Institute of Hydrology

The effect of pre-afforestation drainage on the streamflow and water quality of a small upland catchment

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THE EFFECT OF PRE-AFFORESTATION DRAINAGE ON THE STREAMFLOW AND WATER QUALITY OF A SMALL UPLAND CATCHMENT

by

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Abstract

Drainage* of upland areas is a widespread practice in land management, yet little quantitative information is available concerning its effects. To this end a small upland catchment on peat was instrumented prior to its drainage by open ditches for forestry.

Sediment concentrations in the stream increased by over two orders of magnitude during the draining, and took a number of years to decline to a new equilibrium several times higher than before the drains were cut. The decline in sediment yields after drainage could be described by an exponential decay and this curve was extrapolated to make estimates of the losses after the sampling programme ended. These were substantiated by measurements of sediment accumulation downstream.

Phosphate fertilizer was applied prior to the drainage and the levels of its loss from the catchment in the stream water were monitored.

The draining produced a much peakier stream response with higher flood flows and the time to peak of the stream hydrograph was halved. The annual water yield increased by 5%; attributable mainly to an increase in moderate to low flows resulting from improved drainage of the catchment between storms by the enlarged drainage network.

**The open ditches used to drain land for forestry (and also in moorland gripping schemes) are usually referred to as 'drains' and this nomenclature has been adopted.*

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Deep drainage plough pulled by two crawler tractors used at Coalburn
(Forestry Commission Neg. No. B6601)

1. INTRODUCTION

The side-effects of large-scale forest drainage, such as the influence on water conditions in the surrounding uplands, water discharge, fish life in lakes, ponds and rivers and on nature in general, have so far received little attention. It is apparent that the marked transformations brought about by forest drainage cannot occur without far-reaching effects on nature in general. Studies to clarify these side effects are urgently required.

(Heikurainen, 1968)

1.1 Background and setting

Afforestation is the largest single land use change in Britain today. Between 1945 and 1975 the area planted by the Forestry Commission increased four-fold from 202×10^3 ha to 809×10^3 ha (Forestry Commission Annual Reports), an average annual increase of 20000 ha. Together with an approximately equal rate for private forestry (Mather, 1978) this represents an annual planting of about double the area lost annually to urban development (Best, 1976). The Forestry Commission in a recently consultative document on possible future policies (Forestry Commission, 1977) recommended the afforestation of a further 1.8×10^6 ha, mainly in upland Scotland, which it considered could be achieved without affecting agricultural or urban requirements. This expansion would be carried out over the next half century and increase the percentage of the British uplands under forest from the present figure of 15% to nearly 50% (Centre for Agricultural Strategy, 1980).

The majority of afforestation to date has been on the uplands, and this land is often poorly drained and peaty, requiring draining prior to planting. The purposes of the drainage include the regulation of water and improvement of aeration, the mobilisation of nutrients, the reduction of competition from natural vegetation and the reduction of soil compaction. From 1948 to 1967 about 60% of the planted land was drained (Taylor, 1970) and this percentage will undoubtedly rise as forestry becomes increasingly concentrated on the uplands.

While much attention has been given to comparing the effects of different land uses, and in particular to studying the hydrological differences between moorland and mature forests (e.g. Lewis, 1957; Law, 1958; Anon, 1976) much less is known of the situation prior to the canopy closure of a forest and in particular the effects of the draining operations required for tree establishment.

This study is primarily concerned with the hydrological consequences of the drainage of an upland area for forestry, although the results should also be relevant to upland draining to improve rough grazing (moorland 'gripping'). The cutting of open ditches for afforestation and for improving grazing each occurs on about 25000 ha of land per annum in Scotland alone at the present time (Green, 1979). The results presented here are for the Coalburn (or Coal Burn) catchment, a small Pennine area of blanket peat, and typical of much of the uplands of Britain. Measurements were made to determine the effect of draining upon both the stream water quality (suspended sediment and solute loads) and water quality (peak flows, low flows and water balance). In addition, the loss of fertilizer (often applied at the same time as the drainage) was monitored.

1.2 Description of study catchment

The Coalburn catchment is a 152 ha (1.52 km²) upland area in the headwaters of the River Irthing, some 40 km northwest of Carlisle (Figure 1). With an altitude of about 300 m A.O.D. and a mean annual precipitation of about 1200 mm, the natural vegetation comprised rough pasture of Molinia grassland and peat bog. Most of the catchment is covered by a thick deposit of boulder clay under a thin veneer of peat, although the underlying lower Carboniferous rocks are exposed in places (Figure 2). The original stream network of seven main

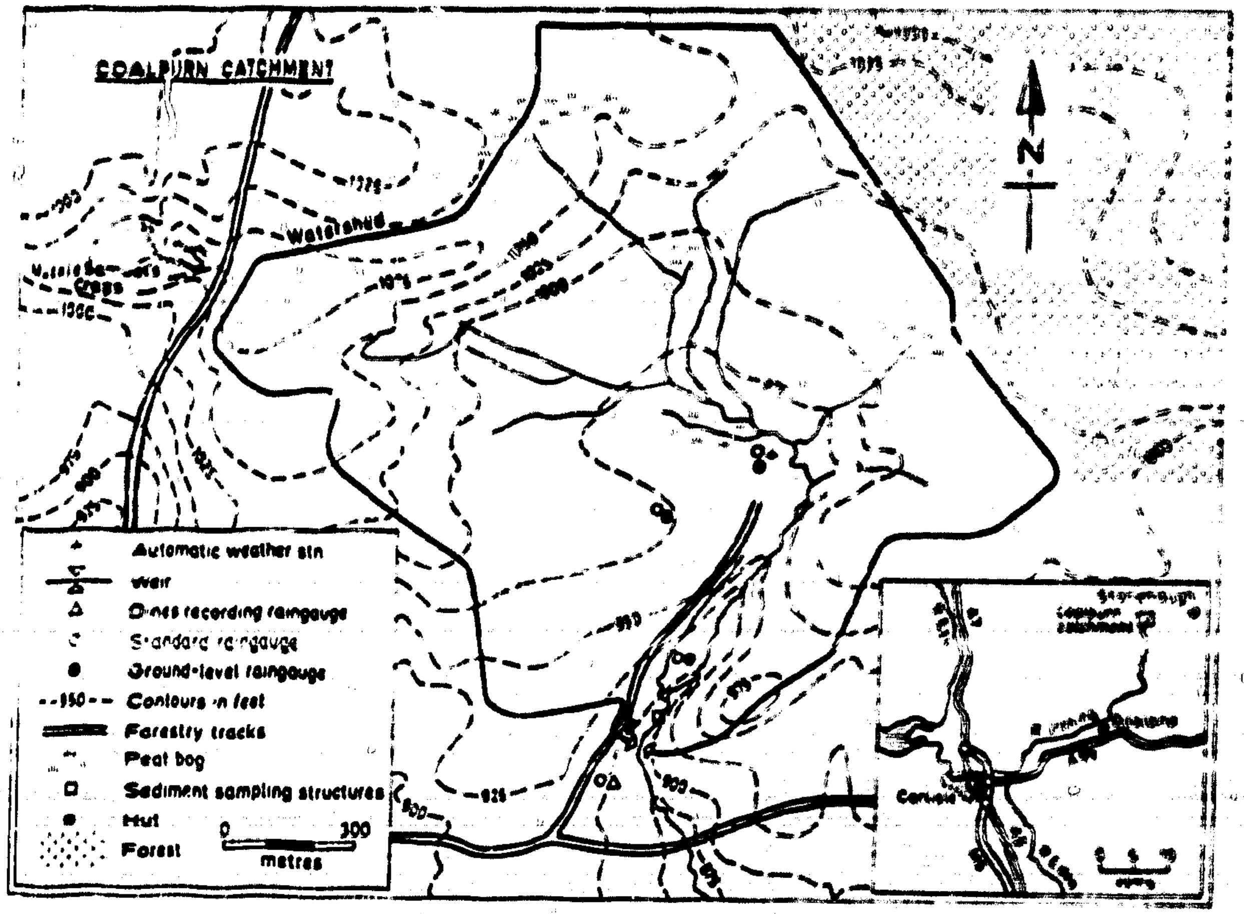


FIGURE 1 Topography and instrumentation of the study catchment

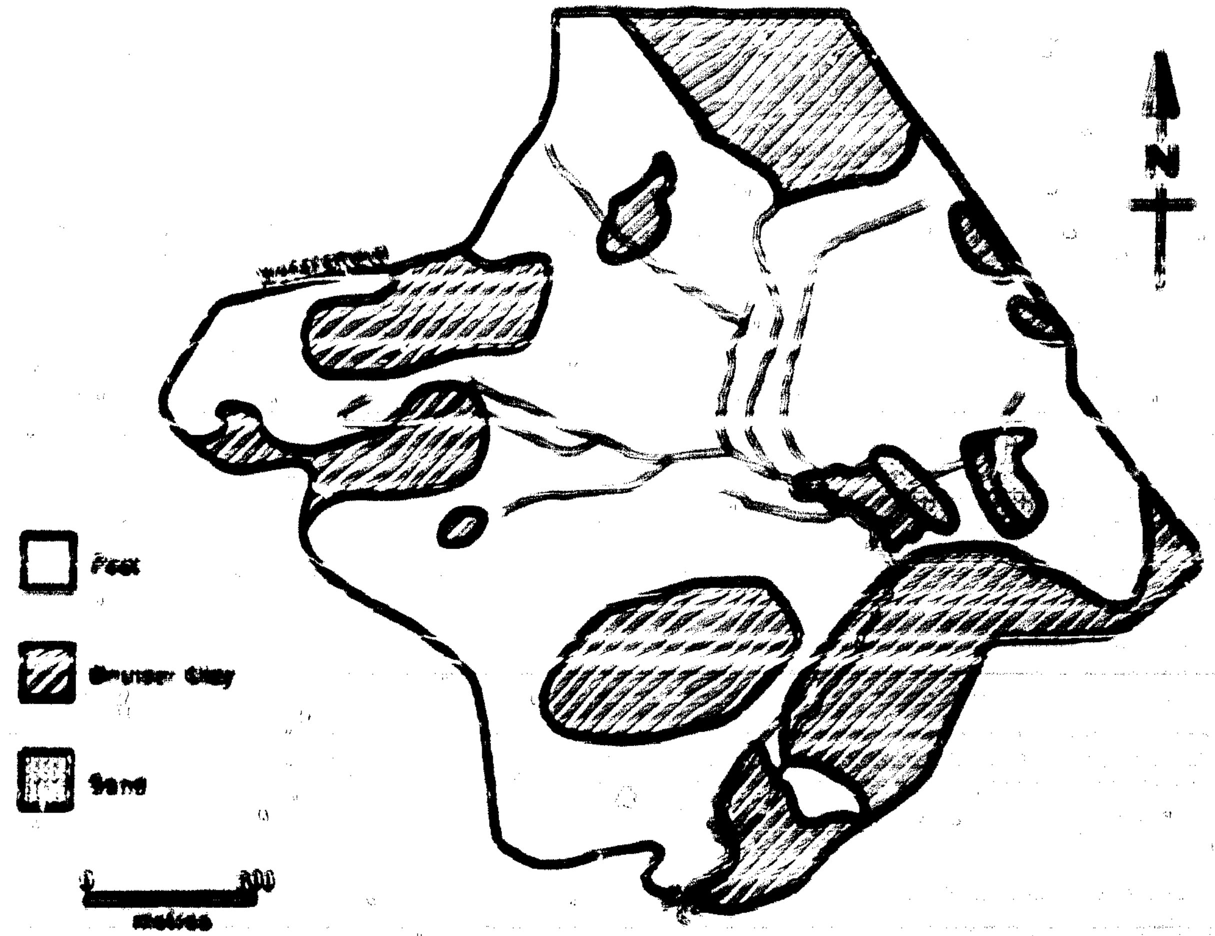


FIGURE 2 Generalised distribution of the principal soil types

tributaries off the main stream, together with several [illegible] ditches, comprised a total length of about 5750 m, and represented a drainage density for the catchment of approximately 3.5 km/km².

By 1966 the Forestry Commission had plans to incorporate the area into the Wark Forest, and the Institute of Hydrology in conjunction with the then Cumberland River Authority (now part of the North West Water Authority) began to collect rainfall and runoff records. After a calibration period of approximately five years, the Forestry Commission ploughed the catchment in 1972 in preparation for the planting of Sitka spruce transplants in the summer of the following year.

The Institute of Hydrology collected stream samples for water quality analyses from about five months prior to draining up to a few months after the transplants were planted. Further samples were collected during the winter of 1978-9, to monitor conditions some six to seven years after the period of disruption, and allowing ample time for the natural vegetation to invade the drains and colonise the areas of bare soil.

[illegible]

[illegible] of the [illegible], they are still [illegible] [illegible] pretty to [illegible] of the catchment is [illegible] of changes up to 1976 [illegible].

3.? INSTRUMENTATION AND METHODS OF ANALYSIS

[illegible] were measured at a number of ground-level monthly gauges and [illegible] by an autographic [illegible] gauge. [illegible] was measured at a compound [illegible] weir, with the water level recorded by a [illegible] and a Fischer and Porter [illegible] punch tape. Water samples were collected using a [illegible] sampler [illegible] at a straight section of the main channel some 50 m upstream of the stilling basin of the weir. Samples were [illegible] taken at 10 points within the cross-section to identify a representative point for the [illegible] samples. [illegible] samples were taken on 22 occasions covering a wide range of discharges, and there was no significant difference between the mean sediment concentrations at any of the points during a [illegible]. The position eventually chosen was in the middle of the channel near the [illegible]. This point had an overall mean value closest to the mean for the whole cross-section, individual readings were [illegible] mean on each occasion, and the point was above the [illegible] water levels.

The sampling interval of eight hours is much longer than would be ideal, but represents a necessary compromise with the immense difficulties involved in collecting samples from such an isolated site, over an extended period. However, whilst this did not provide a sufficiently detailed record to study the variation in sediment concentrations during individual storms, it did give an adequate [illegible] of sediment yields when longer periods such as a week [illegible] were considered.

Suspended sediment concentrations were determined by the Cumberland River Authority in accordance with the specifications in the DOE handbook "Analysis of Raw, Potable and Waste Waters" (D.O.E., 1972), ([illegible], North West Water Authority, [illegible], personal communication). Briefly, the method used Whatman GF/C glass-fibre filter paper which was heated at 105°C for one hour and [illegible]. The accuracy of this method has been estimated from [illegible] tests to have a standard deviation of ±5%.

The chemistry of the water was also studied and measurements were made of the concentrations of total dissolved solids (T.D.S.) and the four cations calcium, magnesium, sodium and potassium. However, because of the water sampling method adopted, chemical analyses of the water could not be performed until a number of days after their collection and the values obtained should thus be regarded as only approximate because of the possibility of sample deterioration and of contamination from the suspended sediment. 1 mg of mercuric chloride was added to each sample to help prevent any bacterial action. The cation

The catchment in summer 1979 showing the small size of the trees (generally under one metre in height)

concentrations were determined using a Unicam SP90A Series 2 atomic absorption spectrophotometer. Total dissolved solids were measured by evaporating a known volume of water dryness and weighing the residue.

2. SUSPENDED SEDIMENT

Water samples were taken for suspended sediment analysis at the time the catchment was drained in 1972-3, and further samples were taken in the winter of 1978-9.

The suspended sediment data may be subdivided into three main periods: pre-draining; during draining; and post-draining.

2.1 Calibration Period (March - July 1972)

It is naturally essential to have a standard against which to compare and relate any changes in the catchment output resulting from the period of change. For this reason water quality data were collected prior to ploughing in order to determine the pattern and extent of the variations from the catchment whilst still in equilibrium. Ideally, of course, a longer period of record would be desirable possibly covering a whole year, but the very limited range in recorded sediment concentrations for an enormous range in stream discharge suggests that the range in behaviour of the catchment was rather limited and may have been adequately covered.

During this period suspended sediment concentrations remained conservative with respect to changes in streamflow, ranging from under 1 mg/l up to only 28 mg/l, with a mean 3.6 mg/l, for a 330-fold range in discharge (from 2.5 to 830 l/s). Sediment rating curves for the period are described in more detail in Section 2.4.2, and were of the form:

$C \propto Q^0$ where C is Sediment concentrations, and

$S \propto Q^1$ S is Sediment discharge, and

Q is Stream discharge

This indicated that the sediment concentration fluctuated little with discharge, and that the observed variations in sediment load were due largely to the fluctuations in discharge. A similar pattern has been observed elsewhere (e.g. Kingston Brook near Nottingham - Potter (1973)). There are several factors that may have been responsible for this:-

The sediment and water waves may have been out of phase, a phenomenon commonly noted in sediment studies, which would give considerable scatter to the rating curve. However, even analysing the rating curves for rising and falling stages separately showed little correlation.

Alternatively, the sampling interval of 8 hours might miss the peak sediment concentrations which occur only briefly, and this would tend to under-estimate sediment loads. However, this effect will be lessened as an increasingly long period of record is considered, tending to balance out the errors in the average and total sediment loads. A large number of samples were taken over the calibration period (about 300), and over 550 samples in all were taken prior to draining (if the 250 or so 12-point samples are included). It is clear that sediment concentrations were generally low compared with studies of other catchments where with equivalent sample sizes concentrations up to at least 1000 mg/l have been noted (eg. Loughran, 1976; Walling, 1974), although they are comparable with the findings of other studies of upland sites (eg. Lewin, et al., 1974; Oxley, 1974).

It is considered that supply, rather than transport limitation was the main cause of the generally low concentrations and the poor rating curve fit, and this conclusion is supported by measurements taken during the draining when much higher sediment concentrations were carried by much lower flows. In all, 60% of the recorded concentrations were under 3 mg/l and 97% were under 10 mg/l. The low sediment availability was probably due to the very low channel slopes, armouring of the channel bed by gravel, and the resistance of the stream banks to the relatively small quantities of streamflow (peak discharges were about 1 m^3s^{-1}).

During the early part of this period there appeared to be an upper limit to sediment concentrations of about 10 mg/l, until the very intense storm on 13th June (with a maximum hourly rainfall of 11.9 mm) which seemed to have crossed a threshold and gave much higher sediment concentrations, with a 28 mg/l maximum recorded, and levels remaining generally well above 10 mg/l until the end of the following day. It also seems to have lowered the stability of the catchment somewhat since in the succeeding period up to the draining, there were another 7 readings above 10 mg/l during fairly moderate flows, and about half in fact occurred during non-rainfall periods, suggesting possibly the release of materials from weakened stream banks.

