WORKING PAPER 252

The effects of pre-afforestation ditching upon the water and sediment yields of a small upland catchment

M. Robinson*

School of Geography
University of Leeds
LEEDS LS2 9JT.

September, 1979

*Now at Institute of Hydrology, Maclean Building, Crowmarsh Gifford, Wallingford, Oxon, OX10 8BB.

CONTENTS

LIST OF FIGURES

THE EFFECTS OF PRE-AFFORESTATION DITCHING UPON THE WATER AND SEDIMENT YIELD OF A SMALL UPLAND CATCHMENT

Abstract

Upland drainage is one of the major land use changes in Britain today. A small, upland, peat-covered catchment was instrumented to investigated the effects of its ditching prior to afforestation. Stream sediment loads increased greatly during and after ditching, and took several years to decline to a new equilibrium level, which was higher than that prior to ditching. It was found that the decline in sediment loads after ditching could be described by a simple model. Water chemistry was measured, and the levels of fertilizer losses were monitored. Ditching increased flood peaks and there was an increase in moderate to low flows; annual water yields probably increased. Possible problems associated with the ditching work include damage to spawning grounds, lake eutrophication and increased flooding.

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 4-fold from 202×10^3 ha to 809×10^3 ha (Forestry Commission Annual Reports), an average annual increase of 20,000 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.

The majority of forestry to date has been on the uplands, and this land is often poorly drained and peaty, necessitating ditching prior to planting. The purposes of the ditching include the regulation of water and improvement of aeration, themobilisation 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 ditched (Taylor, 1970) and this percentage will undoubtedly increase 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 (eg. Lewis, 1957; Law, 1958; Institute of Hydrology, 1976) little attention has yet been paid in this country to the direct effects of a *change* in land use.

This study is primarily concerned with the consequences of the drainage of an upland area for forestry, although the results should also be relevant to upland ditching to improve rough growing (moorland 'gripping'). Ditching for afforestation and for improving grazing, each account for about 25,000 ha per annum in Scotland 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 its ditching upon both the stream water quality (suspended sediment and solute loads) and water quantity (peak flows, low flows and water balance). In addition, the loss of fertiliser (often applied at the same time as upland drainage) was monitored.

1.2 Description of study catchment

The Coalburn catchment is a 152 ha (1.52 km^2) upland area in the headwaters of the River Irthing, some 40 km northeast of Carlisle (Figure 1). With an altitude of about 300 m A.O.D. and a mean annual rainfall of about 1200 mm, the natural vegetation comprised rough pasture of Molinia grassland and peat bog. Most of the catchment is covered with 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 tributaries off the main stream, together with several artificial ditches, comprised a total length of about 5,250 m, and represented a drainage density for the catchment of approximately 3.5 km/km^2.

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 saplings in the summer of the following year.

The Institute of Hydrology collected stream samples for water quality analyses from about five months prior to ditching up to a few months before the saplings were planted. Further samples were collected and analysed by the author 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 ditches and colonise the areas of bare soil.

It should be noted, that despite the age of the trees, they are still relatively small (about 1 m in height), due partly to severe frosts, and their effect on the behaviour of the catchment is assumed to be negligible; the pattern of changes up to 1979 being purely the result of the drainage.

1.3 Instrumentation and methods of analysis

Rainfall was measured at a number of ground level weekly gauges and distributed temporally according to an autographic Dines gauge. Streamflow was measured at a compound Crump weir; with the water level recorded by a Leupold and Stevens continuous recorder and a Fischer and Porter 8-hole punch tape. Water samples were collected using a North Hants model 4B 24-bottle vacuum sampler installed on a straight section of the main channel

