of terraces and palaeochannels testify to a laterally and vertically less stable channel in the past (Peel 1941, 1949); however for at least the last 123 years the channel has occupied essentially the same course.

The channel from the damsite at Yarrow Moor (GR 709879) to the confluence with the river Rede (GR 859821) some 20 km downstream has a mean slope of 0.00174. This is considerably shallower than the rivers South Tyne, Derwent and Allens, (Peel 1941, 1949). At a distance of 19 km downstream of the damsite a marked knickpoint occurs, and the mean slope steepens to 0.00265 to the South Tyne confluence. Peel (1949) attributes the knickpoint to river rejuvenation following post glacial tectonic action. Valley profiles below the Rede confluence exhibit a marked reduction in floodplain width as the channel becomes confined by discrete gorges and rock bluffs. Channel slope in this reach is controlled by bedrock outcrops and mega-riffle forms. Historically this reach has always been more stable than above the Rede confluence, with fewer and temporally less active deposits of traction load.

CHANNEL TOPOGRAPHY: DAMSITE-REDESMOUTH

Channel topography within the post regulation North Tyne reflects the climatic trends in flood frequency and sediment supply over the past 100 years. Figure 2 illustrates the gross changes in active sediment storage within two 20 km reaches of the North & South Tyne and the associated patterns in flood frequency and land-use.

The contemporary channel is characterised by a lack of active gravel bar forms, but instead displays vegetated islands and former gravel bars. Historical analysis shows a general reduction in active gravel area since 1898 but a marked increase in reduction rate since regulation in 1980. This is primarily due to colonisation by riparian vegetation (Petts 1980).

The dominant gravel bedforms exist as an alternating sequence of riffles and pools and a suite of tributary confluence bars. The riffle-pool sequence has remained stable since 1976, and probably since the 19th century except in areas of active sedimentation. Table 2 illustrates the fundamental physical parameters of the reach from the dam to the Rede. A mean riffle spacing of 6.7 w falls within the accepted values for gravel-bed rivers of 5-7 times bankfull width (Petts & Foster 1983), but a significance of only $5r^2 = 13.5$ reflects the dominance of other environmental parameters on riffle spacing. Riffle spacing is shortest in areas of active sedimentation which may reflect the importance of sediment supply (Hooke & Harvey 1983, Fergusson & Werrity 1983, Church & Jones 1982).

In the past, zones of sedimentation and channel instability (Church & Jones 1982, Church 1983, Macklin & Lewin, in press) have existed at eight sites along the North Tyne at: Falstone meander (GR 727824), Ridley stokoe/Llyne (GR 745848), Newton/Hesleyside (GR 809845), Dunterley (GR 823836), Bridgeford (GR 851824), Gold Island (GR 861778), Chipchase Mill (GR 878752) and Chollerford weir (GR 919705). These sedimentation zones have exhibited maximum channel change and riffle migration, although today most of the relict barforms are vegetated and stabilised.

Since impoundment in 1980, bar forms have developed at almost all the tributaries downstream to the Rede confluence. Particularly prominent examples exist at the confluences of Hawkeshope burn, Smales burn and Tarset burn where channel width has been reduced by up to 50%. Tarset bar developed within 3 years after regulation (Petts et al 1987), was removed in 1984, and has since been replaced by a larger bar again within 3 years. Channel depth has been locally increased below the confluences due to scour in the confined channel (Petts 1980, Petts et al 1987, Best 1987) with maximum values attaining 2 m.

Comparisons between cross-sections made by the NWA and FBA in 1978 and re-surveys made by the NWA show localised sediment re-distribution throughout the channel often reflected in a lateral shift in thalweg and an increase/ decrease in depth. Thalweg degradation is most evident up to 3.5 km downstream of the dam, with maximum values (0.5 m) attained around the footings of Falstone bridge (Fig 3); further analysis will be necessary to elucidate the rates and implications of this change.

Re-surveys of FBA 'Charlton riffle' (NWA 'Newton) some 13.5 km downstream of the damsite, show a general degradation of the channel and a maintenance of slope (0.0053) (Fig 4). A distinct channel has developed ,confined between the river bank and mid-channel island reflecting the frequency of regulation discharges. This site is located downstream of the Tarset/ Chirdon confluences and is therefore subject to periodic flooding. Degradation of riffle sites have been reported (Milhous 1982) and can be attributed to the increased frequency of moderate flow events in the absence of sediment supply. Results during a test release indicated flow competence up to 22.4 mm B-axis this riffle site, but a competence of only 8 mm in the upstream pool. Consequently there exists an imbalance in the sediment transport/supply system resulting in a net removal of flow competent particles off the riffle under HEP discharges. Furthermore vegetation of the mid-channel island has increased roughness thereby funnelling flood flows through the riffle, locally increasing erosion potential.