2.2 Drainage period (July-September 1972)

The technique employed to cut the open ditches was to use a deep double moulboard drainage plough, pulled by two Crawler tractors to dig a single drain of about 50 cms depth and at about 5 m spacings. The sod was thrown out equally to each side to provide ridges for the establishment of the young trees. A record was kept by the Forestry Commission of the area being drained, and also of the type of work that was being carried out each week (Figure 3). This was necessary since not all the drains were joined directly to an outlet. Some had their lower ends left blocked, and thus had little effect, until the link and cross drain were ploughed to connect them to the stream system

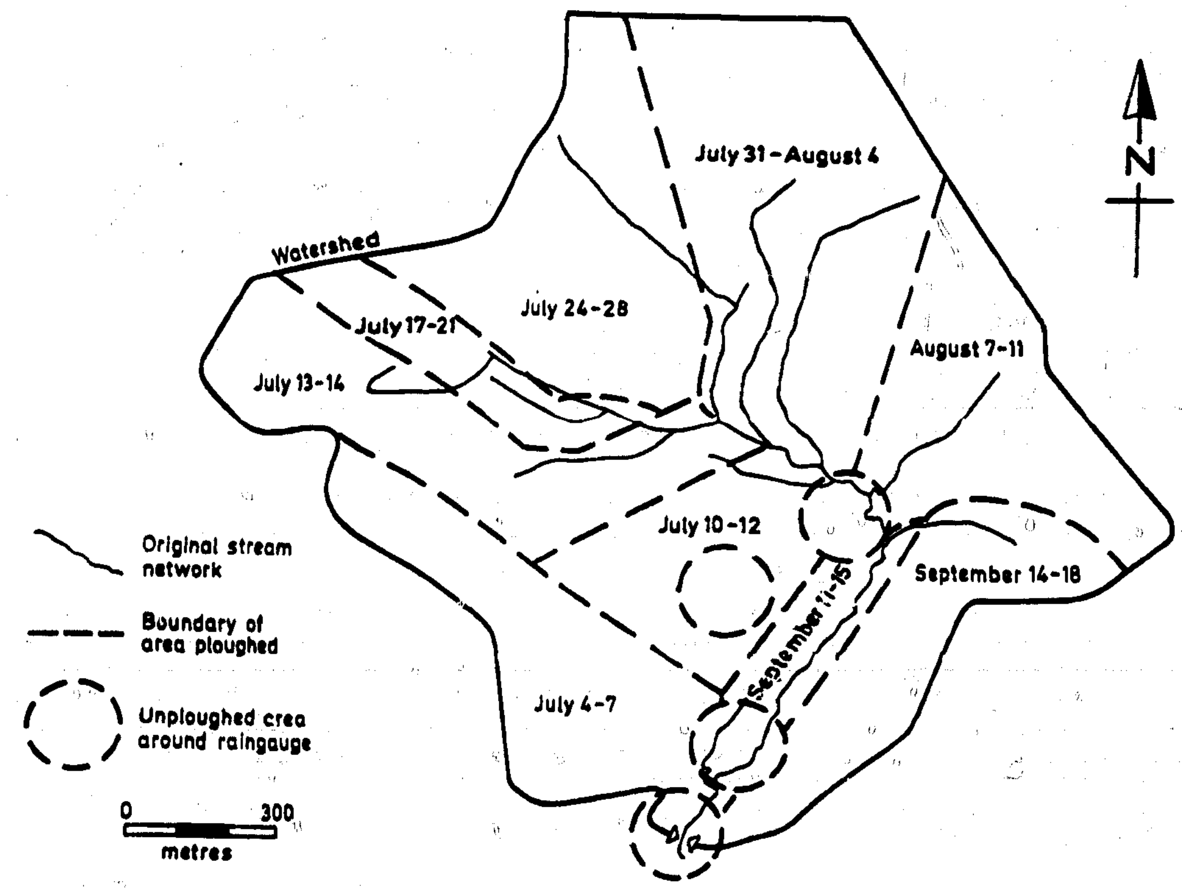


FIGURE 3 Schedule of drainage of the catchmen sub-areas

and when the accumulated water was released in a flood. Unfortunately it was not considered practicable to keep a record of the number of drains in each category. However, this still represents a very detailed record compared with the usual Forestry Commission procedure.

No work was carried out at weekends, and also the two-week annual holiday occurred about two-thirds of the way through the drainage operations. These breaks make it possible to sub-divide the effect of the work both temporally and spatially.

The density of the drains may be calculated from their spacing as about 200 km/km^2, indicating roughly a 60-fold increase on the original stream density. Suspended sediment loads increased dramatically during the draining, with concentrations up to 7720 mg/l, and a mean value of 207 mg/l (cp 3.6 mg/l in the calibration phase). Most of the very high concentrations occurred towards the end of the draining operations when the link and cross drains were being ploughed and a bucket drainer was used to widen part of the main channel.

To gain a better understanding of the processes operating during the drainage phase, water quality measurements were taken for a group of six drains that were cut on Friday 14/7/72 (Davies, 1973). Water samples were taken both in the drains themselves and also in the stream into which they drained, at a point both upstream and downstream. Sampling covered the period from shortly after the drains were cut to nearly two days later (Figure 4). Since no further work was carried out until the following Monday, and there was no rain in this period, the observed rise in stream discharge of about 3 l/s noted at the basin outlet may reasonably be attributed to the release of water from these drains, affecting about 3 ha or 2% of the catchment.

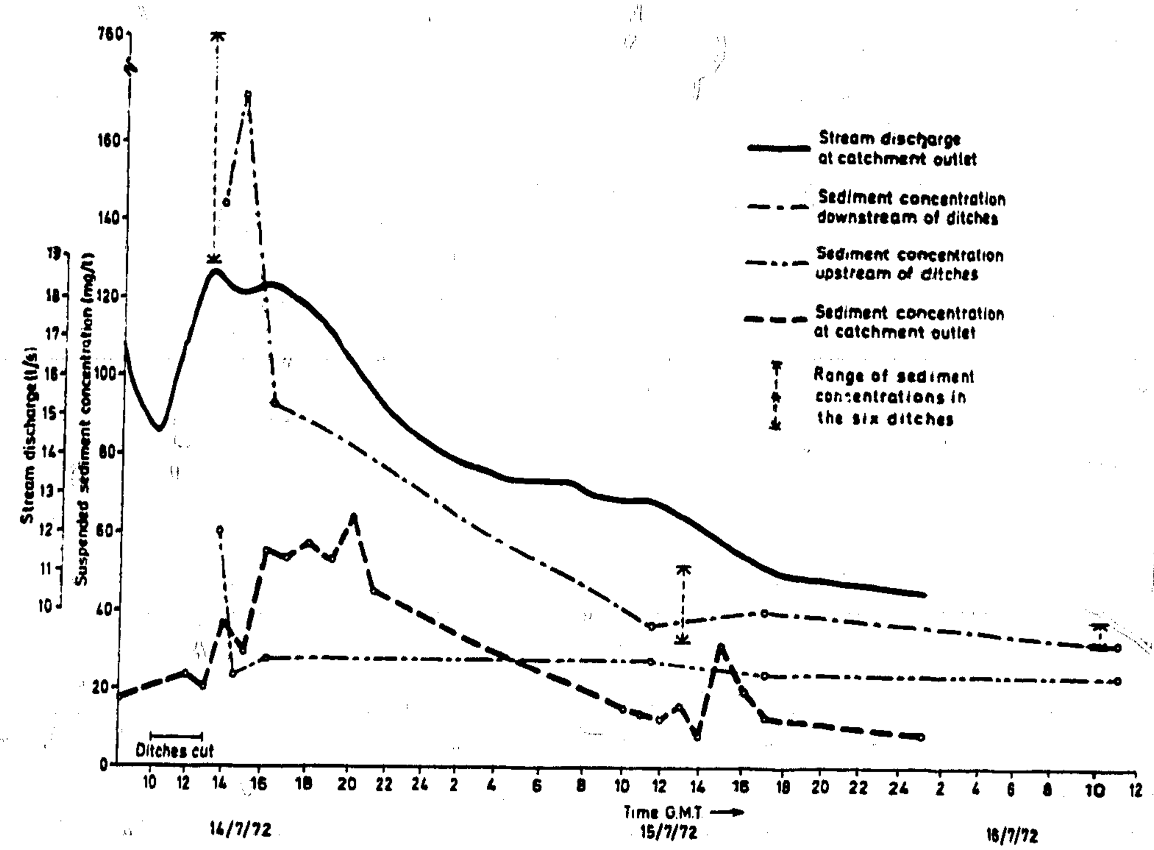


FIGURE 4 **Streamflow and water quality following the cutting of a set of drains**

The net volume of this wave may be estimated by extension of the previous recession curve to have been in the order of 200 m^3 which, assuming that the six drains were all of equivalent dimensions (approx. 1000 m long by 0.3 m wide) would indicate that about 30 m^3 of drainage water was released from each drain representing about 7 mm over the whole area drained. The variation in sediment concentrations is shown in Figure 4, and clearly indicated a steady decline in the sediment release from the time of completion of the drains. An estimated 10 kg of suspended sediment was released from the six drains over the two-day period after they were cut.

The first concentration measurement taken at the site upstream of the drains appears anomolously high for a non-rainfall period compared to

later readings. If this was assumed to have been due to the movement of men or machinery across the catchment, then a fairly constant background concentration of about 25 mg/l was evident. The initial sediment concentrations varied greatly between individual drains (from 128 to 760 mg/l at about 1300 G.M.T. on 14/7/72), and possibly changed rapidly with time too, though unfortunately no further samples were taken until the next day and no record was kept of the order in which the drains were cut.

It is clear that the ploughing of these drains produced a large amount of sediment compared with the background concentrations from the steep and largely unaltered area upstream. The bulk of this sediment was carried out of the catchment within two days, by which time the quantity of water draining had been greatly reduced and the sediment concentrations in the drains were approaching those in the stream above the drains. These results suggest that the cessation of work over the weekends (a period of over 60 hours) would allow sufficient time for the effects of the drainage operations in each week to be separated although of course the existence of the drains would be likely to affect the patterns of storm response and baseflow levels in subsequent weeks.

In the following year the stilling basin was drained for maintenance work to the weir and a distinct pattern of layering was noted in the accumulated sediment, different horizons representing sediment from areas of different soil types. This also gives credance to the idea of subdividing the draining period into weekly intervals to study more closely the effects of the draining upon catchment output, and because the area ploughed each week was known, it permitted the effect of the areal variations in catchment features to be studied as well.

The cutting of the six drains described above produced a sediment wave that lagged after the hydrograph at the basin outlet although this was not necessarily always the case; for example, on the rainless day of 2/8/72 the sediment wave resulting from the drainage slightly preceded the water wave. It is thought that the distance of the area being ploughed to the basin outlet, and the directness of the connection of the drains to the stream network, would have been important factors in controlling the relative timing of the waves at the main sampling point.

It is interesting to note that whilst the largest stream hydrographs during the drainage period were the result of storms, the draining operations themselves were capable of producing small hydrographs with rises of up to, say, 10 l/s recorded during non-rainfall periods.

The draining period was analysed using the records of water quality from the 8-hourly sampling program taken at 0400, 1200, and 2000 hours G.M.T. over each period, commencing at 1200 G.M.T. on the first day and ending at 2000 G.M.T. on the last day. Thus only the period during which ploughing actually took place was included. Readings taken during the night were included for convenience since no diurnal cycle was evident in the sediment yields, the effects of the sediment released lasting some time as shown by the study of yields from the six drains.

From this it was hoped to be able to relate the average water quality properties to determining factors, both static (topography and soil type) and dynamic (the occurrence of storms and ploughing operations). This assumes that the sediment yield at the catchment outlet during a sub-period would be dominated by the ploughing operations in that sub-period on a known area, and that the remainder of the catchment (whether or not already ploughed) had a much less important effect. This assumption whilst not of course strictly true, appears reasonable given the findings of the 6-drain study and the pattern of sediment layering noted in the stilling basin. The results are summarised in Table 1.

TABLE 1 Average sediment loss during the ploughing of catchment sub-areas

	AREA	PERIOD	SIZE (ha)	MEAN LAND SLOPE* (deg)	MEAN FLOW (l/s)	TOTAL RAIN (mm)	RANGE IN FLOW (l/s)	MEAN SED CONC mg/l	SOIL TYPE	TYPE OF WORK
	A	4-7 July	23	10	41	7.5	15-117	184	P,BC	D
	B	10-12 July	11	4	36	11.7	10-82	51	P+BC	D
	C	13-14 July	18	6	19	0	17-22	28	P,BC at top	D
PHASE I	D	17-21 July	8	8	7	0	5-20	55	"	D,LC
	E	24-28 July	21	11	14	6.0	9-22	94	"	D
	F	31- 4 Aug	31	5	20	18.5	6-71	48	"	D
	G	7-11 Aug	19	7	77	22.5	23-190	130	P,S+BC nr stream	D
ANNUAL HOLIDAY										
		29- 1 Sept	-	-	5.3	0	4-7	142	-	LC
		4- 7 Sept	-	-	8.3	8.6	4-39	1667	-	LC,H
PHASE 2		8-11 Sept	-	-	7.5	0	5-8	260	-	LC,H,BD
	H	11-15 Sept	6	-	10	9.6	6-30	487	BC	D,H
	I	14-18 Sept	14	-	7	0	5-9	354	BC	D,H

*NB Land slope may be very different to the slope of the drains.

Notation: soil - P - Peat
P,BC - Predominantly peat with some boulder clay
S - Sandstone
work - D - Cutting drains
LC - Link and cross drains
H - Hand clearing of blocked drains
BD - Bucket drainer used to widen main channel

The draining was divided by the holiday period into two distinct phases according to the nature of the work in progress.

a) Phase 1: Predominantly ploughing drains (4th July - 11th August). In this period sediment concentrations averaged 83 mg/l, with a maximum of 995, and the stream discharge averaged 26.7 l/s with a peak of 191 l/s.

b) Phase 2: Connecting the drains already ploughed to the stream system by cutting link and cross drains, together with clearing blocked drains by hand (29th August - 18th September). Although streamflow was much lower than in the first phase, with a mean flow of under 8 l/s and a maximum of 39 l/s, the concentrations of suspended sediment were much greater, averaging 563 mg/l and rising to a maximum recorded value of 7720 mg/l. However, due to the much lower streamflow, sediment discharge was only about 30% greater (averaging of 4.1 gm/s compared to 3 gm/s in the first phase).

If this second phase had not been so dry (average rainfall was only 1.3 mm/day compared with the mean annual daily rainfall of 3.5 mm) still higher sediment yields would probably have been recorded. This is demonstrated by comparison of the sediment rating curves for the two phases (log sediment load vs log stream discharge). During the first phase there was a fairly good correlation since much of the sediment was brought out by storms or the release of water from the cutting of new drains, whilst for the second phase there was a much lower correlation with some of the highest concentrations being recorded during the start of drain clearing at a time when there was no rain and relatively low stream discharge.

I) PHASE I

In this drain cutting phase, we may examine seven sub-periods based upon the divisions of the draining schedule. The averaged sediment and water conditions have been plotted in Figures 5 and 6. It may be seen that the points tend to fall broadly into three groups, namely:

1. A,G - high streamflow, sediment concentrations and yield
2. B,C,D,E,F - moderate streamflow, sediment and concentration yield
3. H,I - low discharge, high sediment concentration and moderate yield

The ploughing of drains in areas H and I coincided with drain clearance operations which would appear to result in much higher sediment concentrations, and they are therefore discussed later with the rest of the second phase activities.

Clearly the sediment yield over a period reflects the values of both streamflow and sediment concentration, so the mean sediment concentration was chosen in preference as the best available measure of the effect of the draining operations.

Areas A and G had the highest mean concentrations, and this would appear to be related to the prevailing hydrological conditions. The time when they were being ploughed included the highest discharges in Phase I, and their mean flows were greater than the peak flows when some of the other areas were being ploughed. The fact that area A exhibited the higher mean concentration, whilst having the lower mean

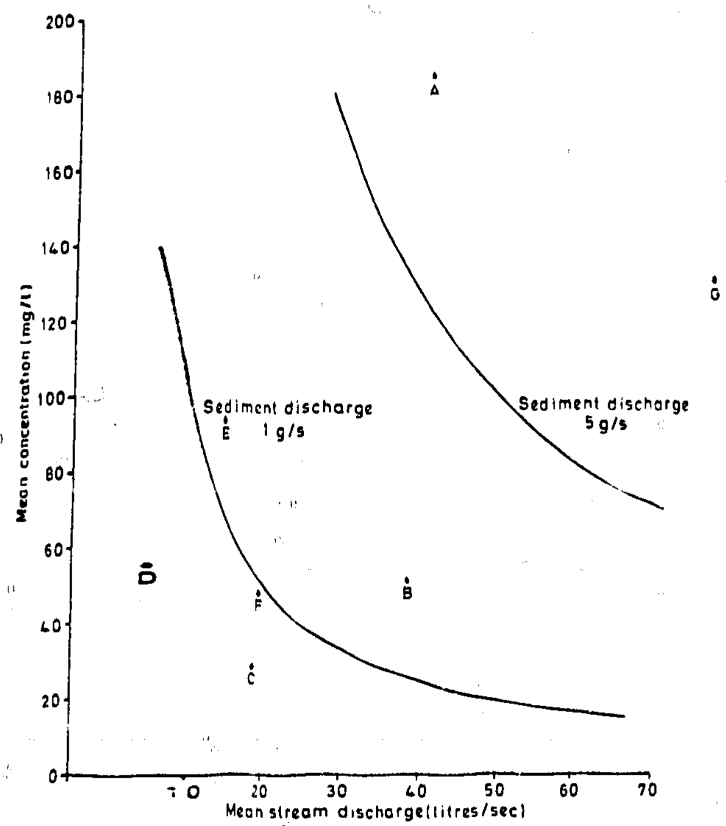


FIGURE 5

Streamflow and sediment concentrations for the sub-areas

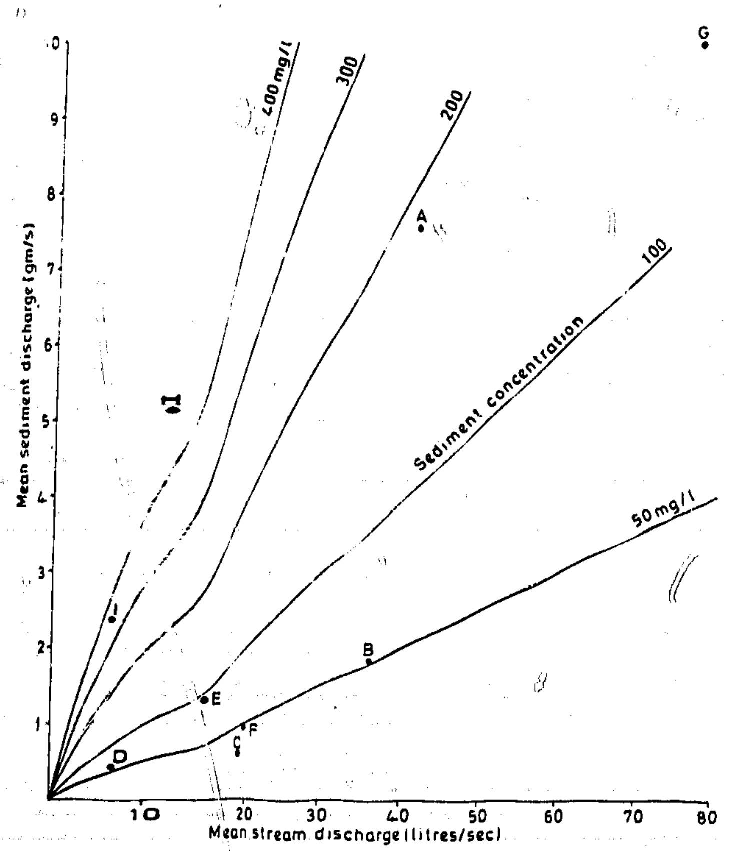


FIGURE 6

Streamflow and sediment loads for the sub-areas

and peak discharge, was due to the occurrence of a very high concentration (995 mg/l) recorded soon after the start of draining, which, given the relatively small number of samples in any sub-period (3 per day) could by itself account for the observed difference. There is no record of why such a high initial value was recorded, but field survey revealed the presence of a small drain running from this sub-area into the main channel at a point about 10 m upstream of the main sampling point. If this was cut at the time the sample was taken it could account for the very high concentration (and the value is similar to the highest concentration measured in the six drains discussed earlier).