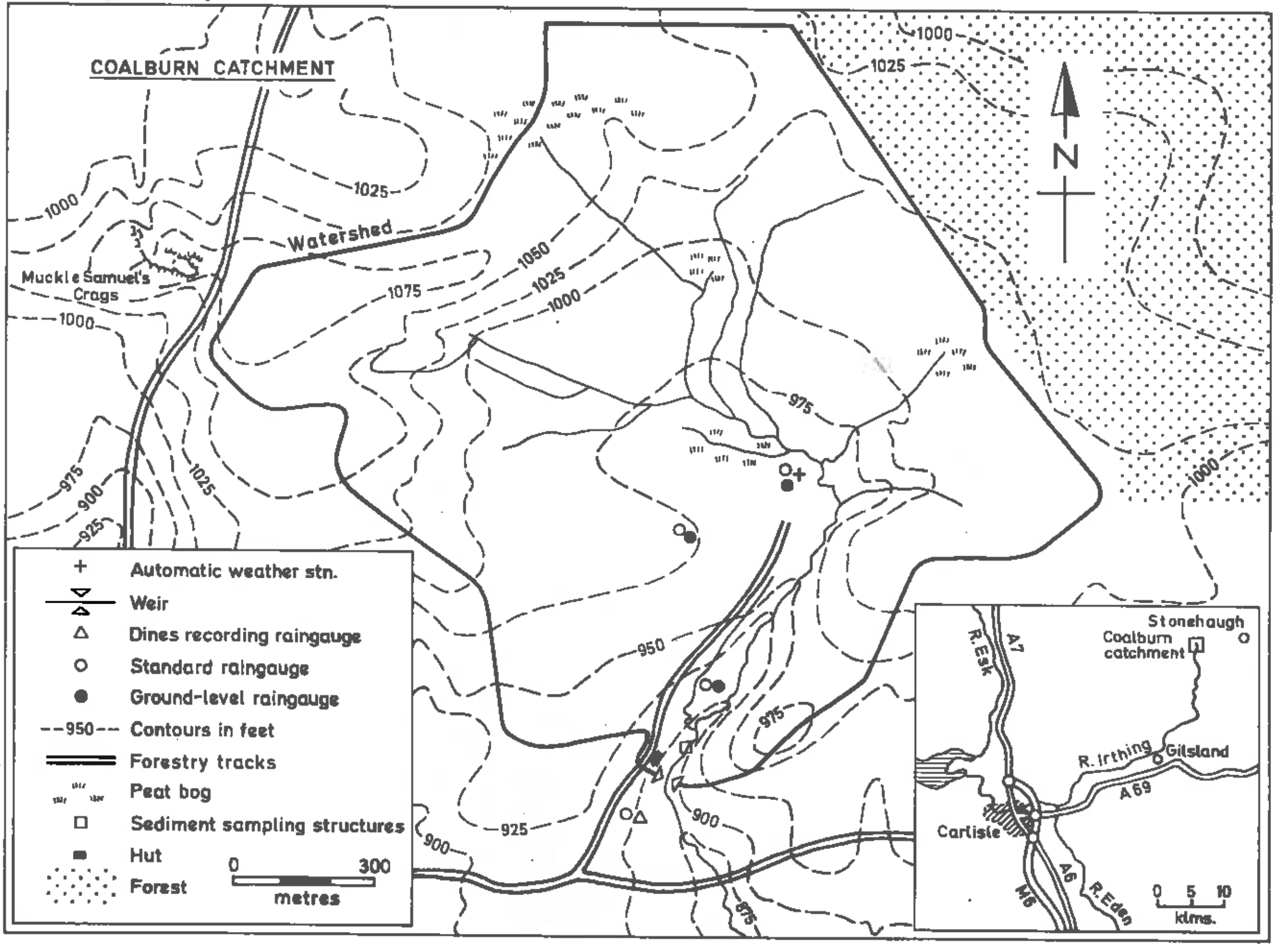


FIGURE 1. Topography and instrumentation of the study catchment

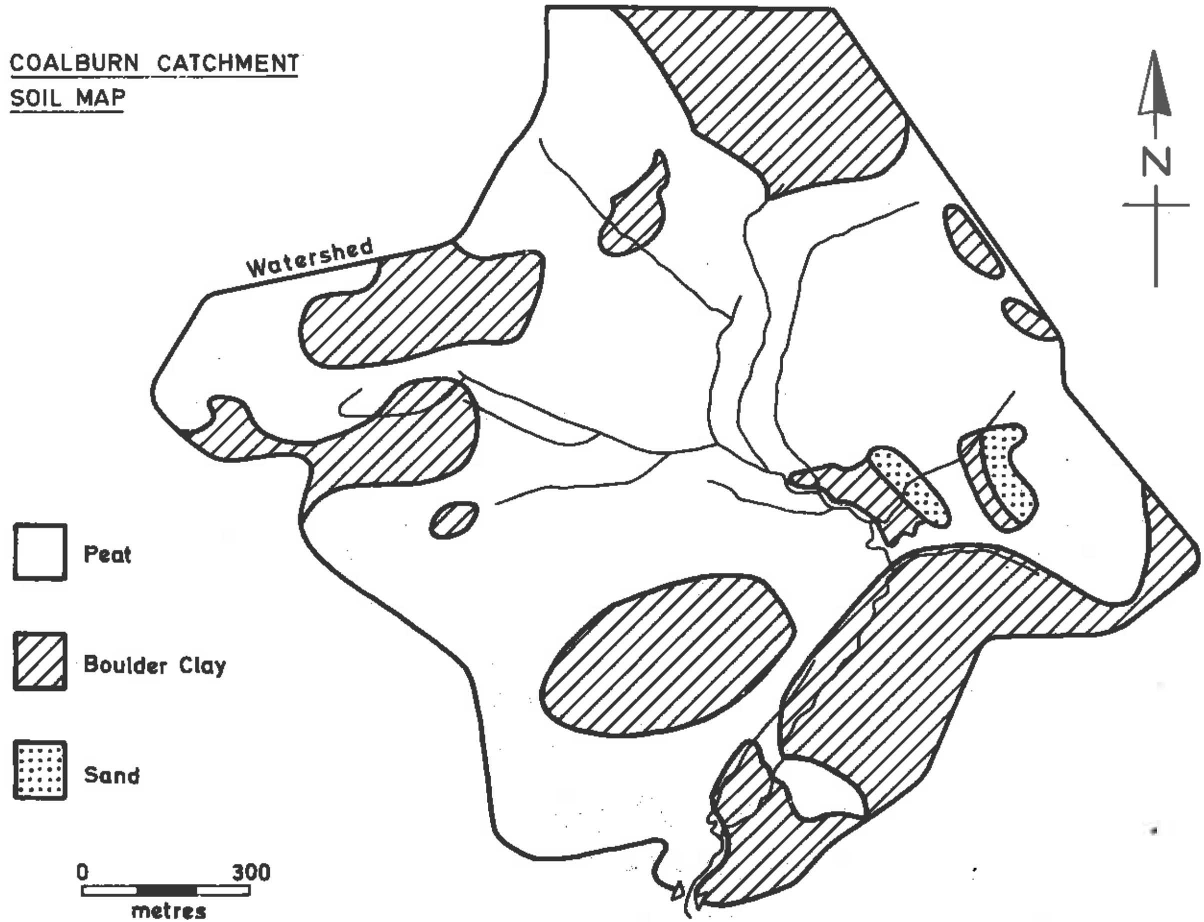


FIGURE 2. Distribution of the principal soil types

some 10 m upstream of the stilling basin of the weir. Samples were initially taken at 12 points within the cross-section in order to identify a representative point for the 8-hourly samples. 12 point samples were taken on 22 occasions covering a wide range of discharges, and whilst there was an apparent tendency for higher sediment concentrations on the left-hand side of the channel there was no significant difference between the mean sediment concentrations at any of the points (using a Student's 't' test). The position eventually chosen was in the middle of the channel near the bed. This point had a mean value closest to the mean for the whole cross-section, individual readings were close to the section mean for each occasion, and the point was under the usual water levels.

The sampling interval of eight hours is much longer than would be ideal since it may miss the sediment peak, but represents a necessary compromise with the immense difficulties involve in collecting records from such an isolated site, over an extended period. However, whilst this does not give an accurate enough picture of the variation with time during individual storms, it gives an increasingly adequate picture of sediment yields as longer period such as a week (21 samples) or even a month (84 samples) are 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" (R. Halliday, Divisional Scientist, North West Water Authority, Carlisle, personal communication). Briefly, the method comprised using Whatman GF/C glass fibre millipore filter paper which was heated at 105^{0}C for one hour and reweighed. The accuracy (reproducibility) of this method has been estimated from later tests to have a standard deviation of ±5% (R. Halliday). The organic matter content of the sediment was estimated by reheating the filter papers at 550^{0}C and reweighing.