SEDIMENTS

Sediments in the North Tyne reflect the supply from tributary source, bedrock outcrops and redistribution of in channel storage. Since regulation bank erosion has been stabilised as a major sediment supply except at Dunterley(GR 823837) and Gold Island(GR 861778).

From the damsite to the Tarset Burn confluence, the bed is characterised by boulders up to 2 m b-axis. These are derived from rock bluffs and tributary inputs. From the tarset confluence to the River Rede, few boulders exist and the channel is stable between banks of alluvium. Below the Rede confluence significant gorges and exposed bedrock bars increase the channel roughness and boulders again characterise the bed.

Two 'benchmark' surveys were conducted prior to regulation; one, of bar head surface sediments in 1960 by the late D G Hall (Hall 1960), and a further survey of bulk riffle sediments was made in 1978 by the FBA (Carling 1979). In 1988 Hall's sites, sites downstream of the damsite were re-sampled together with 14 of the FBA Site identification was positive in all cases, and at the FBA sites accuracy was possible up to 10 m^2. Sampling methodology was replicated for each survey.

Figure 5a illustrates the changes in surface bar-head sediment B-axis for 12 sites downstream of Kielder reservoir since 1960. Values of mean B-axis for the 1960 survey were calculated by regression from 1988 data for particle size and volume (r2=78). The pattern shows a marked coarsening downstream of the damsite until at Tarset Footbridge (GR 774863) a reduction in mean B-axis occurs. Downstream of the Rede surface sediments exhibit a coarsening until the confluence with the South Tyne(GR 917861).

When viewed in context with data from the South Tyne survey (Fig 5b) the pattern of increasing particle size is not attributable to any process other than climatic control. The late 1960's represented a period of increased flood frequency that could be reflected in a coarsening of surface sediments (Milhous 1987). Elucidation of this pattern is provided by the re-sampling of 1978 riffle sites.

Figures 6a & 6b illustrate the patterns of sediment change since regulation, as reflected in both mean B-axis and percentage of material <1 mm B-axis. The latter represents the size range identified as critical (<20% by weight) for successful salmonid spawning ground selection (Crisp and Carling 1989) and egg survival.

Armouring of the riffles has occurred up to 7 km downstream of the dam, and again beyond the Tarset Burn confluence. This is reflected both by the FBA and Hall re-surveys. A reach between 7-10 km downstream of the dam has exhibited a marked fining since impoundment. This may represent the present location of eroded fine material from sites upstream. The movement of a 'slug' of sediment through a gravel bed river has been observed, albeit for coarser clasts (Church & Jones 1982, Church 1983, Macklin & Lewin in press). Reference to Figure 5b indicates a corresponding increase in the percentage of material finer than 1 mm in the fining reach 7-10 km downstream; however except for immediately below the dam, values do not reach levels deleterious for spawning. The high levels below the dam reflect the presence of boulder clay immediately beneath the gravel bed as both suspended solids values and rates of siltation are low. In the reach below Tarset Burn levels remain similar to pre-regulation with the exception of Dunterley riffle.

CONCLUSION

1) The reach below the damsite to the confluence with the Rede has historically been a zone of sediment storage. The present channel has occupied the same course for at least 120 years, with gross channel changes restricted to discrete zones of sedimentation (see 4 below).

2) The current riffle-pool sequence reflects the history of sediment supply and transport prior to regulation. The inter-riffle spacing does not reflect the dominance of any single aspect of hydraulic geometry but rather the subtle local changes variability in gross fluvial environment downstream.

3) Since regulation the rate of reduction in active gravel area by the encroachment of riparian vegetation has increased despite local incision, effectively stabilizing gravel bars, reducing sediment supply and locally increasing channel roughness.

4) Channel topography in the post-regulation North Tyne is dominated by the development of tributary confluence bars at a rate determined by the supply of sediment from individual streams. Locally the impact on the channel is severe, but with time effects might be transmitted downstream as the sediment sink is filled and bypassed by further sediment input. More research is needed to quantify timescales of this phenomenon.