Areas B and F exhibited very similar average concentrations and appeared to have experienced similar hydrological conditions, especially with regard to their range of streamflow and the average daily rainfall (about 4 mm). Each period included one large hydrograph, but that occurring during the draining of area B maintained high levels of discharge for longer, though sediment concentrations were very similar, thus giving B a higher mean discharge and sediment yield than F.

At first sight areas C,D and E show a great deal of variation and little pattern: D has lower mean and peak streamflow than C, but its mean concentration is much higher; E has a similar streamflow pattern to C, yet much higher concentrations (approaching those of the periods when A and G were ploughed). The following picture is suggested: area C had low concentrations due to the low discharges and restricted range in flows in this rainless period. Area D, though also having no rainfall during the ploughing, had a much greater range of flow due to a stream rise of 15 l/s on 19/7/72 which may be attributed to the cutting of link and cross drains. Area E produced very high concentrations despite generally low streamflow. It is suggested that this was the result of the first rain for over a week flushing out material released in this period and accumulated in the previous rainless periods C and D.

The general level of sediment response during the draining of Coalburn may therefore be approximated:

150 mg/l	-	draining in a period of relatively high stream discharge
50 mg/l	-	draining during a period of moderate flow
30 mg/l	-	draining in a rainless period with low streamflow

The study has demonstrated the importance of other factors, in addition to the prevailing hydrological conditions, on the quantities of sediment released by draining. The importance of cutting link and cross drains is shown by the average level of sediment concentration for area D, which was approximately double that of the general pattern above. The large sediment flush resulting from the first rainfall since the link and cross drains were cut (period E) emphasises the importance of the antecedent conditions and ground state.

II) <u>PHASE II</u>

During this phase concentrations were much higher than in the first phase, even though streamflow was generally lower. The predominant work was the connection of the drains already cut to the stream network, and the clearing of blocked drains.

In the first week (29th August - 1st September), concentrations rose from the level of about 25 mg/l observed during the holiday to 140 mg/l as the link and cross drains were cut. In the following week (4th-7th September) blocked drains were also cleared and concentrations reached over 7000 mg/l for flows of only 5 l/s. Rain fell in the latter part of the week but could only raise concentrations to a couple of hundred mg/l. On the Friday and Monday, the 8th and 11th of September, a J.C.B. 'back-acter' bucket drainer was used to widen part of the main channel. Concentrations of up to 500 mg/l were recorded, rising to over 600 during a storm in the intervening weekend. In the last two weeks, areas H and I were drained and drains were hand cleared. Area H produced more sediment, probably due to the higher flows.

It is difficult to ascribe typical values of sediment concentration produced during the different operations since they depended upon the area being worked and its condition. If the drains being linked up to the stream network were cut in a dry period they would have a quantity of sediment available to be flushed out during the next storm. It was also observed that in contrast to the rapid decline after the cutting of the drains, the sediment concentrations during drain clearing remained high over the intervening weekends, indicating a 'carry-over' from one week to the next.

Given these qualifications the levels of mean and peak concentrations that might be expected would be in the order of:

Mean Conc	Max Conc	Type of work
300 - 1 700 mg/l	10 000 mg/l	Hand clearing of blocked drains
200 - 300 "	1 000 "	Bucket drainer widening channels
5 - 150 "	1 000 "	Link and cross drains cut

2.3 Post drainage period (September 1972 to October 1973)

Before considering the long terms effects it is interesting to note the immediate effect upon sediment yields of the cessation of draining. The drainage operations were suspended for the annual holiday in August, by which time most of the drains had been cut, although they had not been cleared of debris. This allowed the immediate response after the two very different draining phases to be isolated and compared.

The holiday period was fairly dry and sediment concentrations were generally in the same range as the baseflow concentrations during draining namely 20-30 mg/l, and rose to nearly 200 mg/l in the only storm (7.6 mm rainfall).

In contrast, the second period of drainage operations had comprised a period when blocked drains were hand cleared and very high concentrations were noted. On completion of this work there was a sudden and dramatic fall in sediment levels from 290 mg/l to 30 mg/l in an eight hour period, through the following dry month concentrations remained at a higher level than in the holiday period, with concentrations of about 30-50 mg/l rising to 720 mg/l in the only storm, (9.7 mm rainfall).

Much of the sediment released by the drainage accumulated in the stilling basin of the weir and a bypass channel was constructed to enable cleaning operations to be conducted (Cumberland River Authority, 197[illegible]). The general maintenance work on the weir commenced at the end of October 1972 and continued over a total period of about nine months, during which streamflow data was recorded only intermittently. In addition there were some breaks in the sediment sampling due largely to problems of a shortage in personnel resulting in the sampler bottles not being changed on a number of occasions. However, in all it was possible to extract data for half this period (predominantly December 1972 - April 1973). This related to the first period since draining with an appreciable quantity of rainfall, and with a mean flow of 45 l/s and mean sediment concentration of 67 mg/l. There were a number of very large storms and on four occasions concentrations of over 700 mg/l were recorded for storms with peak flows up to one cumec. It was estimated that these storms probably carried in the order of 10 000 kg of sediment on their peak days, and probably a total of about 15 000 kg each. This may be compared with peak daily loads of about 3 000 kg during draining (when concentrations were much greater but streamflow was very much less because of the unusually low rainfall), and about 100 kg during the calibration period (which had similar discharges to these winter flows).

It should be noted that the majority of the sediment readings were much lower than these peak values, with over 70% of the readings under 50 mg/l and nearly 90% under 100 mg/l. Only 2% were above [illegible] mg/l. Clearly though, there had been a great increase in the amount of sediment which could become available for transport from the catchment.

There was then a break in the records from May to August 1973, during which there were concurrent flow and sediment data for only a few days, but nearly a hundred sediment samples were taken, with values up to 380 mg/l and a mean concentration of 35 mg/l. Rainfall over the period was close on the seasonal average. The following period when sediment samples were taken and the weir was fully operational again, was unfortunately a period with less than average rainfall. Stream discharge averaged only 11 l/s with a peak of 74 l/s. Sediment concentrations had a mean value of 35 mg/l and, apart from a single reading of 574 mg/l which did not appear to be related to either rainfall or runoff the highest concentration was 320 mg/l.

No further suspended sediment measurements were taken until 1978. This was nearly seven years after the ploughing, by which time it was anticipated that the direct effects of the draining would have ended, and a new equilibrium state would have been attained.

5.4 Pattern of sediment response

Due to the large sampling interval it was considered that the pattern of sediment response in each period would be best described by the use of statistical techniques; firstly the frequency distributions of the streamflow and the main elements of sediment output (sediment discharge and concentration) were examined, and secondly, the rating curves between sediment and streamflow.

5.4.1 Frequency distributions of catchment output

The variation in the catchment output of water and sediment are discussed briefly below. They are summarised in terms of their frequency distributions using the mean and maximum values, together with the coefficients of variation, skewness (zero for the Normal distribution), and kurtosis (a measure of peakedness of the frequency distribution). These coefficients are derived by taking second and higher moments about the mean, and so are sensitive to the presence of extreme values. The parameter values for the different periods are given in Table 2, and are summarised graphically in Figure 7, for the 1972 and 1975 data.

In the calibration period the frequency distributions were all positively skewed and with a higher kurtosis than the normal distribution. The streamflow distribution was the most peaky and highly skewed, and sediment concentration the least. The range in streamflow was much greater than for sediment concentration, and the coefficient of variation of the sediment load was nearly equal to that of the streamflow, being indicative of its closer relation to streamflow than sediment concentration.

Sediment concentrations rose by two orders of magnitude during the draining, and then declined greatly after its completion. This was despite stream discharge being almost the antithesis, falling greatly in the draining period and remaining at a low level in the two post-draining periods (Figure 7). Average sediment concentrations rose only slightly in the wetter period of winter 1972-3, when streamflow was equivalent to that in the calibration period (Table 2). In the 1975 sampling period, the average streamflow was greater than in any of the previous periods, but sediment concentrations had declined still further and were much lower than even in the very dry periods following the draining and in fact were only about three to four times the level of the calibration period. Sediment loads followed broadly the same pattern as the concentration, although the highest loads were not carried in the draining period, but in the succeeding winter.

The higher statistical moments show broadly the same pattern of change and recovery, although this has been distorted by the difference in streamflow, together with the effect of one brief storm in the otherwise rainless first post-draining period (period C in Figure 7). The peak storm discharge of 33. l/s was so great in comparison with the mean flow of only 3.5 l/s that it dominated the calculation of the higher statistical moments of the streamflow distribution. Similarly these statistical parameters of the sediment load have high values in this period. The higher moments of the sediment concentration were

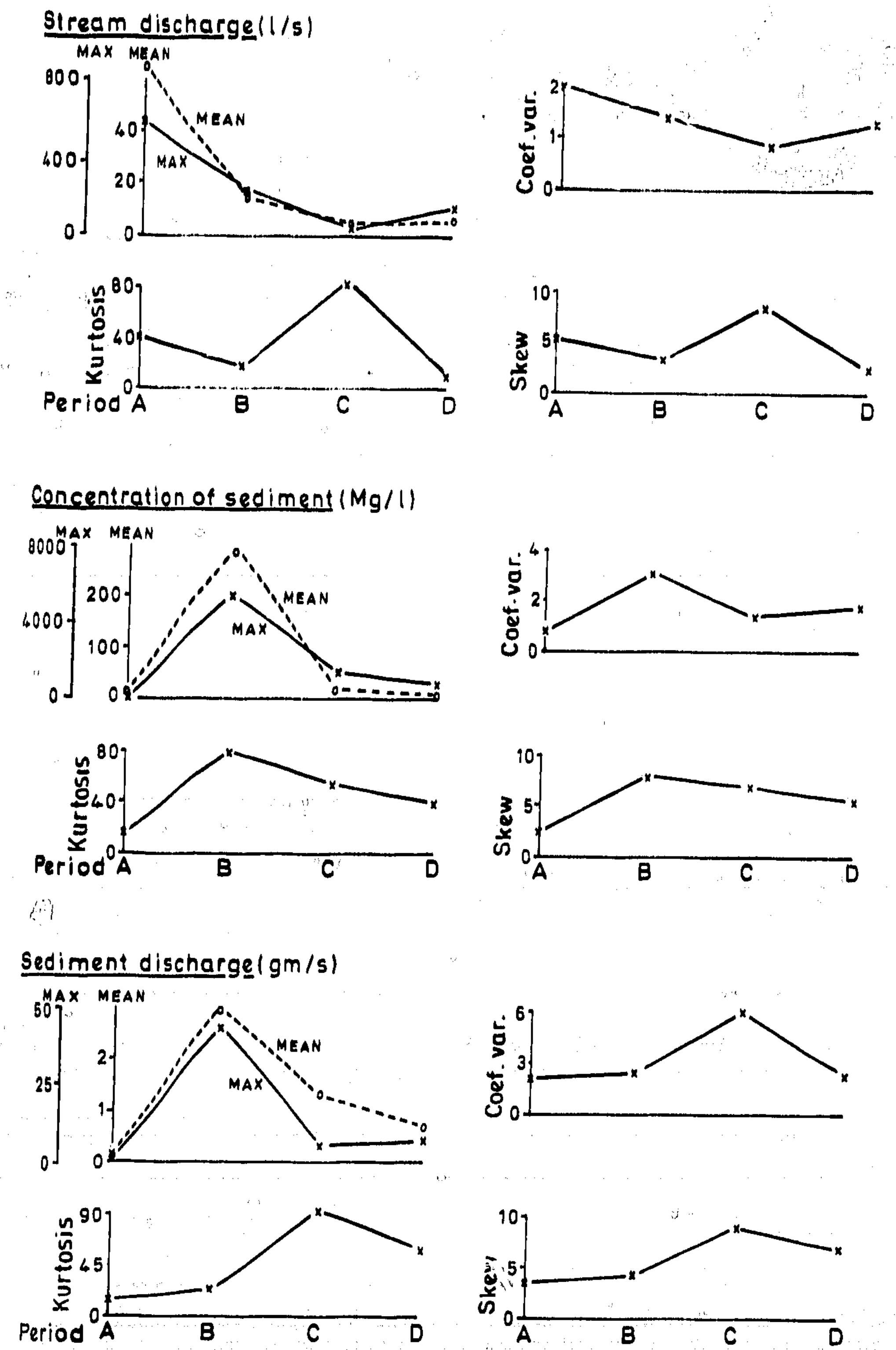


FIGURE 7 **Statistical descriptors of the catchment outputs before, during and soon after draining.**

Period A = calibration period Period B = drainage
Period C = post-drainage (1972) Period D = post-drainage (1973)

less affected by this storm and showed a similar pattern through time to the mean values.

The general trend of the sediment output (both total load and concentration) was clearly one of a dramatic increase in magnitudes during the draining, with more variation than before, and greater skew and peakedness of the frequency distributions. These parameters then decreased through time, although in all cases tending to a value that was still higher than in the calibration period. This resulted from the fact that sediment loads were much more responsive to large storms than prior to draining when the range of sediment concentration had been so limited.

2.4.2 Sediment rating curves for the different periods

The changing pattern of sediment response may also be described by the relation between streamflow discharge and its corresponding sediment load. Sediment rating curves are given in Figure 8 for all the periods.

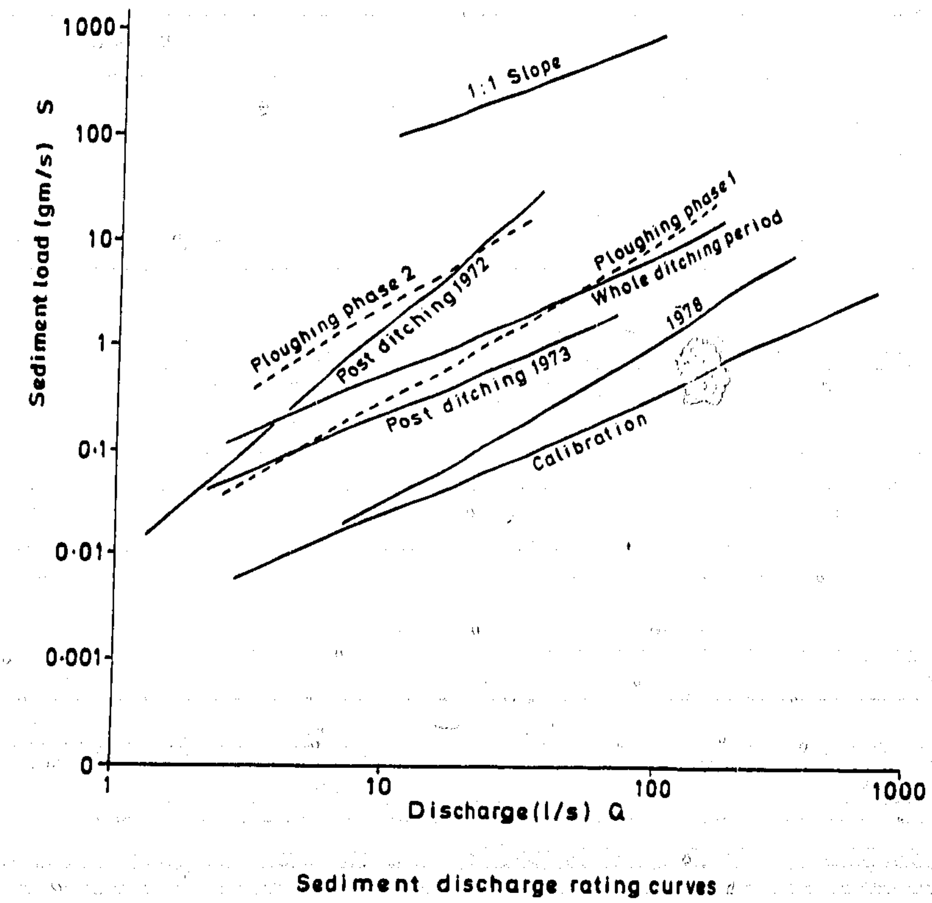


FIGURE 8 **Sediment-discharge rating curves before/after ditching. The length of each line indicates the range of discharge sampled in each period**

Not surprisingly the curve for the calibration period exhibited the lowest sediment load for a given flow, and with a slope only slightly above unity demonstrates the lack of variation of concentration with streamflow. The curve for the whole draining period whilst having higher sediment loads, shows a lower rate of increase in sediment with rising discharge. This appears surprising at first, but if the two drainage phases are treated separately it becomes apparent that they form two distinct populations each with a slope of about 1.6. However, when they are combined, the rating curve must attempt to fit both the high streamflow, moderate sediment levels of phase 1, and the low streamflow, high sediment concentration of phase 2. The result is a curve with a much lower slope of about unity.

The ratings for 1972 and 1973 show progressively lower levels of sediment for a given discharge, indicating a decline in the level of sediment response after the very high concentrations of the ploughing period. The very steep curve for post-draining values in 1972 was largely due to one extreme point.

The pattern of decline in sediment yields indicated by these curves is further substantiated by the results of the fieldwork in 1978 which showed that levels have declined still further, though have remained greater than in the pre-draining period. The greater availability of sediment after draining was demonstrated by the increased response to higher streamflows, with a sediment rating curve now of the form:

$$S \propto Q^{1.5} \quad \text{where } S \text{ is sediment discharge}$$
$$Q \text{ is stream discharge}$$

Tentative estimates of the magnitude of annual sediment yields may be made and indicate about 4.5 tonnes per year prior to draining and about 18.5 tonnes in 1978. These values must however be treated with a great deal of caution due to the short sampling periods considered.

2.5 Catchment recovery to a new equilibrium level

It is both interesting and instructive to study the manner and the rate of the recovery of the catchment, from the disruption caused by the ploughing operations, to the establishment of a new equilibrium.

2.5.1 Pattern of changes in sediment yields

Estimates of the total weekly suspended sediment loads were first made in order to study the changing level of sediment yield through time. This was the approach adopted by Painter *et al* (1974), but note their graph was incorrectly drawn and has unfortunately been reproduced elsewhere, e.g. Clarke and McCulloch (1979). The correct weekly estimates are given in Figure 9 and Table 3.