Water chemistry was also studied and measurement 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 method of sampling adopted, chemical analyses of the water could not be performed until a number of days after their collection; and so due to the possibility of sample deterioration and of contamination from the suspended sediment, the value obtained should be treated as only approximate. 1 mg of mercuric chloride was added to each sample to help prevent any bacterial action. The cation concentrations were determined using a Unicam SP90A Series 2 atomic absorption spectrophotometer. Total dissolved solids were measured by evaporating a known volume of water to dryness and weighing the residue.

Every effort was made to ensure that the methods of sample collection and analyses used by the author in 1978-9 were compatible with those employed earlier.

2. SUSPENDED SEDIMENT

Water samples were taken for suspended sediment analysis over an 80 week period 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-ditching; during ditching; and post-ditching.

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 was 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 <1 mg/l up to only 28 mg/l, with a mean of 3.6 mg/l, for a 330-fold range in discharge (from 2.5 to 830 l/s). 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 be 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.

Secondly, the sampling interval of 8 hours might miss the peak sediment concentrations which may occur only briefly, and this would tend to underestimate 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 ditching (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 other studies of upland sites (eg. Lewis, et al., 1974; Oxley, 1974).

Supply, rather than transport limitation is considered to be the main cause of the generally low concentrations and the poor rating curve fit observed here, and this conclusion is supported by measurements taken during the ditching period when much higher 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 under 1 m^3s^{-1}).

During the early part of this period there appeared to be an upper limit of sediment concentrations at 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 28 mg/l maximum recorded, and concentrations 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 ditching, there were another 7 readings between 10 and 20 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 Ditching period (July-September 1972)

The technique employed was to use a deep double mouldboard drainage plough pulled by two Crawler tractors, to dig a single ditch of about 80 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