5) Degradation is apparent immediately downstream of the damsite but is not severe. Attention should be drawn to apparent scour around the piers at Falstone bridge. Re-distribution of sediments within the channel has occurred particulary at the Newton riffle 13.5 km downstream. Degradation has been effected by hydraulic winnowing under HEP flows and intensified flood routing through the riffle due to island vegetation.

6) Armouring occurred between 1960-1978 throughout the North Tyne primarily in response to a period of increased flood frequency. Subsequent to regulation channel armouring has continued on riffles: a) up to 7 km downstream of the dam, at b) at discrete sites below the Tarset Burn. A zone of fining is evident between 7-10 km downstream of the damsite.

7) Rates of riffle sedimentation by fines are highest after a storm and nearest a tributary. Sedimentation is lowest closest to the damsite. The dam is not a significant source of fines, but HEP flows mobilise fines brought in by tributary floods. In general the absolute content of fines in the North Tyne system is too low to cause major siltation problems.

METHODS OF AMELIORATION AND RECOMMENDATION

Two categories can be identified for ameliorating the impact of regulation schemes upon sediments and channel topography.

I Pre-regulation environmental impact assessment and recommendations

II Post regulation adaptive stragegies and implementation.

Category I would entail the identification of sediment characteristics, yield and distribution in the context of time. Considerations of the projected environmental impact of regulation flows upon the sediment criteria identified above would be required before recommendations for amelioration could be made. A structured monitoring scheme would be implemented at this stage including complementary surveys of channel biota and water quality.

Pre regulation environmental impact assessments could identify areas of likely deleterious channel/sediment change. A monitoring scheme should be introduced to index any system changes and target any necessary adaptive strategies.

An example of a Category I recommendation would be the siting of dams immediately upstream of tributary inputs, in order to ameliorate sediment starvation problems of degradation and armouring.

Category II is the option available to existing regulation schemes and also provides the flexibility for Category I decisions in response to change. Adaptive strategies would be identified through the monitoring programme implemented in Category I.

For the North Tyne, preliminary recommendations can be made to ameliorate channel armouring and degradation at selected spawning riffles, and methods to control the growth of tributary confluence bars.

a) Growth of tributary confluence bars Serious bar development has occurred at the Tarset burn confluence. Existing amelioration involves the removal of gravel by mechanical excavator. This is carried out on average every 3 years. The gravel is dumped on the bank or used by the local farmer.

A provisional recommendation would involve reinstating the Tarset burn gauging station and indexing dam releases to sediment transporting tributory flows. Releases from the dam could be made to coincide with sediment supply events. The releases would need to be of sufficient discharge to mobilise sediment supplied from the burns. The result would be the transport of material away from the bar zones and redistribution at sites downstream. Furthermore, sediment supplied in this way, coupled with the higher discharges could be effective in reducing rates of riffle armouring.