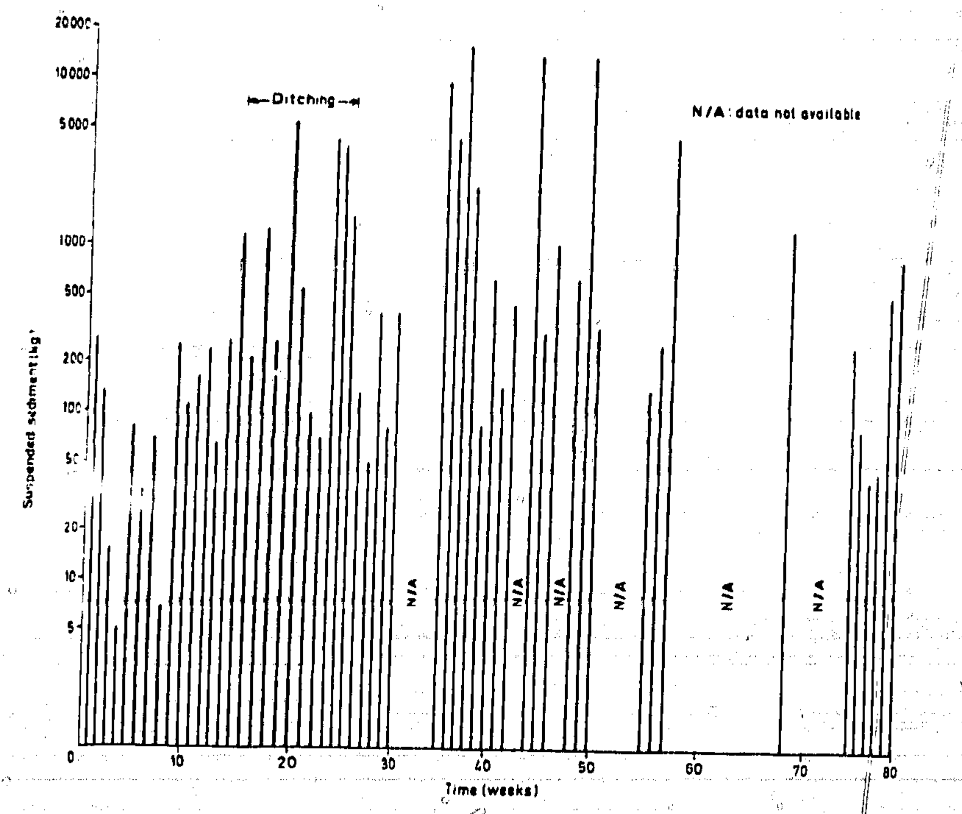
However, as can be seen from the figure, the general trend of the data was severly distorted by the very irregular pattern of rainfall during the period. Thus, the wet calibration period which had very low

TABLE 3 Coalburn weekly suspended sediment loads (kg)

WEEK	kg	WEEK	kg	WEEK	kg	WEEK	kg
1	275	21*	98	41	140	61	N/A
2	160	22*	70	42	450	62	N/A
3	15	23*	4100	43	N/A	63	N/A
4	5	24*	3795	44	13340	64	N/A
5	80	25*	1420	45	300	65	N/A
6	35	26	130	46	1000	66	N/A
7	70	27	50	47	N/A	67	N/A
8	7	28	380	48	630	68	1250
9	250	29	70	49	13240	69	N/A
10	110	30	390	50	320	70	N/A
11	100	31	N/A	51	N/A	71	N/A
12	230	32	N/A	52	N/A	72	N/A
13	65	33	N/A	53	N/A	73	N/A
14	270	34	N/A	54	N/A	74	N/A
15*	1185	35	9500	55	170	75	250
16*	210	36	4120	56	250	76	80
17*	1270	37	15240	57	420	77	40
18*	260	38	2230	58	N/A	78	45
19*	5342	39	85	59	N/A	79	500
20*	535	40	595	60	N/A	80	810

* Ploughing period   N/A - Break in sediment or discharge record for at least part of the week.

FIGURE 9 Weekly suspended sediment loads



sediment concentrations produced weekly sediment yields similar to those occuring immediately after draining when, although concentrations were much greater, stream discharges were very much lower.

In order to reduce the effect of individual wet and dry periods on the overall pattern of change in sediment yield, it was considered preferable to relate the sediment to the passage of discharge rather than of time. Thus, dry periods when little material was moved would be given much less 'weight' than high rainfall periods when large quantities of water and sediment were discharged from the catchment.

A double mass curve of sediment yield and streamflow was constructed and is shown in Figure 10. From inspection of the graph it is clear that prior to draining there was a very stable relationship. At the start of draining, sediment loads increased dramatically, and the two phases of draining can be readily identified, with the intervening holiday period when little sediment was carried from the catchment. After draining the relationship was much more irregular, tending to steepen during storm periods, when large quantities of sediment were carried and concentrations were high, and flattening out somewhat during periods of low flow when less sediment was carried out. As has already been noted, the post-draining pattern was one of generally higher baseflow concentrations than before (about 30 mg/l cf. about 3 mg/l) and with a greatly increased sediment response to storm flows. In the largest winter storms after draining, quantities of sediment were carried in a single day equivalent to the yearly output prior to drainage.

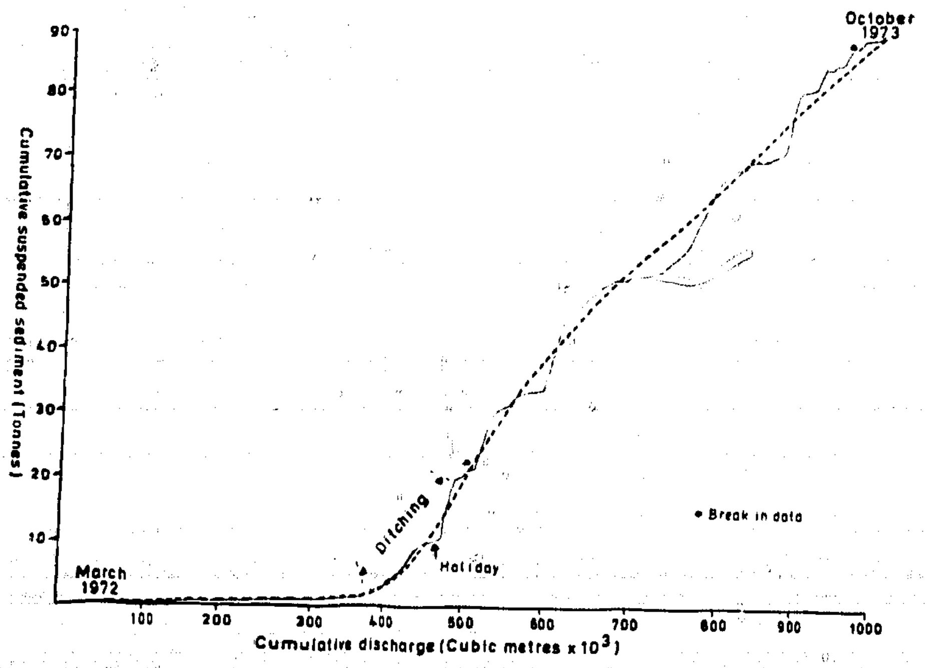


FIGURE 10 **Double mass curve of streamflow and suspended sediment output from the catchment. Breaks in the data resulted from work to excavate sediment that was accumulating in the stilling basin of the weir.**

The broad trend of the catchment sediment yield may be studied by fitting a smooth curve through the double mass plot to filter out the effects of the individual wet and dry periods. An automatic curve fitting routine could have been used, but would have involved an initial assumption as to the nature of the relation which would have influenced the result. A moving average model would have led to the loss of data at each end of the series, whilst a polynomial fit tends to give rise to oscillations unless a large number of terms are used. Both these methods involve an arbitrary assumption concerning the number of terms to be used. Given reasonable assumptions about the accuracy of the data and of the amount of detail that might be required, it was considered that fitting a smooth curve by eye was justified. It should be noted that the main break in the data occurred towards the end of the period and thus would have had a minimal effect on the fitting of this curve.

The slope of this line gave the sediment load per unit discharge, and therefore represented the changing level of sediment concentration. It was considered that this parameter would most clearly demonstrate the changing pattern of sediment output, and so the ordinates of the smoothed double mass curve were digitised using a d-mac pen table, and a simple computer program used to calculate the changing slope along the line. Figure 11 shows the averaged sediment concentration derived by this method and plotted against the cumulative discharge. In this way it was felt that the effects of the irregular rainfall pattern would have been filtered from the data to yield a picture of the underlying trend of catchment response.

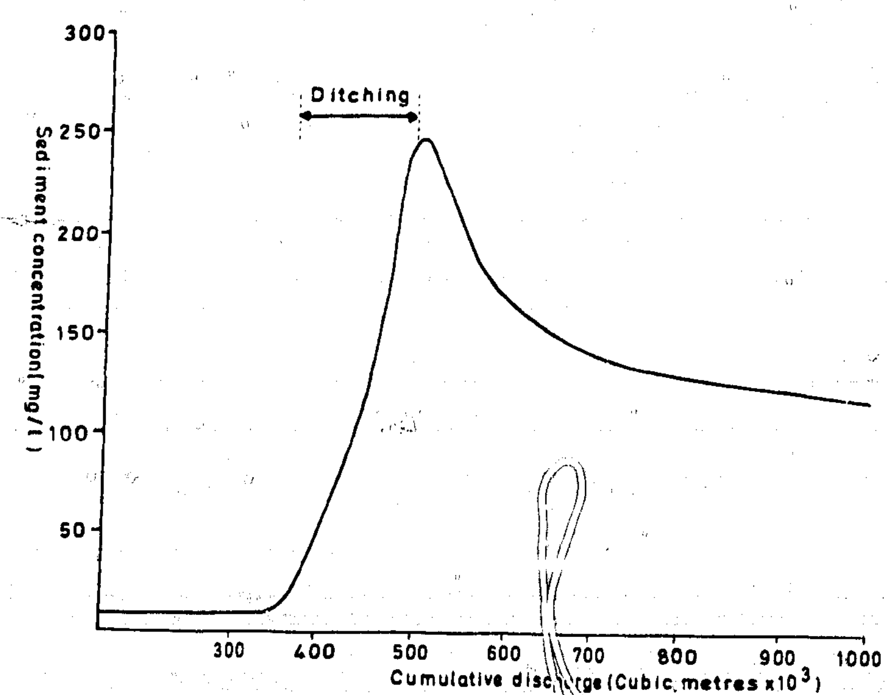


FIGURE 11 **Averaged sediment concentrations**

It should be recognised that since this curve represents the derivative of the smoothed double mass curve, it will be very sensitive to changes in the position of the cumulative curve. Thus, towards the end of the period, when the position of the smoothed curve was less certain, small differences in positioning would have magnified effects for the final concentrations in Figure 11, and the latter part of this curve must be considered to be tentative.

However, the general pattern of change in concentration shown in the figure is not in doubt, and given this picture of behaviour we may turn to examining the underlying physical processes operating.

2.5.2 Factors affecting catchment recovery

Theoretically it might be expected that the ploughing operations would alter the sediment response of the catchment in two ways. Firstly, by the direct effect of the mechanical changes to the area, and secondly, indirectly through the changed hydrological behaviour.

The direct mechanical changes to the catchment were clearly evident. Over 250 km of drains were ploughed, involving the upheaval of the order of 6×10^4 m^3 of material. This made large quantities of sediment available for removal and exposed large areas of bare soil [illegible] erosion. However, both of these effects would be largely transient [illegible] vegetation began to cover and bind the bare soil and as sediment was [illegible]shed from the catchment. In spring 1974 it was estimated that there [illegible] about 100 m^3 of loose mineral soil in the drainage system [illegible] et al, 1974)*. If we assume a bulk density val[illegible] [illegible] [illegible]ly representative of clay soils (e.g. Brady, 197[illegible] this would [illegible] about 130 tonnes of sediment, and constitute a s[illegible] [illegible] to several years sediment yield at post-draining [illegible].

[illegible] changes resulted from the altered hydrological reg[illegible] [illegible] increase in drainage density. The effect [illegible] is [illegible] storm water from the catchment has been [illegible] in Section 5 and involved a much more 'peaky' [illegible] if all other factors were to have remained [illegible] storm response might be expected to hav[illegible] [illegible] of sediment yields.

Examination of contemporary photographs and visits to other newly drained sites indicates that sediment losses were probably derived almost entirely from within the drains, losses from the earth ridges being comparatively minor since the plough deposited most of the material as a fairly intact mass to form a ridge about one metre from the drain edge. Furthermore, these ridges would have contained the surface vegetation mat dug from the drain which would have served both to hold the material together and to facilitate a fairly rapid covering of vegetation.

In contrast, colonisation of the bare drains and of the loose material that had fallen back in from the plough would have been a much slower process and it seems doubtful if any significant plant cover would have become established before the second year after draining (S.R. Eyre, Leeds University personal communication). Some seven years after the draining the main plant types observed in the drains include grasses, mosses and rushes, with species including *Eriophorum, Sphagnum, Juncus, Vaccinium, Plantago, Ranunculus* and *Cirsium,* though some of the smaller plough drains did not contain vegetation due to shading by the Molinia grass on the drain tops.

A study of erosion of material from the drains was carried out in the 18 month period after draining (Painter, *el al.*, 1974) and concluded that mechanical erosion by flow was negligible, freeze-thaw and the flaking of dry surfaces being the dominant processes. This is perhaps not surprising when the enormous density of the network is considered, providing only a small area contributing to each, and it should also be noted that due to the generally gentle relief, the majority of drains had relatively low gradients. It is also of interest to note that the maximum measured rates of downcutting were reported to have been lower for drains in peat than in mineral soil, a phenomenon which has also been noted in Scotland (Graesser, 1979) and in mid-Wales (Newson, 1980), being related to the greater bulk density and cohesion of the peat, together with the more frequent exposure of the underlying mineral material on the steeper slopes.

Unfortunately the author was unable to obtain further details of this survey, or to ascertain the manner in which the relative importance of the erosional processes had been determined. However, field inspection of the drainage network at the present time indicated that although two gullies had formed in the south-eastern part of the catchment where main drains carried water down a steep (30°) slope to join the main stream channel, the majority of the drains had retained their original form. The larger gully was reported to have cut down nearly one metre by March 1974, and when re-examined in 1979 was found to have cut down only about a quarter as much again, indicating that even where a gully had formed it was tending towards a new stable state (Graf, 1977).

2.5.3 A tentative model of catchment behaviour

Following the discussion and observations of Section 2.5.2 concerning the physical processes operating in the catchment, it seems reasonable to assume that the very high rates of sediment yield following the draining would have resulted predominantly from the loss of the available loose material within the drains. After some time this supply of sediment would be exhausted and further sediment yields would result solely from the erosion of new material.

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*This value should be treated with considerable caution since only a rounded value is quoted, no information is given on its density or how the amount was estimated, and it may have included fresh erosion since draining.

FAINT ORIGINAL

A simple two component model may thus be suggested to describe the level of sediment concentration, and is shown in Figure 12. This comprises a large and rapidly declining component representing the flushing out of the loose material from the drains, and a much smaller and probably much more constant component representing the loss of material by erosion of the bare soil surfaces.

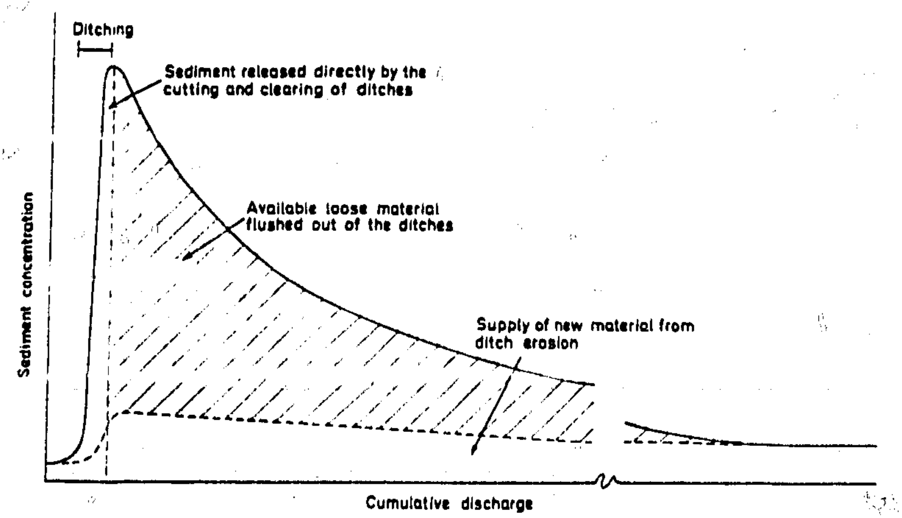


FIGURE 12 Generalised model of sediment output after drainage

We might expect the rate of sediment output of the loose material to be related to the quantity still remaining, and so an exponential curve was fitted to the declining limb of Figure 11 to yield the equation:

$$C = 168\ e^{-.001056\ Q} + K$$

where C is the sediment concentration (mg/l)

e is the base of natural logarithms

Q is the cumulative discharge since ditching ($m^3 x10^3$)

K is the supply of fresh material by erosion; here taken as a constant value of 15 mg/l, (based on the concentrations observed in 1978, by which time the bulk of the loose material in the drains would have been stabilised by plant growth or flushed out of the drains).

This equation was derived by fitting the central portion of the curve between 100 and 400 $m^3 x10^3$ in Figure 11, which was considered to be the most representative section, thus avoiding both the immediate effects of the drain clearance and the uncertainties of the final part of the curve (due to the less certain fit of the smoothed curve near the end

of the data, and the effect of the main period of missing data in summer 1973).

This decay curve may then be extrapolated to make tentative estimates of later sediment levels. Values of cumulative discharge were calculated from the available discharge records together with estimates of flow for the period when the weir was inoperative. Using this curve suggests, for instance, that the material released by the draining would have been largely removed within four years (Figure 13). It must be remembered however that the model predicts average yields and does not consider the effects of individual storms.

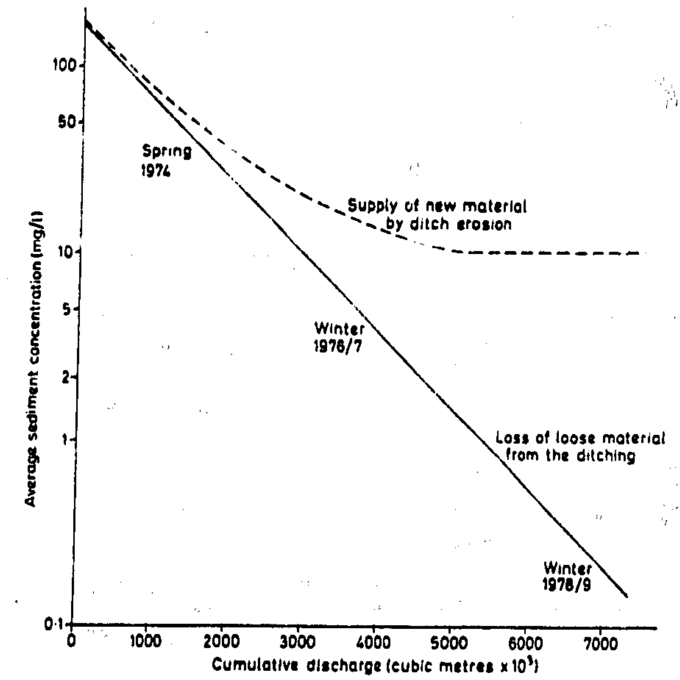


FIGURE 13 Model predictions of sediment load

The rate of sediment loss after ditching can perhaps be expressed most meaningfully in terms of the 'half-life' of the remaining loose sediment. This may be calculated from the exponential decay curve as:

$$\frac{\ln 2}{b}\quad m^3 x10^3 \text{ of flow}$$

where ln is natural logarithms

b is the power term constant of the decay curve (0.001056).