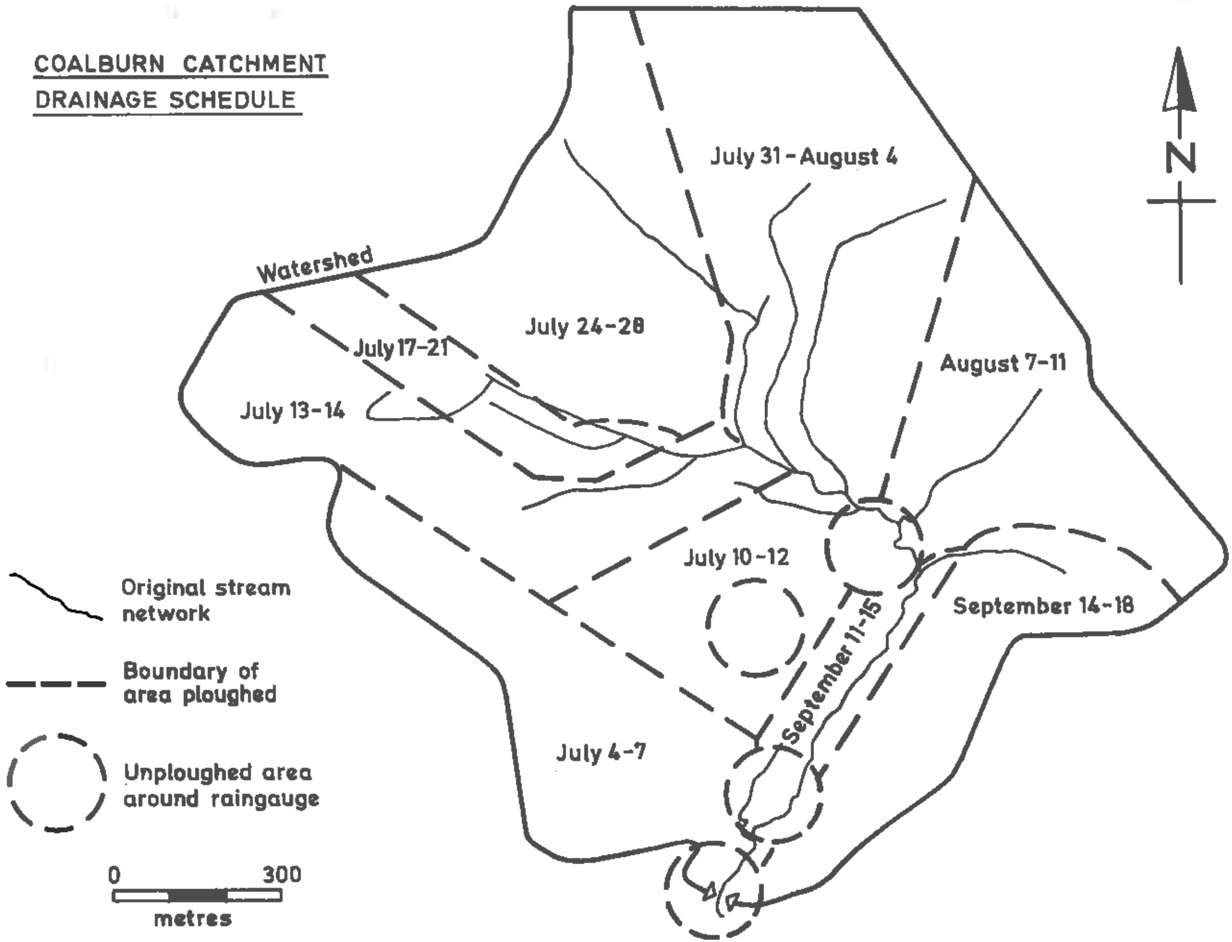


FIGURE 3. Ditching schedule of catchment sub-areas

since not all of the drains were joined directly to an outlet, but rather had their lower ends left blocked, and thus had little effect, until the link and cross drains were ploughed to connect them to the stream system 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 ditching was carried out at weekends, and also the two-week annual holiday fell about two-thirds of the way through the ditching period. These breaks make it possible to sub-divide the effect of the work both temporally and spatially.

The drainage density of the ditches 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 ditching period compared with the previous period, with concentrations ranging from 2 mg/l 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 ditching operations when the link and cross drains were being ploughed and a J.C.B. bucket drainer was used to widen part of the main channel.

In order to gain a better understanding of the processes operating during the ditching phase, water quality measurements were taken for a group of six ditches that were ploughed on Friday 14/7/72 (Davies, 1973). Measurements were taken both in the ditches 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). No further work was carried out until the following Monday, and as there was no rain in this period, so the rise in stream discharge of about 3 l/S noted at the basin outlet may be reasonably attributed to the release of water from these drains, affecting about 3 ha or 2% of the catchment.

The net volume of this wave may be estimated,by extending the previous recession curve to have been in the order of 200 m^3 which, assuming that the six ditches 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 ditch, representing about 1 mm over the whole area drained. The variation in sediment concentrations is shown in Figure 4, and clearly indicated a decline in the sediment release from the time of completion of the ditches. An estimated 10 kg of suspended sediment was released from the six ditches.