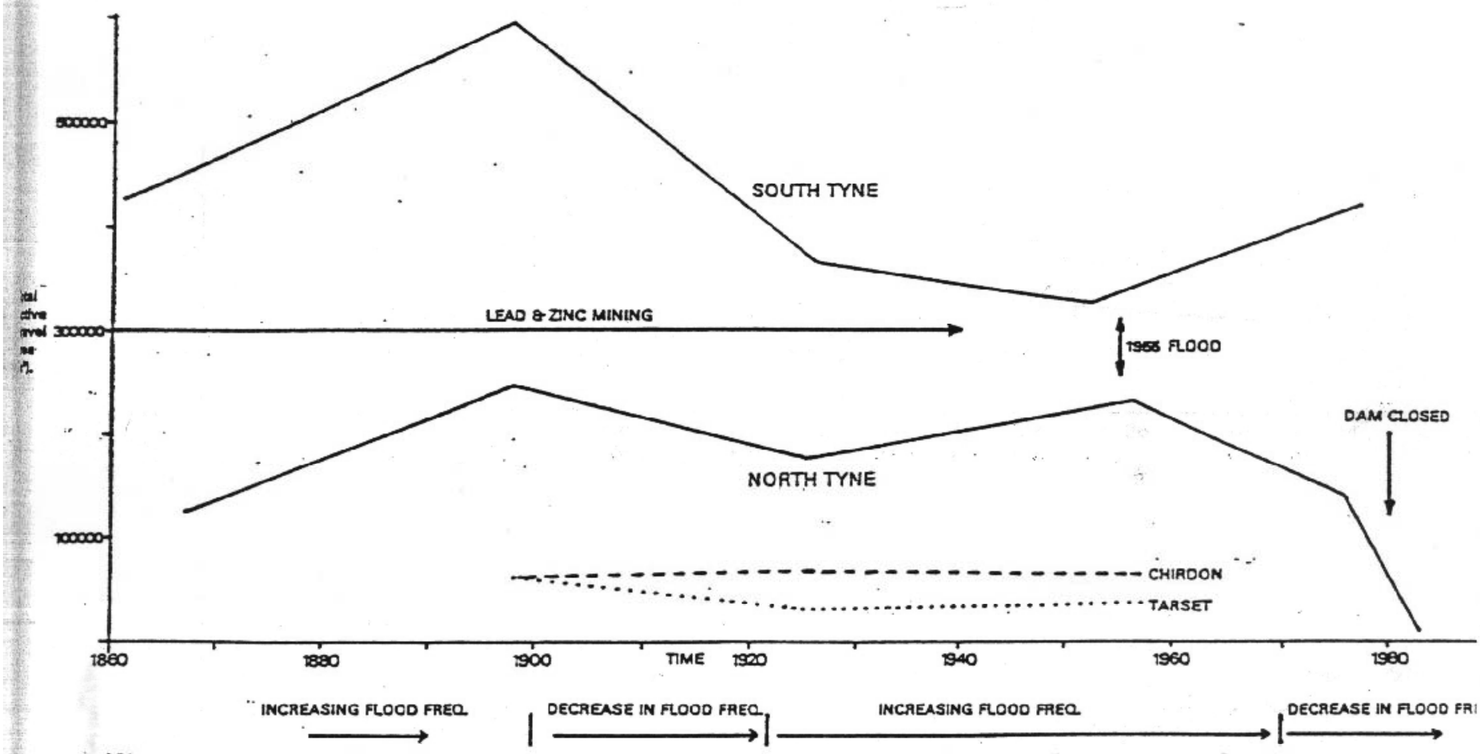
b) Armouring and degradation of spawning beds:- material removed from tributary confluence bars could be used to seed riffles identified as armouring. Riffle construction is documented successfully in recent literature (Brookes 1987, 1988). The character of riffle sediment prior to regulation should be used to determine the size distribution of reconstruction material.

c) Monitoring of the current 32 cross sections should be continued, with the addition of site specific sections at the FBA sites at Falstone meander, Ridley Stokoe, Charlton and Newton, and at selected tributary confluences, and at locations below the Rede confluence. Provisional monitoring timescales should average out to once a year at the triutary sites and once every 3 years at riffle sites. Flexibility should be allowed for, should rates of change require longer/shorter term monitoring. The use of an echo sounder should be considered for surveys in deeper water (> 45 cm).