This indicates that on average half the remaining material would have been removed in each passage of $660x10^3\ m^3$ of runoff, or about 7 months duration given the mean annual flow of $1170x10^3\ m^3$.

We may also estimate the total quantity of loose material, from the area under this curve, as having been about 160 tonnes, which together with the 19 tonnes of sediment released during draining would be equivalent to nearly half a century of sediment loads at pre-ploughing 'natural' erosion rates. This helps to underline both the enormous effect of the draining upon the catchment system and also the dramatic rate of recovery to a new equilibrium.

It is of course necessary to treat such estimates with caution given the great extrapolation of the curve, and several checks were made, comparing the predicted loss of material with estimates by other means.

2.5.4 Verification of the model

Much of the sediment carried from the catchment was deposited in the stilling basin of the weir giving a lower bound to the amounts carried and this provided an opportunity to make an independent estimate of sediment loss. The stilling basin was drained for the maintenance work in 1973 and in May the accumulated sediment was measured and excavated.

An unknown quantity of sediment had accumulated in the five years from the construction of the weir up to the draining, but, sediment loads before draining were low, and even if all the sediment was trapped would probably have only represented about 25 tonnes (Section 2.4.2). The method adopted to estimate the accumulated sediment was by surveying the bottom of the stilling basin at over 200 grid points before and after excavation, and although it was not possible to ensure that the new base coincided exactly with the original level any difference should however be small since the stilling basin was cut into bedrock. This survey gave an estimated total volume of about 77 m^3 of sediment. Samples taken from the basin in summer 1979 in a dry weather period of little flow had densities of between 0.36 and 1.44 gm/cm^3. Taking an average value of 1.4 gm/cm^3 indicates about 110 tonnes of sediment had been trapped. If 25 tonnes is assumed to have accumulated prior to draining this would suggest about 85 tonnes of sediment had accumulated during draining and up to May 1973.

The measured sediment loss over this period comprised [illegible] tonnes during draining and another 66 tonnes afterwards. However this included only about 47000 m^3 of flow after drainage, and it has been estimated that a further 260000 m^3 went unrecorded when the weir was inoperative. A crude estimate of the sediment output in this period may be made by increasing the sediment load in proportion to the extra discharge, which would add an additional 55% or 36 tonnes, to give a sediment yield since the start of draining of about 120 tonnes.

The cumulative discharge since ploughing was about 720000 m^3 by May 1973, and from the exponential decay model proposed above we can estimate a sediment load of 95 tonnes, which, together with the measured loss during draining and an allowance for new erosion would give a total of about 115 tonnes.

Not surprisingly the agreement between the measured suspended sediment yield and that derived from the exponential decay model was very close (under 5% difference). The value based on the exponential decay model is slightly lower since it made allowance for the levels of sediment loss during the period of missing data to have declined somewhat from those recorded in the period immediately after the ploughing.

The estimated quantity of sediment in the stilling basin was much lower than these values and suggested an overall trap efficiency of about 70%. This does not of course mean that 70% of the sediment load at any given time would be trapped. The trap efficiency would probably vary during each storm and with storm magnitude as well as tending to decline through time as sediment accumulated and the volume of the pond was reduced (Reed, 1978). This figure then represents the integration of all of these factors.

It was originally intended that another estimate of the sediment deposition in the stilling basin could be obtained when it was next drained in 1978 for periodic maintenance work on the weir. This would have provided another estimate of sediment yield for comparison with predictions by the decay curve model. Unfortunately this work had to be postponed several times by the Water Authority due to bad weather and staff shortages, and has to date not yet been carried out. Therefore, an estimate of the volume of sediment in the basin was made in summer 1979 during a period of low water level when much of the sediment was exposed. From this it was estimated that there was about 70 m^3 of material, with a weight of approximately 100 tonnes.

The exponential decay model predicted that about 65 tonnes of sediment would have been lost from the catchment between May 1973 and June 1979, and making an allowance of about 18 tonnes per annum due to fresh erosion (see Section 2.4.2), this would give a total sediment yield over the period of about 175 tonnes. If a trap efficiency of 70% is assumed to be applicable (since the amount of sediment deposited in the basin in 1979 was very similar to that measured in 1973), this would give a total load of 145 tonnes which represents a difference of only 19% in the estimated sediment totals for the six-year period when the catchment was still in disequilibrium.

It might well be expected that the trap-efficiency of the stilling basin would be lower than in the period up to 1973 since in the former period much higher sediment concentrations were carried and the potential for deposition on entering the basin would have been much greater. The value of a 60% trap efficiency for the period 1973-1979 (based on the predicted sediment loss from the catchment and the estimated deposition in the basin) does not therefore appear unreasonable.

A further test of the model was to compare the predicted levels of sediment concentrations with those actually observed. It would obviously be invalid to use any data upon which the curve was originally fitted, but the samples collected at the end of 1973 were not used in the fitting of the curve (see Section 2.5.3), and could be used to test the predicted levels at a time over a year after the end of the ploughing.

It is clear that the quantities of bed load were negligible in comparison to the suspended sediment loads, and in fact accounted for under 1% of the total sediment load. The suspended sediment measurements may therefore be taken as a good approximation of the total particulate loss of sediment from the catchment.

The measurement period extended from shortly before the cessation of draining on 20/9/72 up to, and including, the large winter storms in November and December. It is evident that whilst suspended sediment quantities declined after draining, but increased again in the large winter storms, the bed load quantities in comparison showed a steady decline. This was despite the fact that bed load transport is usually considered to be largely confined to storm events.

The variation in bed load may also be shown to follow an exponential decline through time after drainage and had a relationship of the form:

$$C = 252\, e^{-.000052\, Q}$$

where [illegible] bed load concentration (gm/m^3)

e is the base of natural logarithms

Q is the cumulative discharge (m^3)

The decline after draining was much more rapid than for suspended sediment with a 'half-life' of about 13500 m^3, which represents a time of about four days assuming the long period average daily flow.

The small quantity of bed load is thought to be due to the lack of suitably sized particles in the soil, together with the low competence of the main stream (resulting from the small total flows and generally gentle channel gradients) making it unable to transport the larger pebbles eroded from the boulder clay and which were then left to line the channel bed. In fact it is possible that the quantities of bed load described here may be overestimated since even the small effect on flow caused by the presence of the trap may have been sufficient to cause some deposition of suspended sediment given the extremely high concentrations that occurred.

3. NATURAL WATER CHEMISTRY

In parallel to the study of the mechanical removal of material from the catchment study was undertaken as an undergraduate project of the solute concentrations in the stream water (Davies, 1973). This was to determine if the cutting of the drains and consequent alteration of the catchment moisture regime had changed the pattern of chemical erosion.

3.1 Description of observed solute levels

Water chemistry analyses were conducted on thirty-seven samples taken during the calibration period, and covering a hundred-fold range in discharge. This was obviously insufficient to describe the detailed temporal pattern over this period but was considered adequate to describe the general extent of solute variations. The results are summarised in Table 5.

TABLE 5 Stream solute concentrations: range and mean values

Period	Sampling Discharges (l/s)	Solute concentrations (mg/l)				
		Ca	Mg	Na	K	T.D.S.
Calibration	4-853	0.7-8.2	0.5-1.2	2.9-6.4	.06-1.0	30-90
	43	3.0	0.7	4.6	0.4	55
Draining	7-77	3.6-5.7	0.9-1.5	4.1-5.0	0.7-1.1	110-170
	31	5.0	1.2	4.6	1.0	140
Post-draining (1972)	2.4-3.6	11.3-12.1	2.9-3.1	5.9-6.1	0.8-1.2	80-120
	3	11.7	3.0	6.0	0.9	95
1978-1979	41-374	4.0-6.1	0.7-0.84	2.8-4.2	0.5-1.4	40-7[illegible]
	152	4.7	0.8	3.6	0.7	[illegible]5

The concentrations were very similar to values for calcium, sodium and potassium published by Crisp (1966) for the Rough Sike catchment, a small Pennine upland area in the Moor House National Nature Reserve.

The variation in concentration with streamflow was studied; an inverse relation with discharge has often been reported for solute concentrations (the well known 'dilution effect' first noted by Hem in 1948). Although considerable scatter occurred, the relations are given in Table 6. These relations are also very similar to those found by Crisp

Calcium concentrations were negatively correlated to discharge whilst potassium was weakly positively related and sodium appeared to be little affected by discharge.

Other studies of solute behaviour (e.g. Foster, 1978) have generally noted an inverse relation between discharge and cation concentrations with the exception of potassium ions. The positive relationship of

TABLE 6 Solute-discharge ratings prior to draining

Solute	Relation	Coefficient determination	Significance*
T.D.S.	$CaQ^{-.03}$	3%	Not sig at 5% level
Ca	$CaQ^{-.27}$	42%	Sig at 1% level
Mg	$CaQ^{-.06}$	15%	Sig at 1% level
Na	$CaQ^{+.001}$	0%	Not significant
K	$CaQ^{+.08}$	3%	Not sig at 5% level

*Tests of the significance of the sample correlation coefficient were made using Student's 't'.

potassium with streamflow is related to the manner in which potassium ions are held by the colloidal fraction of the soil.

Samples taken during the drainage period were bulked for the individual sub-periods, prior to analyses. The values given should be treated with some caution since the bulking necessitated [illegible]rage time before analyses. The values refer to samples ta[illegible] the first draining phase, a[illegible] they were all near the upper end [illegible] the range in concentrations not[illegible] during the calibration period. This might be expected since the drainage operations would have released water which had been stored in the soil for some time. For example Davies (1973) reported T.D.S. values of up to 260 mg/l for water draining from a freshly cut drain.

Only a further four samples were analysed in 1972 after the draining was completed. These figures showed generally higher concentrations for all solutes than prior to draining and exhibited an especially dramatic increase in calcium levels.

3.2 Discussion of findings

There was an apparent increase in solute levels after draining, and the relative abundanc[illegible] of the four main cations altered from Na>Ca>Mg>K to Ca>Na>Mg>K. It has been suggested that this represented a change in water chemistry from a predominantly peat catchment to a boulder clay type as the influence of the inorganic soil was increased through its exposure by the drains (Davies, 1973; Institute of Hydrology, 1973). This argument was lar[illegible]y based upon the fact that prior to draining a water sample had been analysed from a tributary in both a peat area and in a boulder clay area. Much higher concentrations of calcium, magnesium and total dissolved solids were found in the stream draining boulder clay (17.5, 4.5 and 240 mg/l respectively) than in that draining peat (1.7, 0.35 and 60 mg/l).

However, no record was made of the sampling locations, stream characteristics or flow conditions, and there was only a single sample from each soil type. Furthermore, no allowance was made for the fact that the stream discharge was very different in the periods immediately before and after draining, both in terms of mean values and the flow range. In fact, the highest flow during sampling after draining was lower than the smallest flow sampled prior to draining. The most noticeable increase in concentration was for calcium, and to a lesser extent magnesium and total dissolved solids; sodium and potassium showed little evidence of change. This corresponds exactly with the pattern of behaviour that might have been expected for very low flows from an examination of their solute-discharge rating relations (Table 6).

To examine whether a genuine change had occurred in the pattern of chemical denudation of the catchment, the pre-draining solute rating curves for total dissolved solids and calcium were used to estimate the concentration that might have been expected for the low flows after draining. This gave values of about 57 mg/l and 6.2 mg/l respectively, which were both much smaller than the measured concentrations. However, this assumes that the relationships were indeed log-log linear, and it has been demonstrated that more complex equations may give a better description (eg. Walling, 1974). The solute-discharge relations prior to ploughing are plotted in Figures 14 and 15, and it is evident that the double logarithmic curves gave a very poor fit to the low discharge, high concentration values. It was considered that a non-linear curve might give a better fit to the data, and quadratic logarithmic curves were tried. This gave an improved fit to the calcium concentrations, with an estimated calcium concentration of 12.2 mg/l for a discharge of 2.5 l/s, so indicating that differences in discharge conditions alone could probably have been capable of accounting for the observed differences in solute concentrations. The picture for the T.D.S. concentrations was confused by the greater measurement errors involved; the values were obtained by evaporating a water sample and weighing the residue, and the errors involved (weighing and hygroscopic errors) would be at least of the order of ± 5 mg/l, and the concentrations measured were only quoted to the nearest 10 mg/l (Davies, 1973). A quadratic logarithmic relation gave little improvement over the double log fit, and a predicted value of 70 mg/l. A curve was then fitted by eye and gave an estimated value of about 80 mg/l, which is reasonably close to the post-draining mean concentration of 95 mg/l.

Given the small number of samples, the large amount of scatter in the solute rating curves and the immense difference in stream discharge levels in 1972 before and after draining (due to differences in rainfall), it is felt that there is insufficient evidence to substantiate the claim that the drainage resulted in a fundamental change in the pattern of chemical erosion in the catchment.

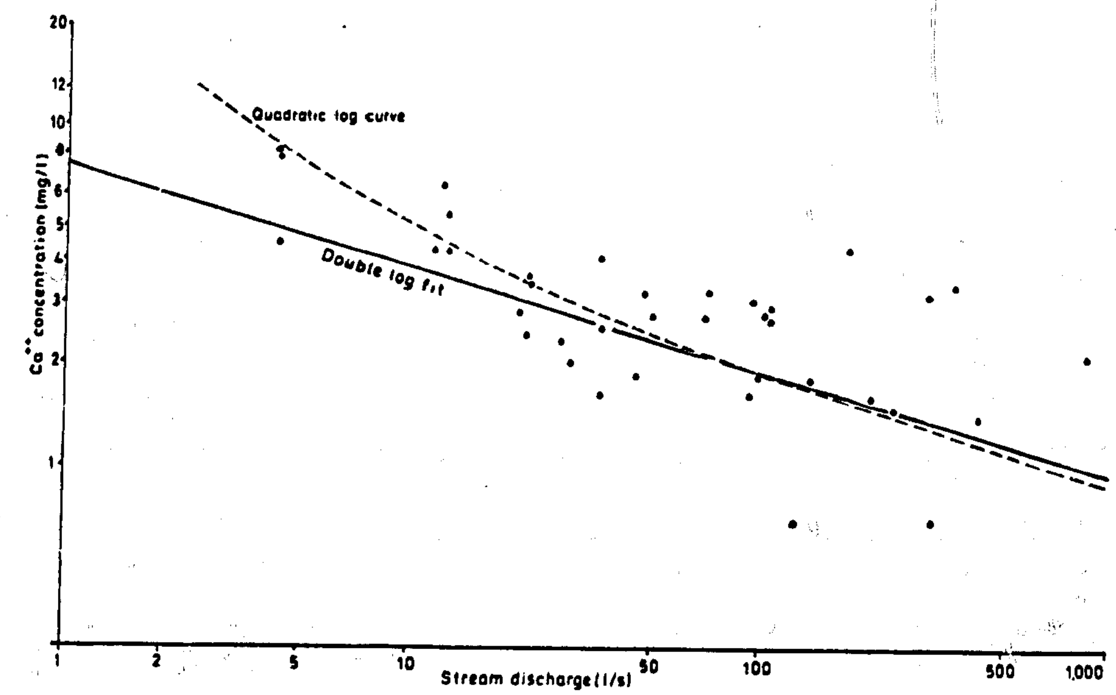


FIGURE 14 **Relation between calcium concentration and flow before drainage**

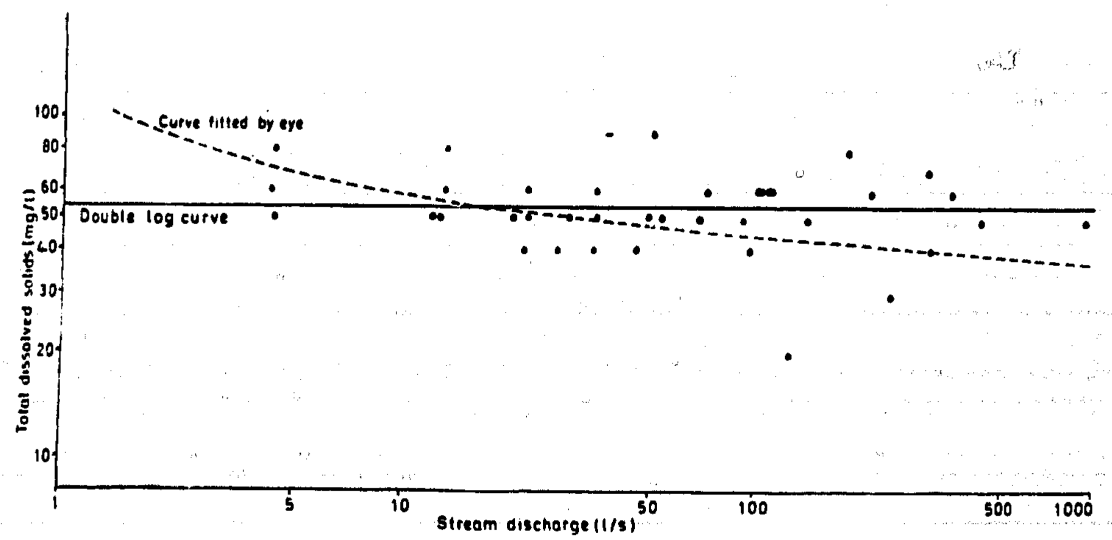


FIGURE 15 **Relation between total dissolved solids and flow before drainage**

This conclusion has been further supported by sampling in 1978-9, when in a period of fairly average rainfall, all the solute concentrations were found to be similar to the value recorded prior to the ploughing, both in absolute terms and also relative to one another (Table 5). There would appear thus to be a 'cross-over' point at about 15-20 l/s, below which calcium was the most abundant cation in the stream water and above which sodium was dominant.

It is interesting to note that the total annual dissolved load would have probably been in the order of 40 tonnes/km^2, which is greatly in excess of the mechanical erosion, being about 12 times the pre-drainage load and about three times present levels. A similar picture has been shown for other humid temperate catchments (Oxley, 1974; Walling, 1971). Dissolved loads increased during draining as water which had been in contact with the soil for some time was released, so that, for only a short period during and after draining were suspended sediment losses greater than dissolved loads.

4. FERTILIZER LOSSES

Upland soils are generally poor in nutrients and the addition of phosphatic fertilizers has become almost the rule on peat soils (Seal, 1973). Ground rock phosphate was applied to the catchment from the air in May 1972, some nine weeks prior to the draining and laboratory analyses of phosphate (PO_4) concentrations in the stream runoff were carried out by the Cumberland River Authority in accordance with D.O.E. (1972). The analysis comprised the determination of particulate and dissolved orthophosphates by colorimetry using a molybdate reagent. Organic phosphates and polyphosphates were converted to orthophosphates by acid hydrolysis. Problems of interference due to the peat were countered by the use of blank determinations on the samples (A. Hollington, North West Water Authority, personal communication).

4.1 Phosphate concentrations in the stream runoff

Measurements of phosphate concentrations in the stream water commenced in April 1972, about a month before the application of fertilizer, to study the natural levels as a base for comparisons. Phosphate concentrations were generally low with values ranging from 0.01 to 0.06 mg/l and a mean concentration of 0.016 mg/l. Concentrations were not related to discharge levels, although this may have been due to the fact that the concentrations measured were of a similar magnitude to the accuracy of the techniques used (about 0.01 mg/l). The observed values were comparable to levels of about 0.02 to 0.1 mg/l phosphate recorded in the Rough Sike catchment in Westmorland (Crisp, 1966).

Within a few hours of the aerial application of the fertilizer, phosphate levels in the stream increased from 0.01 to about 0.27 mg/l, probably resulting from rock phosphate which had fallen directly into the natural stream channel network. In succeeding storms more phosphate was washed down the stream network and concentrations rose as high as 1.5 mg/l. Levels between storms remained at about 0.25 to 0.35 mg/l, ie. about 15-20 times the previous natural level. Phosphate concentrations were positively related to discharge by an equation of the form:

$$PO_4 \propto Q^{0.5}$$

where PO_4 is phosphate concentration
Q is stream discharge.

The low exponent of the relationship (0.5) results from the small range in concentration values compared to the 400-fold range in discharge.

It should be noted however, that despite the great increase in phosphate levels with a mean concentration of 0.5 mg/l they were still much lower than the concentrations of many other elements (see Section 3). This is due to the fact that water soluble phosphates are precipitated in very insoluble forms in most soils and in acid soils would bind to iron and aluminium oxides and hydroxides, and to soil colloids.

Phosphate concentrations increased further with the start of drainage operations, and during the first draining phase ranged between 0.7 and 2.2 mg/l with a mean value of 0.1 mg/l ie. double that prior to ploughing. Concentrations were no longer simply related to discharge but fluctuated in an apparently random way as the draining progressed.

During the two week annual holiday period in August phosphate concentrations declined slightly with a maximum value of 1.1 mg/l and a mean of 0.8 mg/l, but concentrations still showed no correlation with discharge.

Phosphate concentrations increased again in the drain clearance period, with values recorded up to 1.5 mg/l. Concentrations fluctuated little with discharge, being related rather to suspended sediment concentrations (ie. the pattern of the drain clearance operations).

Unfortunately the analyses were only continued for a few weeks after the end of the drainage work, and as mentioned in Section 2 this was a generally dry period with low streamflows. It is not immediately clear, therefore, if the low phosphate concentrations (0.2-0.6 mg/l) were the consequence of the low runoff levels or the result of the exhaustion of the remaining available phosphate. At the time it was felt that the latter explanation was the most likely: "... by the end of September (five months after the application of the fertilizer) a fairly steady level was maintained at about ten times that found in the catchment prior to fertilizing." (Institute of Hydrology, 1973).

However, despite the limited range in streamflow in this period, it has been found that phosphate concentrations were positively related to discharge in the form:

$$PO_4 \propto Q^1$$

This strongly suggests that the phosphate levels were limited by the low streamflow levels, and would have been much higher if the weather conditions had been more typical (ie. much wetter).

4.2 Quantities of phosphorus lost from the catchment

The loss of elemental phosphorus from the catchment may be estimated from the recorded concentrations of phosphate described above, and be related to the total quantity applied.

The rock phosphate was applied at the rate of 375 kg/ha and comprised 30% P_2O_5, 45-50% CaO, and the balance of silica, fluorine, iron and aluminium which occurred in the natural rock. The total weight of rock phosphate applied was thus 57000 kg, of which 8440 kg represented phosphorus.

The loss of elemental phosphorus before fertilizer application was very low, amounting to only about 0.094 kg/week or 0.032 kg/ha/year. This may be compared with the average loss in drainage water in England and Wales of 0.06-2.3 kg/ha/year (Owens, 1970). Since the annual phosphorus input in the rainfall over Britain is about 0.2-1.0 kg/ha (Allen, *et al.*, 1968), this clearly shows how the land surface acts as a 'sink' for phosphorus due to the binding of phosphorus in insoluble forms.

The quantities of phosphorus lost during and immediately after the ploughing are given in Table 7 below.

TABLE 7 Phosphorus losses at Coalburn

Period		Average flow (l/s)	Loss over Period (kg)	Equivalent annual loss (kg/ha/year)
Pre-fertilizer	(6/4/72-1/5/72)	28	0.354	0.032
Post-fertilizer	(2/5/72-3/7/72)	40	75.8	2.9
Draining phase 1	(4/7/72-11/8/72)	27	13.9	0.876
Holiday	(12/8/72-28/8/72	10	2.1	0.297
Draining phase 2	(29/8/72-20/9/72)	8.1	2.9	0.334
Post-draining	(21/9/72-4/10/72)	3.8	0.74	0.134

The total loss over the five month period was 96 kg which represents under 2% of the applied phosphorus. In addition, further losses would have occurred in the succeeding wet winter.

5. HYDROLOGICAL EFFECTS OF THE DRAINING

5.1 Introduction

The purpose of the draining was to modify the moisture regime of the catchment, and it might therefore be expected that the pattern of runoff from the catchment would be altered in some way as a consequence. Unfortunately no measurements were made of the soil moisture, so this discussion must necessarily be restricted to changes in the hydro-meteorological inputs and outputs of the catchment, and in particular the catchment water balance and the pattern of storm runoff. The boulder clay and sandstone bedrock underlying the peat are thought to be impermeable and the catchment is considered to be watertight.

The only previous study of the hydrological changes at Coalburn, was that of Williams (1977), and initially it was intended to largely refer to his conclusions. However, after a preliminary examination of the data and of the methods of analyses adopted, it was considered that a detailed re-examination of the basic data was justified, but since Williams' analyses were based upon much the same data set it was felt that they should be referred to in the text for comparison, and where the author reached different conclusions, the possible reasons for the disagreement are discussed.

Changes in catchment runoff were studied at a variety of scales, ranging from the annual water balance down to individual storm responses and low flow conditions.

5.2 Storm runoff

The effect of the drains upon storm runoff patterns was studied by comparison of sets of storm hydrographs before and after draining.

5.2.1 Time distribution of storm runoff

Storm hydrographs will vary with storm rainfall patterns and catchment conditions, thus making comparison between periods very difficult. A simple and objective method of comparing hydrograph shapes was required and it was considered that the use of hydrograph analyses would be appropriate to provide non-dimensional runoff hydrographs for comparison.

The unit hydrograph has always posed theoretical problems, such as the definition of net rainfall and runoff, although these are problems for much more sophisticated models too (Nash and Sutcliffe, 1970). More recently it has become fashionable for the criticism to be centred on the inherent non-linearity of the flow processes. Evidence of non-linearity has however proved to be surprisingly elusive, and the Flood Studies Report (NERC, 1975), for instance, failed to produce any clear evidence for non-linear ideas. This may be due to the fact that many basin parameters such as total flowing channel length, lag time, and stream velocity, become increasingly constant with high flows. One study (Minshall, 1960) is often quoted as demonstrating systematic variations in unit hydrograph parameters with increasing storm intensity, but must be treated with caution due to the very small catchment area (0.1 km^2), the fact that the unit hydrographs were not standardised to a common time interval, and the relationship derived used only a few of the data points (Robinson, 1976). In addition, the method of net rainfall separation adopted may have tended to induce an apparent negative correlation of lag with storm intensity (Lowing, 1976).

It is not intended to discuss further the merits or demerits of the unit hydrograph method, except to say that despite its critics it will continue to be widely applied until another practical method can be proved to be superior.

One hour unit hydrographs were derived by the 'least squares' technique adopted in the Flood Studies Report (NERC, 1975) for one period before drainage and two periods after. For each period about a dozen unit hydrographs were obtained, and a mean unit hydrograph produced by averaging the individual parameter values. The range in values of some of the main parameters of the unit hydrographs for individual storms are given in Table 8 together with the mean values for each period.

TABLE 8 Summary of the main parameters of the unit hydrographs

Period	Time to peak	Peak flow	Base length (hours)
1969-71	4-6 (5)	.122-138 (.130)	34-39 (36)
1973	1-3 (2.2)	.161-254 (.188)	17-24 (18)
1976-77	1-4 (2.2)	.138-.219 (.168)	13-26 (19.5)

Mean values are given in parentheses.

Figure 16 shows the mean unit hydrographs for each of the three periods and demonstrates clearly that the drains provided a much more peaky runoff response, with approximately a halving of the time to peak and an increase of about 40% in the peak flow value.

The individual unit hydrographs were then examined in order to determine if the apparent differences before and after drainage could have occurred simply by chance. A Mann-Whitney U-test (eg Pearson and Hartley, 1972) indicated that the differences in both the times to peak and the peak flows *were* significant (α = .005) before and after drainage. However, the differences between the two post-drainage periods were *not* significant.

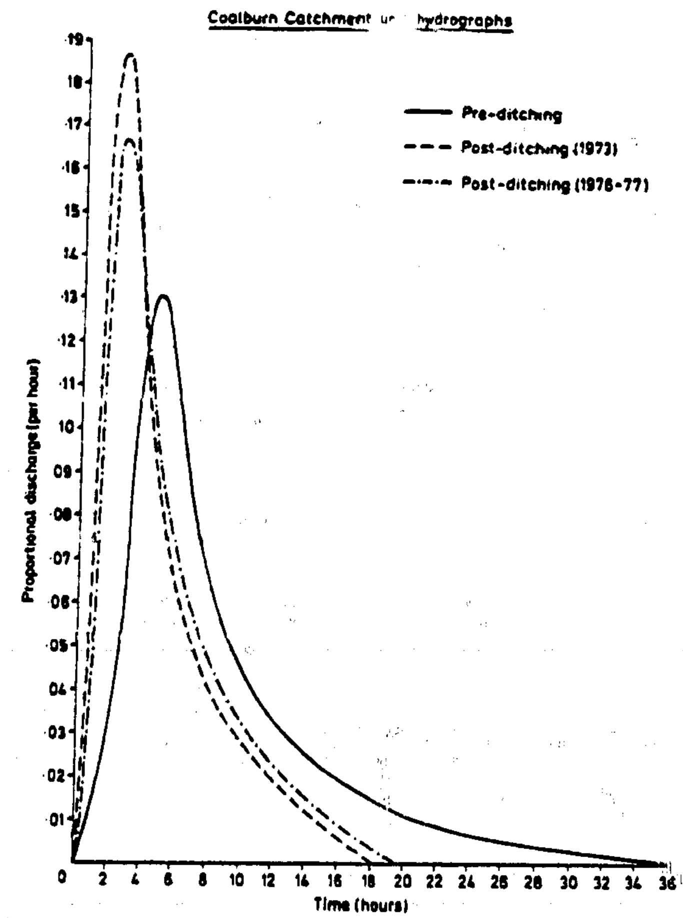


FIGURE 16

Averaged one hour unit hydrographs before and after drainage

In some catchment studies a seasonal difference in the unit hydrograph has been noted (eg Harvey, 1971). The Mann-Whitney test indicated there was *no* significant seasonal difference in any of the unit hydrograph parameters *either* before or after drainage.

It is interesting to note that the unit hydrographs derived for the period four to five years after drainage showed a slight decrease in peak flow and an increase in time base compared with those derived in the year following drainage. Whilst the differences were not statistically significant and could have been accounted for by chance, they may also be interpreted as resulting from the growth of vegetation in the drains. The reduction in peak flows may be expected to continue, and once the trees have reached maturity it is claimed may result in a more stable pattern of flow than from the original undisturbed moorland:

> "I am sure you are right that ditching causes an increasing liability to flash floods and only occasionally will initial ditching increase the storage capacity. It is when the growing trees, by their increased transpiration loss and by the addition of layers of litter, both cause the drying of the soil and increase the storage capacity in the surface

layers, that the classical picture of the forest as a moderator of flows and a beneficent influence on the frequency of flooding is realised." (W.O. Binns, Forestry Commission, personal communication).

Conversely, a preliminary study of a grassland catchment and one under mature forest (with drains) indicated a more rapid runoff response from the latter under identical rainstorm inputs, and this was attributed to the forest drains (Newson, 1979). Further work is needed to clarify this important aspect.

5.2.2 Total storm runoff

In considering the flood potential, we must of course consider the total flow to be apportioned in addition to the time distribution of that flow. About 15-20 storm events covering a range of magnitudes were sampled both before and after the draining to study the relation between storm rainfall and the percentage runoff.

It was noted that in each period the largest runoff percentages were associated with the storms having the highest maximum rainfall intensities, and since there was also a tendency for greater storm intensities prior to draining, the analysis was confined to storms with a limited range of maximum intensities. An arbitrary maximum value of 3.5 mm/hour was adopted (excluding the three most intense storms from each sample).

This yielded equations of the form:

Before: % R.O. = 0.848 R + 22.9 $r = .29$

After: % R.O. = 2.601 R + 7.84 $r = .78$

The relationship between storm rainfall and runoff was much stronger after the draining, and this may indicate a decrease in the importance of antecedent conditions. The importance of catchment storage may still be evident for small storms (under 8.5 mm total) for which these equations indicate a decrease in percentage runoff since draining, possibly due to the somewhat drier soil conditions being able to absorb a greater portion of the rainfall. For storms with greater than 8.5 mm rainfall, the improved runoff provided by the drains, outweighs the improved storage, and the percentage runoff increased steadily.

Frequency distributions for storm magnitudes are not available, but daily rainfall frequencies have been analysed (Figure 17B). For the whole period of record, 60% of the total rainfall occurred on days with over 7.6 mm rain, and 40% of the total rainfall occurred on days with over 12.6 mm. These figures probably tend to overestimate the importance of small storms somewhat, since many of the larger storms will be cut between different rain day records. But it appears likely that the overall effect of the drains on storm runoff yields would have been limited to a modest increase. This conclusion appears to be confirmed by the daily flow duration curves for streamflow (Figure 17A), which show little change in storm runoff patterns for day with greater than the mean annual flow.

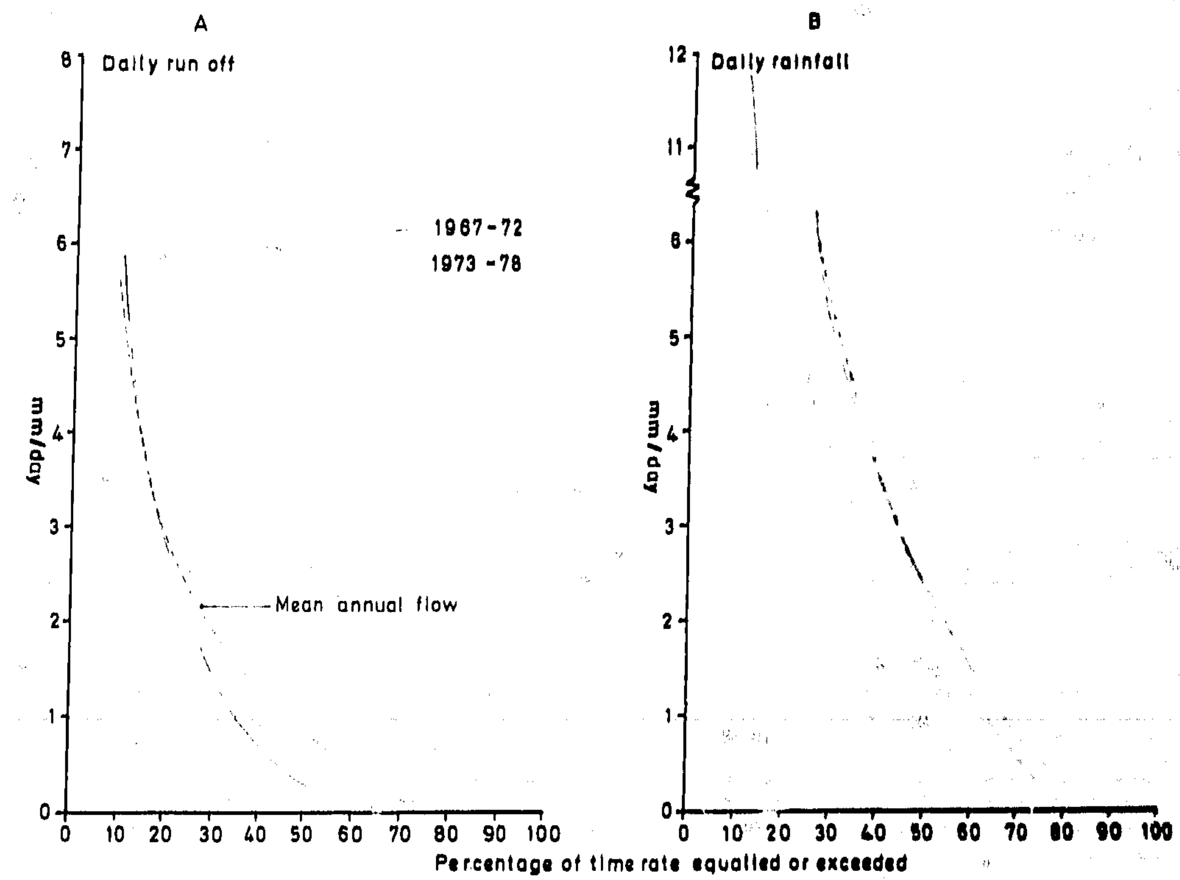


FIGURE 17 Cumulative frequency curves for rainfall and runoff

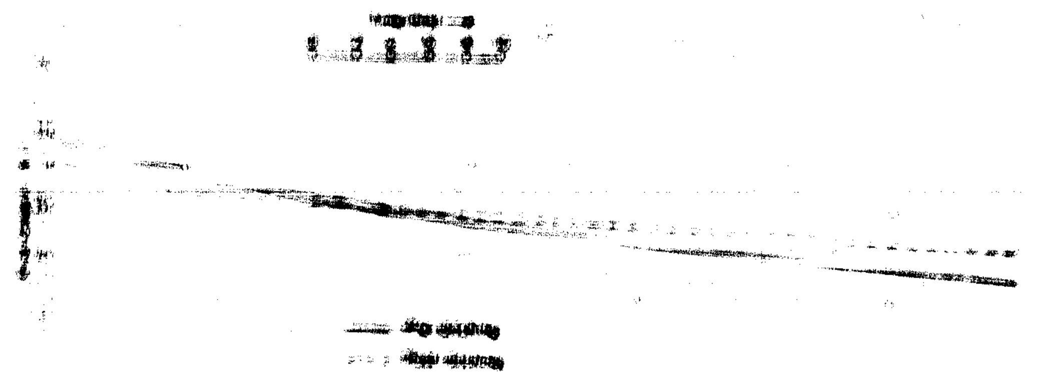
An additional factor restricting any increase in storm runoff volumes may be the presence of the turf ridges on each side of the drain. These would effectively limit the contributing area for surface runoff to the one metre wide strip between ditch and ridge, and prevent the two metre wide zone between ridges (40% of the catchment), from contributing to runoff except by sub-surface seepage.