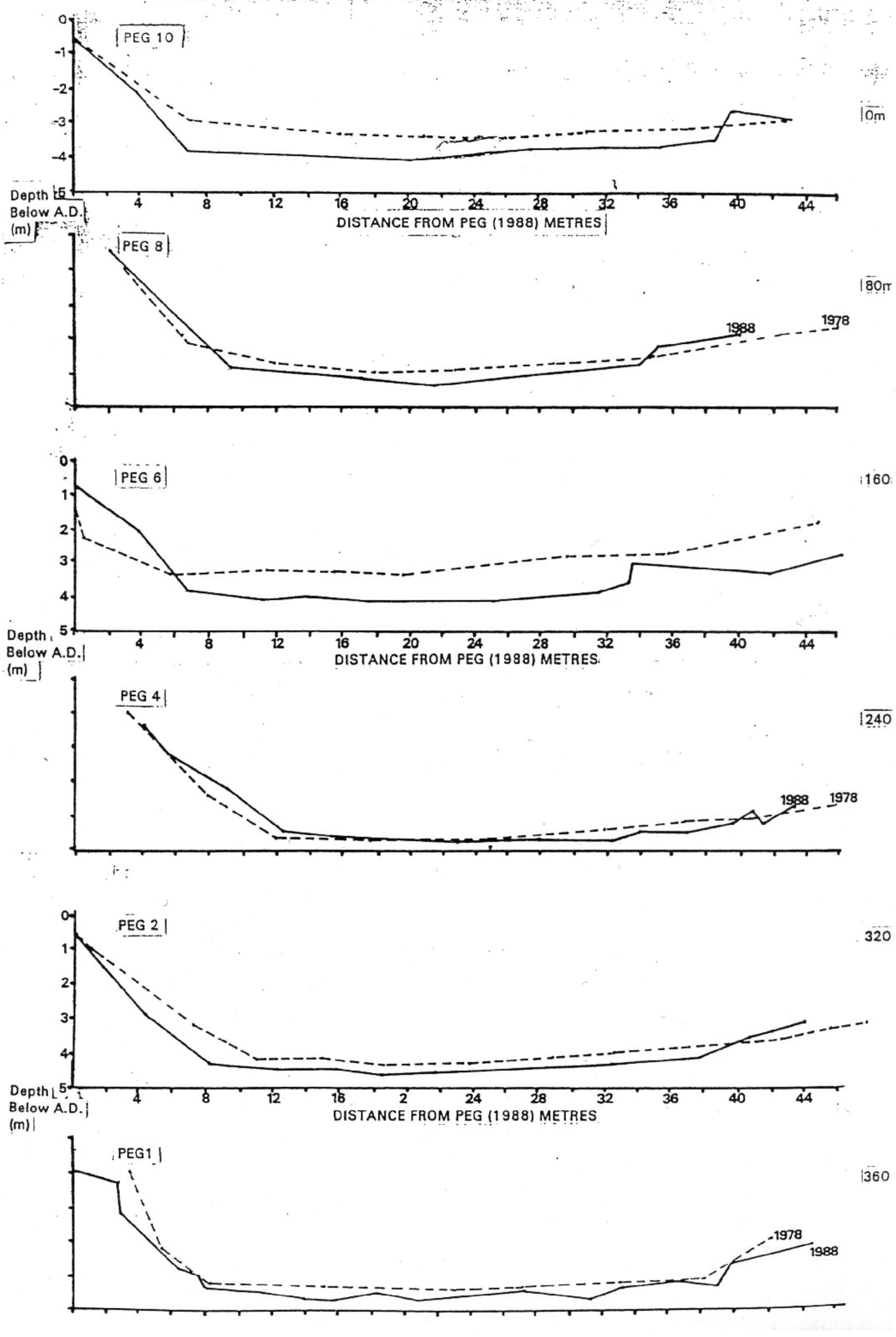
d) A gravel sampling scheme should be effected to monitor rates of armouring and siltation. FBA sites should be re-sampled with the addition of sites below the Rede confluence associated with maintained cross-sections. The use of bulk sampling methods at specific site locations should be augmented by surface layer analysis according to the method outlined by Wolmann (Wolman 1954). Re-sampling should be made every 3 years but with flexibility allowed for at sites experiencing accelerated or extended change.

It is recognised that economic constraints exist that may preclude the implementation of these recommendations. However, if monitoring schemes are developed, integration of existing biological and water quality surveys should be considered when sites are selected.