5.3 Low flows

The presence of the ditches may affect the pattern of drainage between storms as well as during them. The period after draining included the 1975-6 drought and although Coalburn was not as severely affected as many areas (Clarke and Newson, 1978) it might be expected that there would have been a greater proportion of time with low streamflow, and a lower flow rate for a given frequency of occurrence. In fact the daily flow duration curves show that the opposite occurred, and the level of flow at a given frequency was higher than before (Figure 17A). This also, at first, appears a surprising result considering the greater rate of streamflow recession after the draining noted in the unit hydrograph study (Section 5.2.1).

[illegible] of low flows, master recession curves [illegible] from a number of storms before and after ploughing. [illegible] uninterrupted recessions, and [illegible] analysed, so as to reduce any irregularities in [illegible] due to evaporation losses.

[illegible] before and after ploughing are shown in Figure 18, [illegible] that after an initially more rapid decline during [illegible], the post-draining recession rate becomes much lower and [illegible] than for the earlier period. [illegible] of water into the drains between storms, [illegible] between the ridges, and partly due to the [illegible] reaching parts of the catchment which were [illegible], if ever, drained of surplus soil moisture except in [illegible]



[illegible] Master depletion curves before and after draining

[illegible] that this conclusion conflicts with that of Williams [illegible] the draining had had no effect on the catchment [illegible] between storms. A possible explanation [illegible] conclusions drawn from basically the same [illegible] may have mixed recessions from different seasons [illegible] evaporation rates). The recessions for the [illegible] from the two previous summers [illegible] which had very high potential evaporation rates (up [illegible] reserves would have been excep[illegible]. Such conditions have been shown to lead to steeper [illegible]

[illegible] the general level of stream discharge in rainless periods [illegible] by a change in the Baseflow Index (Institute of [illegible]. This index represents the proportion [illegible] runoff estimated by the given separation procedure [illegible]. Prior to draining this averaged 0.108, [illegible] yearly values ranging between 0.065 and 0.136. However, [illegible] after draining the average value of the index doubled to [illegible] values of between 0.196 and 0.230.

To determine if such a change could have been caused by climatic factors, the index was calculated for a number of other catchments in the area. None of these showed any tendency for change over the same period.

The individual annual values of the Baseflow Index for Coalburn were then tested by the Man-Whitney U test and found to be significantly different ($\alpha = .05$) before and after draining.

5.4 Water yield

The presence of the drains has been shown to have affected the drainage of runoff both during and between storms, and there might be expected to have been a change in the overall water balance, and hence runoff yield from the catchment as a result. The data period available at present extends from January 1967 to March 1978, and includes a break from November 1972 to June 1973 during maintenance work on the weir. This unfortunately only provided a relatively short period of data before and after ploughing for comparison, but it was nevertheless hoped that it would be possible to determine any tendencies to change and estimate their magnitude. As discussed in Section 1.2, the trees are still very small, and it was assumed that their effect on water losses to date have been negligible.

5.4.1 Annual water balance

The annual water balance for the catchment was determined for both calendar years (January-December) and water years (October-September). The latter is preferable theoretically to reduce exchanges in catchment moisture between years, but use of the former permitted five years of data prior to draining to be analysed instead of four. The following discussion therefore centres on the calendar year data, although identical analyses were performed for the water year data, and the results are given for comparison. The main components of the annual water balance are given in Table 9; all measurements are in millimetres.

The annual percentage unoff after drainage increased by about 4.5 (3 for the water year data) despite the fact that the annual rainfall was somewhat lower. A comparison was then made of the main elements of the annual water balance, to determine whether or not there were statistically significant differences between the two periods. A Mann-Whitney U test indicated that neither the decrease in rainfall or increase in runoff between periods was statistically significant. However, the increase in the percentage runoff was significant ($\alpha = 0.1$) for both the calendar and water year data. Ideally we should prefer a more stringent level of significance, to ensure that a change had occurred, but it should be recognised that the power of the test has been limited by the small sample sizes (the *power* of a statistical test tells the probability of *correctly* rejecting the null hypothesis of no change, when a change has in fact occurred, and will increase with the sample size). A parametric test such as a t-test assumes further information about the data (normal distributions and equal variances) and has greater statistical power (ie. it gives a more sensitive test with equivalent sample sizes). It is not possible to ensure that these

TABLE 9 Major components of the annual water balance

	Rainfall (R)	Runoff (Q)	% Runoff	Loss (R-Q)	$\hat{Q}$
Pre-draining:					
1967	1480	998	67.4	482	995
1968	1304	822	63.0	482	873
1969	1084	724	66.8	360	721
1970	1297	914	70.5	383	868
1971	990	655	66.2	335	655
Mean:	1231	823	66.9	408	822
Post-draining:					
1974	1292	856	66.2	436	865
1975	1100	795	72.3	305	732
1976	1159	818	70.6	341	773
1977	1264	966	76.4	298	845
Mean:	1203	859	71.4	345	804

($\hat{Q}$ is the predicted annual runoff from a simple rainfall-runoff model described later).

assumptions are valid with the small quantity of data available here, but but if the t-test is assumed to be valid and is applied to the data, the increase in the percentage runoff is significant at the α = .05 level.

Several earlier studies have noted a higher water yield from a drained catchment than from an undrained one although the mechanism was often unclear (eg Conway and Millar, 1960: Mustonen and Seuna, 1972; Green, 1970). Daily flow duration curves for the two periods are give in Figure 17A and show an increase in flow levels below the (pre-drainage) mean annual daily flow. Since the slopes of these curves represents the frequency of occurrence of the given daily flows, we can see that the greatest change (represented by the greatest difference in slopes for a given runoff value) was for daily flows of between one and three millimetres (about 20-50 l/s average flow). A Mann-Whitney U test was applied to the flow duration curves for the individual years and indicated that the increase in the daily flow with an exceedance probability of 95% was highly significantly (α = .01).

It was then decided to study the data in more detail to try to determine the type of processes operating. As a first step, the quality of the data had to be checked, in case there had been any change in the standard of data collection that could have accounted for the apparent increase in yield. The Coalburn catchment is a research catchment with a high standard of instrumentation, and random errors should therefore be small. Possible systematic errors were then investigated.

(1) Revisions of a stage-discharge relationship which are not applied to earlier data may lead to apparent changes in runoff patterns. However, the same relation has been used over the whole period. The channel improvement and drainage operations may have increased stream velocities but any effect of this would have been to increase the streamflow discharge for a given stage, and thus lead to underestimates of discharge rather than overestimates since draining (eg. Wilcox, 1979). Much of any change in velocities would probably have been lost in the stilling basin. Any effect of the accumulation of sediment in the stilling basin would also have tended to lead to underestimates of runoff since ploughing, rather than overestimates.

(2) The raingauge network has been reduced over the period, but this was achieved by removing redundant gauges which did not materially affect the areal totals. In common with most upland sites it is however difficult to determine how accurately the network measures snow.

(3) Measurements in the catchment indicated the drainage and exposure of bare soil had lowered the albedo from 0.15 to 0.13 (Institute of Hydrology, 1973). This would have given rise to a slight increase in evaporation losses since draining. Estimates of potential evaporation at the catchment are only available since the installation of an Automatic Weather Station in 1973. Earlier estimates were made from a meteorological station at Spadeadam, some 12 km away, but were found to be about 10% lower due to site differences, and are therefore not comparable.

(4) In areas of relatively low slopes the drainage area of an undrained catchment may be difficult to define, and the provision of an artificial drainage network may alter the area, casting doubt on water balance comparisons. To avoid this problem a boundary drain was cut around the undrained catchment, the outset of the project, in order to define its area more precisely. This drain was cleaned out when the catchment was drained and care was taken that the forestry drains did not cut across this boundary drain.

In short, there does not appear to have been any change in the data collection and processing which could account for the apparent increase in runoff and, in fact, any changes that might have occurred would have acted to decrease the streamflow measured after ploughing the drains.

In order to study the change in runoff more closely, it would be helpful to establish a model of the relationship between rainfall and runoff prior to draining, and use this to predict the runoff that would have occurred after the ploughing, if this relationship had not been altered. These values may then be compared with the runoff values actually observed after the draining. A simple linear relation has often been found between annual rainfall and runoff, and has been given a semi-physical interpretation (Diskin, 1970). This approach was also adopted in a similar study of the hydrological effect of the draining of the Brenig catchment (Green, 1970).

The relations for the annual calendar year data for the two periods were:

Pre-drainage: $Q = 0.693\,R - 29.8 \qquad r^2 = 92\%$

Post-drainage: $Q = 0.606\,R + 130 \qquad r^2 = 52\%$

The pre-drainage equation was used to generate predicted annual runoff totals for the whole period, and are listed in Table 8. The difference between the actual runoff and the amount predicted are given in Figure 20, and this clearly shows an apparent trend to higher runoff values after draining. The negative residual for 1974 was possibly due to a large transfer to moisture into the succeeding year (December, 1974 having 120 mm more precipitation than runoff). The overall increase in yield over that predicted after drainage may be estimated as 220 mm 6.8% of the total runoff, (4.6% for water years).

5.4.2 Seasonal water balance

For this analysis, the annual totals were divided into two seasons comprising winter (October-March) and summer (April-September). The former would generally contain 'wetting up' conditions, whilst the latter contains the period when the catchment was drying out. The data are summarised in Table 10.

TABLE 10 Major components of the seasonal water balance

(NB Values have been rounded to the nearest mm)

PRE-DRAINING							
Winter				Summer			
Period	R	Q	% Runoff	Period	R	Q	% Runoff
1967-8	926	729	78.7	1967	669	343	51.2
1968-9	494	455	92.1	1968	632	310	49.1
1969-70	577	446	77.3	1969	579	259	44.7
1970-71	652	599	91.9	1970	575	305	53.0
1971-72	542	465	85.8	1971	475	196	42.8
Mean	638	539	84.5	Mean	582	283	48.6
POST-DRAINING							
1973-4	542	480	88.6	1974	497	235	47.3
1974-5	794	636	80.1	1975	642	370	57.6
1975-76	546	478	87.5	1976	449	199	44.3
1976-7	622	593	95.3	1977	584	315	53.9
1977-8	763	704	92.3				
Mean	653	578	88.5	Mean	543	279	51.4

There was obviously a great deal of variation between individual years, but overall these results show little evidence of a change in the seasonal runoff balance, with an increase in percentage runoff after ploughing occurring in both seasons. The increase was slightly greater for winter than for the summer, but this was probably due to the fact that there was a slight tendency to wetter winters and drier summers from about the same time as the draining.

This conclusion contrasts with the study of Williams (1977) who argued that there had been an increase in winter flows and a decrease in summer flows, due to the increased drainage network removing excess water in winter more efficiently, leading to a greater drying of the soil in summer. The method Williams adopted was to divide the year into the two seasons, and to carry out a regression analysis of the *monthly* rainfall and runoff totals for each. The regression lines before and after draining for each season were then compared.

Several aspects of Williams analysis may be criticised however.

Firstly:

> "The linear regression model is not applicable in cases where there is appreciable carryover or lag between rainfall and runoff". (Diskin, 1970).

Changes in catchment moisture storage in a given month may be of a similar magnitude to the precipitation or runoff, due to factors such as snowfall, snowmelt, the timing of the rainfall, or very dry ground conditions. There were, for instance, a number of months with over 100% runoff, clearly reflecting the release of water from a previous period. Secondly, months which lay too far from the regression lines were discarded from the analysis for this and for no other reason. This subjective decision to ignore data is less than satisfactory, and would invalidate the subsequent use of significance tests (Barber, 1976). These tests incidentally indicated that only the winter increase was significant (no level was given). Nevertheless, Williams assumed that there had been an equivalent decrease in summer runoff, since a double mass curve analysis of runoff at Coalburn and from nearby Kielder Burn had indicated no change in the relation before and after draining (and hence no change in the total annual runoff).

Kielder Burn was however rejected here as a 'control' catchment in this study for a variety of reasons. Firstly the period of common data was very short, with only two years of records prior to ditching. Secondly, the Kielder Burn catchment is 40 times larger than Coalburn, giving a different seasonal moisture regime and seasonal changes in the slope of the mass curve line which tended to obscure any change in slope. Finally, the stage-discharge relation for Kielder Burn was revised in July 1973 (the start of the common data period after draining), and has been further revised since then. The new relations have not yet been used to recalculate the historical data and it is not possible to say how they would have affected the calculated yields (M.J. Storey, Northumbrian Water Authority, personal communication). Unfortunately no other suitable gauged catchment could be located to act as a 'control'.

It is interesting to note that Williams observed for the monthly data:

> "Using the full data record the analysis shows a slight but consistent increase in runoff for any given rainfall".

From his graph, the average monthly increase was approximately 4 mm, indicating 48 mm/year, or about a 5.8% increase in the average annual runoff. This compares very closely with the increase suggested in Section 5.4.1.

The available evidence therefore seems to indicate that the observed increase in water yield was not confined to a particular season, but represented an increase in flow throughout the year. Attention was then turned to trying to identify the mechanism responsible for the changes in stream runoff.

5.4.3 Possible physical mechanisms causing a change in yields

A number of possible physical causes of the small apparent increase in yield were then investigated and are discussed below:

(1) The presence of the drains might lead to a reduction in soil moisture levels in the catchment, and during the period of this decline there would be a temporary period of increased flow while water was drained from the wetter areas and from the newly created turf ridges. This might be expected to lead to an increase in low flows. However we would also expect any change to decrease over time, and this was not observed (Figure 19). The release of significant quantities of water

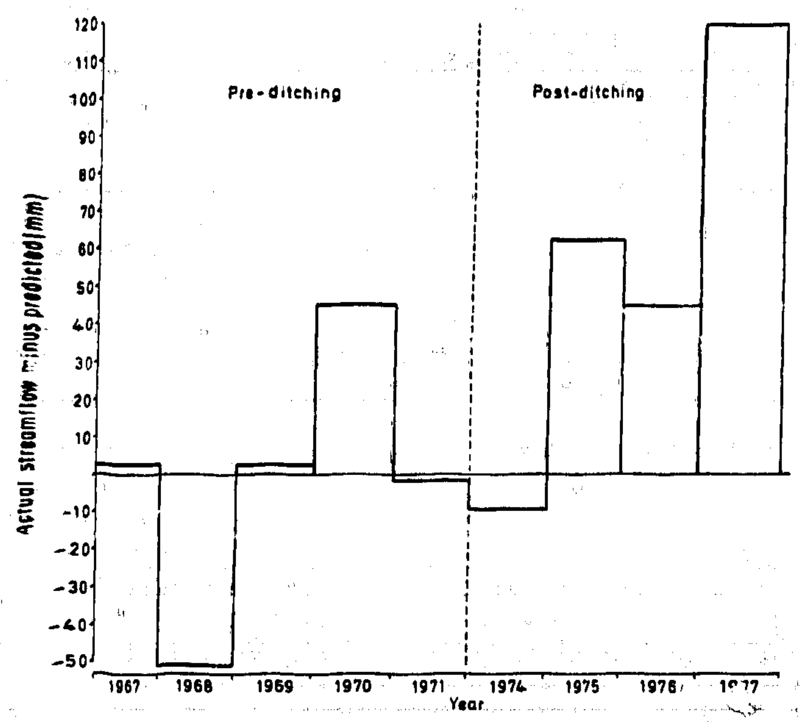


FIGURE 19

Deviations of actual streamflow from predictions

after drainage has generally been associated with much deeper and wetter peat bogs such as raised bogs (eg. Wilcox, 1979), than the conditions at Coalburn. Furthermore, the period immediately after drainage (when the rate of release would be greatest) was not included in the analysis due to the maintenance work being carried out on the weir. The release of large quantities of water is also generally associated with a drying out and shrinkage of the peat, resulting in a measurable lowering of the ground surface (eg. Burke, 1972). No measurements were made at Coalburn, but work at nearby sites in the Kielder and Wark forests found no lowering of the ground surface after drainage (D.A. Thompson, Forestry Commission, personal communication).

(2) The drier soil conditions may have led to a reduction in evaporation losses since:

> "The results of drainage are a fall in the water table and decreased transpiration, so drainage must increase runoff" (Heikurainen, 1973).

However, this would lead to peat shrinkage, for which there is no evidence, and would also probably tend to even out streamflow (and especially reduce flood flows in summer), but there is no evidence of this from the study of catchment unit hydrographs. Peak flows increased after drainage and there was no significant difference between seasons.

(3) The open drains account for about 10% of the catchment area, and if they returned 100% of the rainfall that fell into them, instead of 67% average runoff as from the rest of the catchment, this could lead to an increase in water yield of up to 3.3% of the annual rainfall. Such an increase would however be largely confined to storm events rather than to augmenting low flows and would probably be greater in summer (when catchment losses are greatest).

(4) The increased drainage network would allow runoff contributions from areas far from the original network, which previously had probably only rarely contributed to runoff. This would probably lead to an increase in storm runoff, and we might expect an increase in low flows as well. There would probably be little change in the seasonal balance.

(5) The draining would expose areas of bare soil, and since evaporation losses from bare ground are lower than from vegetated surfaces, this might have led to a decrease in evaporation losses and consequently an increase in runoff. This explanation was suggested for the increase in runoff from the Brenig catchment (Green, 1970). But it does not appear valid for the Coalburn catchment due to the rapid revegetation of the turf ridges and colonisation of the drain sides. Furthermore, this mechanism would lead to a reduction in the higher runoff yields through time, as the bare soil became vegetated. There appears to be no tendency for the runoff residuals to decrease through time at Coalburn (Figure 19), and this explanation was therefore rejected.

The most likely mechanism to account for the observed changes in runoff from the catchment would thus appear to be (4), namely that the increase in the drainage network allowed drainage to occur between and during storms from parts of the catchment which had previously made little contribution to stream runoff.

6. IMPLICATIONS FOR OTHER CATCHM ENTS

If this case study is to be of more than merely local interest, it is important to outline its context, discuss the general features observed, and try to ass... the practical significance of the re...

With the likely continued expansi n of British forestry, and an increasing concentration on the uplands, much larger portions of upland catchments will be forested in the future. These areas provide the collecting grounds of many of the country's major water supply reservoirs, and much of the land will have to be drained prior to afforestation. The study catchmer is typical of many of these upland areas, and it is hoped that the results of this investigation will go some way to providing quantitative estimates of the effect of such drainage operations, which may be of use to reservoir managers, foresters, agriculturalists and ecologists.

6.1 Stream sediment loads

It was estimated that about 120 tonnes/km^2 of sediment was carried from the catchment in the streamflow as a direct result of the draining, which represents a loss of only about 0.2% of the total 60000 m^3 of material that was excavated to create the drains.

The study provided a rare opportunity to observe sediment levels *during* the draining operations. Sediment concentrations were seen to be dependent upon the *type* of work being carried out, the prevailing weather conditions, and to some extent the antecedent conditions. Topographic and pedological differences appeared to have little effect, though this may be largely due to the small size of the catchment (1.5 km^2) limiting these variations.