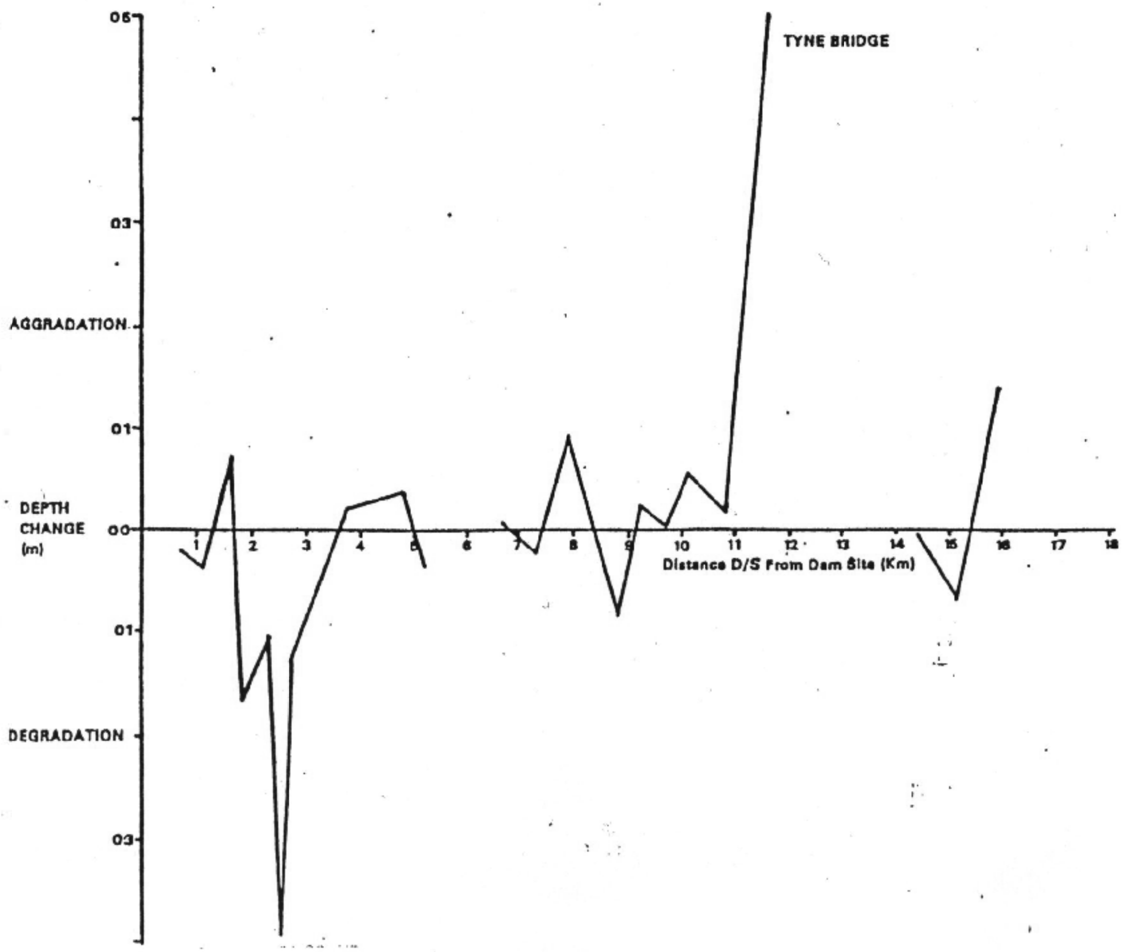
CHANGES IN TOTAL ACTIVE GRAVEL AREA SINCE 1860 FOR TWO 20Km REACHES ON THE RIVERS NORTH & SOUTH TYNE SHOWING MARKED REDUCTION ON THE NORTH TYNE SINCE 1981 REGULATION FOR H.E.P.



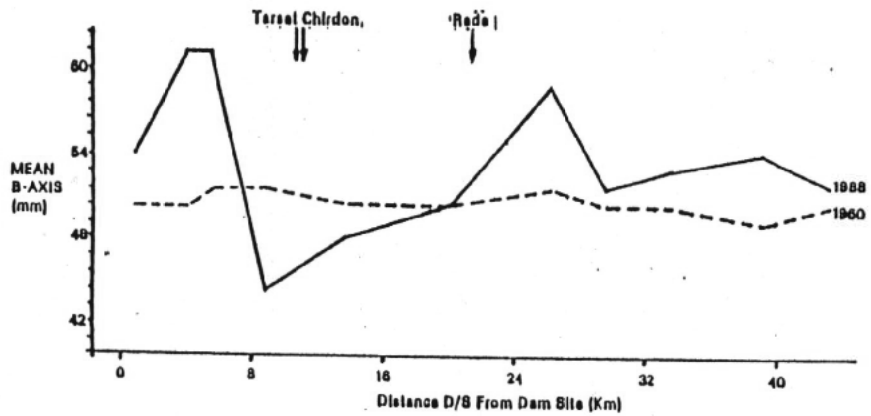
CHANGES IN CROSS-SECTION AT A 400m SALMON SPAWNING RIFFLE, 13.5Km D/S OF KIELDER DAM SITE FOLLOWING 10 YEARS OFREGULATION. RIVER NORTH TYNE. (After Carling 1979).



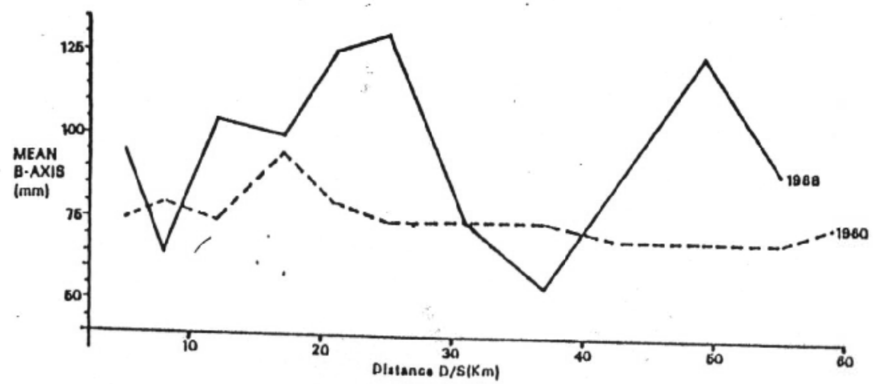
CHANGES IN THALWEG DEPTH FORA 20Km REACH OF THE RIVER NORTH TYNE BELOW KIELDER RESERVOIR SINCE REGULATION FOR H.E.P. (After N.W.A. Surveys 1978-1988).



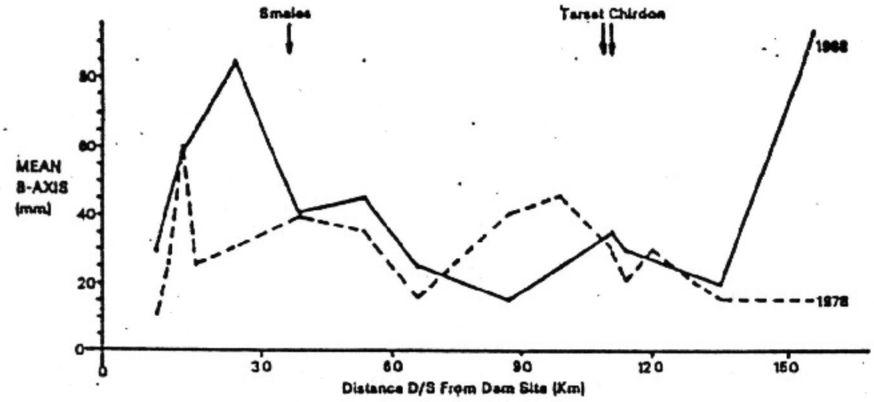
DOWNSTREAM CHANGES IN MEAN BAXIS BELOW KIELDER RESERVOIR
FOR 1960 (After Hall 1964) AND 1988. RIVER NORTH TYNE, NORTHUMBERLAND



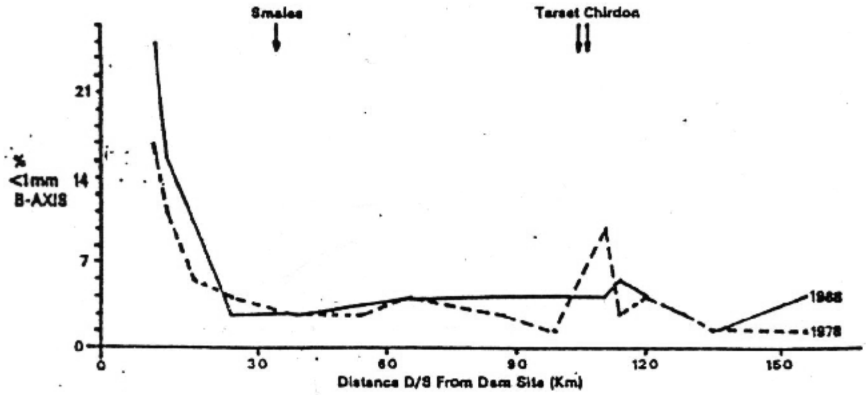
DOWNSTREAM CHANGES IN MEAN BAXIS BELOW KIELDER RESERVOIR
FOR 1960 (After Hall 1964) AND 1988. RIVER SOUTH TYNE, NORTHUMBERLAND.



DOWNSTREAM CHANGES IN PARTICLE MEAN B-AXIS BELOW KIELDER RESERVOIR FOR 1978 (After Carling 1979) AND 1988. RIVER NORTH TYNE, NORTHUMBERLAND.



CHANGE IN % MATERIAL <1mm BAXIS FOLLOWING REGULATION, FOR A 16Km REACH ON THE RIVER NORTH TYNE BELOW KIELDER RESERVOIR, NORTHUMBERLAND



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