There was a dramatic increase in sediment levels during and after draining, with concentrations rising from a previous level of generally under 10 mg/l, to above 7000 mg/l. Even greater yields would probably have resulted from a catchment with steeper slopes and more mineral soil of a suitable grain size distribution, but it is thoug likely that the observed rapid rate of decline to a new equilibrium level higher than before draining would be a general feature. The fact that it was reached without any influence from the young saplings suggests that it would be a feature of moorland drainage schemes too although sediment loads would probably be lower due to the much wider drain spacings generally adopted. The most important conclusion regarding sediment yields is therefore that on a regional scale the effect of the draining is determined more by current rates of drainage, than by the total cumulative area drained.

Possible practical problems posed by the increase in sediment loads were then investigated. If the bulk of the sediment released by the drainage operations is carried as suspended sediment, then it will be transported rapidly in the stream and deposited in any reservoir downstream, thus reducing its capacity, and so possibly "there are serious implications for the afforestation of catchments containing reservoirs" (R. Hey, University of East Anglia, personal communication). However, reaction from members of Water Authorities contacted was generally the increase in yields would probably not have any serious con... on reservoir storage:

> ...will be limited interest from Water Authorities in the ... yield figures because of the low levels of sediment ... n most impounding reservoirs" (R. Wood, Severn Trent ...ter Authority, personal communication)

...increased sediment loads may cause a number of local ...blems due to the larger quantities of sediment that will be deposited ...ere flow velocities are reduced. This may lead to ch...ges in the stream channel downstream of an area of increased sediment yields (eg. Wolman, 1964) and also necessitate expensive removal from structures such as the stilling basin of a weir (as happened at Coalburn) or from the fire ponds used by the Forestry Commission. Increased sediment loads may sometimes cause problems of reduced storage for small reservoirs too. For example, the Boltby reservoir, in Yorkshire, some 10 km north-east of Thirsk, was built in the 1880s and had a low rate of sediment accumulation. However, some years ago the Forestry Commission ploughed the area around the reservoir, and the local water undertaking expressed great concern at the large quantities of mineral sediment that were being carried down into the reservoir, resulting in the Forestry Commission building ponds to trap the sediment (T. Johnstone, personal communication).

A more general problem resulting from sediment loads may be an ecological one:

> "Sediment loads released by ploughing operations are certainly controversial. Fishery interests in particular, believe that the release of sediment has a detrimental effect on the spawning success of trout and salmon". (I.R. Smith, Institute of Terrestrial Ecology, personal communication)

It has been shown that very high concentrations of suspended mineral solids (200000 mg/l) can directly cause the death of fish within a few hours, due to a coating of silt forming on the gills (eg. Wallen, 1951). The effect of lower concentrations (<1000 mg/l) for more prolonged periods appears to be more indirect, by making fish more susceptible to adverse conditions in their environment (Herbert and Merkens, 1961), and Cole (1935) for instance found that a 20000 mg/l concentration was not harmful to initially healthy fish, but hastened the death of unhealthy individuals. Sediment concentrations at Coalburn rose above 1000 mg/l for only short periods, and even in the wet winter of 1972-3 were under 100 mg/l for most of the time, so any direct physiological effect on fish would probably have been very limited.

The effect of increased sediment loads in streams has, however, often been blamed for a reduction in fish stocks and a change in fish populations from game fish such as trout and salmon in clear water, to coarse fish in muddy waters (eg. Tarzwell and Gaufin, 1953).

> "There is abundant evidence that sediment is detrimental to aquatic life in salmon and trout streams. The adult fish themselves can apparently stand normal high concentrations without harm, but deposition of sediments on the bottom of the stream will reduce the survival of eggs and alevins, reduce aquatic insect fauna and destroy needed shelter. There can scarcely be any doubt that prolonged turbidity of any degree is also harmful". (Cordone and Kelley, 1961).

In the spawning season after arterial drainage work in Ireland, a 93% mortality rate of salmon fry in natural redds was noted (Toner, *et al.*, 1964) and Hassler (1970) reported a 97% mortality in northern pike eggs covered with 1 mm of silt. Fish may also avoid spawning in turbid streams, and several instances have been reported of salmon going to spawn which have been observed deliberately avoiding muddy tributaries (eg. Cordone and Kelley, 1961). Drainage work in Scotland, associated with hill land improvement as well as with forestry, has recently been accused of harming fish stocks and trout farms (eg. Graessner, 1979) and a similar claim was made some years earlier in Lancashire (Stewart, 1963). The fact that the area being drained does not support a large fish population itself, should not be taken to mean that fish stocks will not be affected:

> "It is possible that the effects of ditching on stream temperature and sediment loads further downstream may have a more serious impact on fish populations than the direct disturbance at the actual work site. This is particularly true in situations where the drainage ditches form the uppermost reaches of a stream system and do not themselves contain significant fish populations (Hill, 1976).

The quantity of sediment released as a consequence of the draining of Coalburn amounted to the order of nearly half a century's load at pre-ploughing rates and it was carried from the catchment in under 10% of that time. Present loads remain at about four times pre-draining levels. Drainage work is concentrated in summer (when the ground is at its driest), and sediment loads would have little time to decline significantly before the spawning of fish in the following autumn and spring. If such work is carried out on a large scale it would appear almost inconceivable that it should not have a detrimental effect, for at least a number of years, upon fish stocks, both in terms of numbers and fish species, and possibly total recovery would never be achieved.

6.2 Water chemistry

6.2.1 Natural water chemistry

Cation concentrations and total dissolved solids were measured as part of an undergraduate project. Only a small number of samples were taken, and streamflow discharge rates were very different before and after drainage. However, it would appear that no great change occurred in the general levels of these solutes as a result of the draining, although a temporary increase may have occurred as soil water drained from the catchment. It is not clear what influence, if any, the phosphate application may have on the solute levels.

6.2.2 Fertilizer losses

Rock phosphate fertilizer was applied to the catchment a short time before the draining, and its loss in solution from the catchment was monitored, for two main reasons. Firstly, the phosphorus carried in the stream represents a loss of expensive fertilizer, and secondly it plays an important role in eutrophication.

Phosphorus is often found to be the principal nutrient limiting aquatic plant populations (Lee, 1973; Taylor, 1967), and small increases in phosphorus concentrations may stimulate the growth of blue-green algae and other organisms, making rivers and lakes unsuitable for recreation and increasing water treatment costs. Increased growth of floating and bottom rooted plants reduces streamflow and complicates other aspects of water management (Taylor, 1967). Soluble phosphorus is probably the form most important to the biology of lakes since it is readily available to plants. The excessive production of aquatic plants is usually more significant in lakes or reservoirs than in rivers since lakes retain their nutrients for a much longer period and they are therefore available for aquatic plants such as algae (Porter, 1975). Fish populations may also be affected since the plants consume oxygen all the time for respiration but only produce oxygen in photosynthesis during daylight. Fish mortalities may then occur during the night, or if the overproduction of algae leads to a shortage of food, then large numbers of algae start of die off, leading to a depletion of the dissolved oxygen in the water.

A critical level of 0.01 mg/l of phosphorus has often been quoted for algal blooms, although many exceptions have been noted. This would represent a level of about 0.03 mg/l of phosphate (PO_4), and whilst concentrations prior to application were below this level, those after were greatly in excess, with levels before drainage averaging 0.5 mg/l, and increasing to 1.0 mg/l during draining. It would thus appear that unless another nutrient (such as nitrogen) was limiting growth, there would be likely to be problems of excessive aquatic plant growths following the large scale application of fertilizer. A study of lakes in Northern Ireland (Gibson, 1976), for instance, found much higher phosphorus levels in lakes with fertilized forest catchments, and considered that the loss of phosphorus would continue for several years after application.

A second reason for studying the phosphorus concentrations was concerned with trying to minimise the loss of fertilizer in the drainage waters whilst still making it available to the young transplants. One possible means is through altering the timing of the application. If fertilizer is added prior to draining, the plough will overturn the surface mat to create a ridge for tree establishment, and some phosphorus is lost during the drainage. This probably amounted to under 2% of the applied phosphorus during and shortly after drainage and though a lot more phosphorus would undoubtedly have been lost after that, it represents an acceptably low figure (W.O. Binns Forestry Commission personal communication). An alternative method is to apply the phosphate after the drains are cut, but a large amount will then fall directly into the drains and be washed out of the catchment. We may make an estimate of the losses from this technique by assuming them to be equal to the percentage of the catchment comprising open drains. This gives a figure of about 10%, which is considerably more than that measured at Coalburn, and suggesting that this would be a much more wasteful method of application.

The final decision on the best time to apply the fertilizer would also have to take into account the importance to later tree growth of phosphorus being available during the early tree establishment period (since it may take a year or more for the transplants' root system to reach the phosphorus rich sandwich layer at the base of the ridge, whilst if it was applied to the surface after draining it would be available sooner to the surface roots).

6.3 Hydrology

There has been a great deal of controversy regarding the hydrological effects of peat drainage. The Peat and Fen working group of the NERC hydrology committee which tried to reconcile the apparently conflicting views of the effects of peat cover, and of changes to that cover, summarised the situation graphically "even where there is firm evidence or well-based opinion, it seems to be conflicting, even to the point where different people describe the same evidence in different terms" (Green, 1973). It was unable, for instance, to determine the effect of drainage on the flood hydrographs, since there were cases of *increased* flood peaks with drainage (eg. Conway and Millar, 1960), and examples of *decreased* flood peaks (eg. Burke, 1968).

It has been shown that the properties of peat soils (such as permeability and bulk density) will alter after drainage, and that the changes differ for different peat types (Egglesmann, 1972). Using this fact, it has been suggested that differences in peat type *alone* might be capable of accounting for the different effects (McDonald, 1973). Thus, the drainage of a Sphagnum catchment (eg. Conway and Millar, 1960) would lead to increased flooding since Sphagnum compacts with drainage, reducing its storage volume and its permeability. The catchment studied by Burke (Burke 1968), on the other hand, was composed of non-Sphagnum peat, which would alter little with drainage, and would thus result in drier soils and greater storage capacity, tending to reduce flood flows.

This interesting argument may, however, be something of an over simplification for several reasons. Firstly, the *effect* of the drainage is measured by reference to conditions prior to draining (or to an undrained catchment). Large differences may exist between undisturbed catchments (such as the efficiency of the natural channel network), and hence in their hydrological responses, thus resulting in a non-uniform 'datum' against which to assess any change.

Secondly, McDonald only compared two catchments - Moor House (Conway and Millar, 1960) and Glenamoy (Burke, 1968), and made no allowance for the very great differences in drainage *intensity*. The drains at Moor House are about 0.5 metres deep and 14 metres apart (field measurement), whilst those at Glenamoy are about twice as deep and about four times closer together (Burke, 1968; Burke, 1972).

It would appear that there may be two (sometimes conflicting) processes operating as a result of peat drainage:

a) The increased drainage network will facilitate rapid runoff,

b) The drier soil conditions will provide greater storage for rainfall.

These processes will possibly themselves be subject to considerable modification. Thus, the effect of the channel network will depend upon the extent of the original network - if, for instance, it was of very limited extent, and runoff was limited to a small part of the catchment, then drainage might increase the total runoff, although the hydrographs might become less peaky since the 'centre of gravity' of the catchment storm runoff generation zone will have been moved further from the mouth, and also sub-surface flow will be encouraged.

The increase in available soil moisture storage after drainage will depend upon the degree of any surface compaction (Egglesmann, 1972) and also upon the actual amount of lowering of the water table (which will depend upon the intensity of drainage, and in particular the ditch spacing, in addition to the type of peat).

Information was not available on the initial natural drainage network at the two catchments, although details of the artificial drain networks have been described above, and may be compared. At Glenamoy, the purpose of the ploughing was to drain the land for agriculture, and yields are given for various crops including, oats, kale, potatoes and rye grass (Burke, 1968). With a drain spacing of 3.6 m the water table was kept more than 40 cms below the surface throughout the growing season.

In contrast, the draining at Moor House was designed merely to improve the standard of rough grazing on the catchment. A review of such 'moorland gripping' schemes (A. Stewart, Research Assistant, Moor House Field Station, personal communication) suggests that the improvement in vegetation resulting from the drainage is much more limited than has often been thought, and that drier soil conditions are generally restricted to a small distance either side of the drain. Field [illegible] at [illegible] itself indicated that the lowering of the [illegible] table was restricted to at most 2-3 metres each side of a drain, and that mid-way between them the water table depth below the surface [illegible] 9 ± 15 cms, and was not appreciably different to depths [illegible] (R. [illegible], personal communication).

[illegible], the effect of the draining at Moor House has been much less than that at [illegible], and it is suggested that this was largely due to the different drainage techniques employed (although this is not to [illegible] the importance of peat type, rather to recognise that it is one of a number of factors controlling the effect of a drainage scheme on flood flows).

The [illegible] in hydrograph peaks following the drainage at Coalburn may [illegible] in terms of the proposed framework above. The catchment [illegible] fairly high natural drainage density of 3.5 km/km², which was [illegible] by the draining to give a drain spacing of 4.0 m. The peat comprises predominantly *Eriophorum* and *Sphagnum*. Thus the catchment is intermediate between Moor House and Glenamoy, having [illegible] to the former and a similar drain spacing to the latter. Unfortunately there was insufficient time to study water table depths, [illegible] appear likely that any lowering of the water table is [illegible] that the ground does not seem any [illegible] than undrained area (T. Johnstone, Chief Forester, Wark, personal communication), and the purpose of the ploughing was more to provide material for the ridges (in order to create an elevated drier site for initial tree establishment) than to actually lower the water table. The material at the edges of the drains would be drained "to some extent, but this depends very much on plough depth, spacing and soil characteristics" (W. O. Binns, personal communication).

The limited amount of any increase in storage through a fall in the [illegible] water table and the likely unimportance of peat compaction, together with the enormous increase in drainage density provided the [illegible] increase in hydrograph peaks noted at Coalburn. Furthermore, since Forestry Commission peat drainage would appear to have little effect on soil moisture in the early years of tree establishment, it would seem likely that such work would generally result in an increase [illegible], but a great deal more investigation is needed before quantitative predictions can be made of the effect of a given scheme.

The data after drainage suggests that there was a small (5%) increase in the annual water yield, and this proposition is strengthened by the fact that a review of possible measurement errors indicated that they would [illegible] to underestimate flows after ploughing (and hence underestimate any [illegible]), and also since an increase in runoff after draining has been noted in other studies. Green (1976) noted a 10% increase after the drainage of the Brenig catchment and Mustonen and Seuna (1972) noted a [illegible] increase in annual runoff from a catchment in southern Finland after making allowance for soil moisture changes. An increase in flow was noted throughout the year, and low flows were increased. A drainage experiment on [illegible] bog in central Finland noted a 100% increase in runoff as the distance between drains was reduced from 60 m to 5 m (Huikari, [illegible]).

An increase in annual runoff of 5% is sufficient to be of interest to reservoir managers, and especially if much of it occurred in times of low flows (‛. Storey, Northumbria Water Authority, personal communication). Furth· ˌata from Coalburn will necessarily be limited as the saplings grow ˌaturity, and begin to effect the water balance (eg. Anon, 1976). It ma, ˌherefore be worthwhile to consider a study of the hydrological effects of upland drainage (and preferably for catchments without trees), to determine the resultant changes in both flood risk and overall water yield. Drained moorland might perhaps represent the 'optimum' land use around an upland reservoir, with higher water yields than either forest or undrained moorland.

6.4 Conclusions

This report describes the work carried out at an experimental catchment to measure some of the effects of an upland drainage scheme. The author has attempted to set the results in context with other related studies, and to assess their practical significance by reference to published work or informed opinion.

Stream sediment loads were observed to increase greatly after draining, and to decline to a new, though higher, average level within 5 years. It would appear likely that the greater sediment loads would not have any great significance for the loss of storage in reservoirs although silting may cause a number of localised problems and may be important in small reservoirs when a large part of their adjoining catc ent area is drained.

Of more importance may be the effect of the larger sediment loads on fish stocks. Healthy fish may withstand enormous concentrations of sediment, but even a shallow covering of silt (eg 2 mm) on spawning grounds may be sufficient to kill most of the eggs, since it impairs the circulation of water round the eggs, which is necessary for them to utilise the dissolved oxygen required in their development. It would seem likely that more than sufficient sediment would b eleased by drainage schemes to affect breeding grounds downstrea nd in particular the spawning success in the autumn and spring followin he drainage. The increased ment levels will continue for a number of years, and probably always remain above pre-draining levels - even under mature forest (eg. Newson, 1980) and it is therefore difficult to assess how long or how complete, the recovery of fish stocks may be.

Another environmental problem associated with the drainage may be the release of excessive amounts of phosphorus into the stream system after fertilizer application (nitrogen was not applied at Coalburn, and therefore not measured), leading to problems of algal blooms in lakes and reservoirs, anaerobic conditions, fish mortalities and difficulties of water treatment.

The unit hydrograph peaks at Coalburn increased by about 40% and it would appear likely that upland drainage usually leads to an increase in flooding. This may be especially significant since the effects of land drainage on downstream flood peaks are likely to be most evident where extensive drainage activity occurs in the upper portions of a river basin (Hill, 1976). There may however, also be a beneficial effect of an increase in water yields.

The work has highlighted three main groups of problems which may be caused by upland drainage schemes (both for forestry and for grazing land). All the groups have a common feature in that their effects are, to some degree, temporary. Thus, the bulk of the sediment released by drainage works will have been removed, and a new, though higher, equilibirum level of sediment loss reached, within say 5 years; phosphate losses will probably continue for no longer than 10 years (eg. Gibson, 1976); and an increased risk of flooding will probably be largely reduced after canopy closure of the trees - say 20 years (although the concept of a mature forest being able to reduce extreme flood flows is not accepted by all).

Some of the undesirable effect may be reduced by short-term measures such as the use of temporary sediment traps (eg. Reed, 1978), or the artificial restocking of fish populations. However, a more comprehensive solution could be achieved through a change in management policy. At present U.K. forests are usually even aged, so that large areas must be drained at approximately the same time. If instead, the timing of the work could be staggered so that only a small portion of a drainage basin was undergoing change in a particular year (or number of years), then many of the undesirable effects would be 'diluted' by water from the rest of the catchment, and thus limiting them largely to just the area undergoing change.

On a more general level this study indicates that many of the changes resulting from forestry drainage are in fact in the opposite direction to traditionally held ideas of the effect of forests. These views were largely based on work on established forests overseas, particularly in the USA, where such drainage is not common. In Britain however most forestry is on peaty soils and drainage is a necessary part of site preparation. It is these drains rather than the young saplings that may be expected to exert the dominant hydrological effects in the *early* stages of afforestation. With cropping cycles of 50-60 years duration for managed forests in the U.K. (C.A.S., 1980) this early phase may comprise an appreciable part of the cycle - perhaps as much as a third - and so possibly 30% of a managed forest area would be on average in this early tree establishment stage, making it a significant land use category in its own right.

Furthermore it is not certain to what extent the effects of the drainage will remain throughout the length of the cropping cycle, and so when making comparisons of say, flood risk or soil erosion between (usually drained) forests and (often undrained) moorlands it may be difficult to distinguish between the effects of the drains and the trees. Overseas studies of undrained forests may therefore not be directly applicable to the U.K. situation due to the need to consider the additional effect of the drains.

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