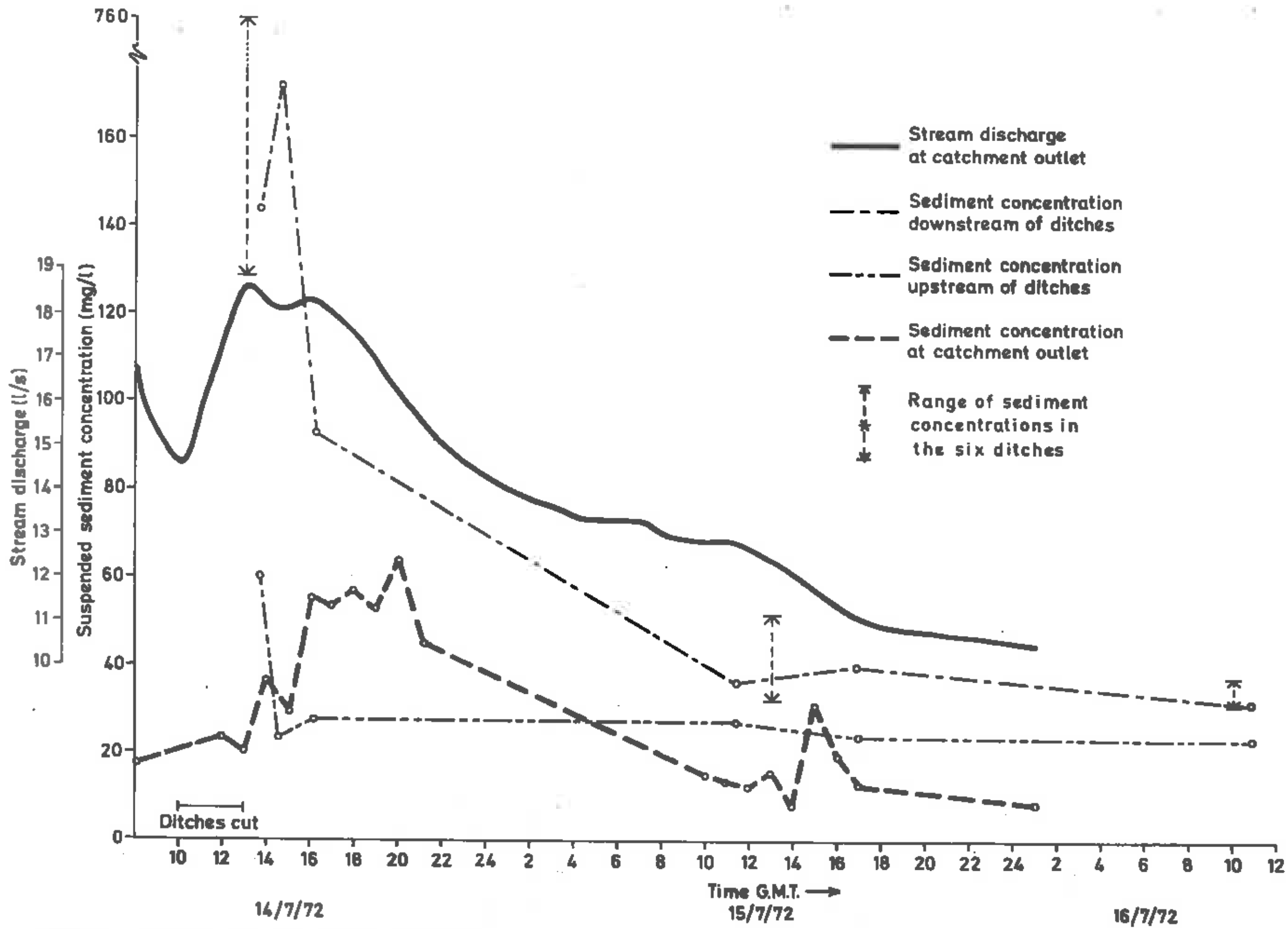


FIGURE 4. Sediment loss from 6 newly cut ditches

The first concentration measurement for the site upstream of the ditches appears anomolously high for a non-rainfall period compared to later readings. If this is assumed to be possibly due to movement of men or machinery across the catchment, then a fairly constant background concentration of about 25 mg/l is evident. The initial sediment concentrations varied greatly between drains (from 128 to 760 mg/l at about 1300 G.M.T.), and possibly changed rapidly with time too, though unfortunately no more measurements were taken until the next day and no record was kept of the order in which the ditches were cut.

The general picture is clearly that the ploughing of the new ditches produced a large amount of sediment compared with the background concentrations from a steep and largely unaltered area upstream. The bulk of this new sediment was carried out of the catchment by the end of the second day after ditching, by which time the quantity of water draining from the ditches had been greatly reduced and the sediment concentrations in the ditches were approaching those in the stream above the ditches.

These results suggest that the cessation of ditching over the weekends (a period of over 60 hours) would allow sufficient time for the effects of the ditching operations per se to be separated for the different periods, although of course the very existence of the ditches would be likely to produce new patterns of storm response and baseflow levels. 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 (Ken Blyth, Institute of Hydrology, personal communication). This also gives credance to the idea of subdividing the ditching period into weekly intervals in order to study more closely the effects of the ditching upon catchment output, and, since the area ploughed each week was known, it permitted the effect of the areal variations in catchment features to be studied as well.

These ditching operations produced a sediment wave which followed the hydrograph, but this was not necessarily always the case; for example on the rainless day of 2/8/72 the sediment wave 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 ditches to the stream network would have been important factors in controlling the relative timing of the waves at the main sampling point.

TABLE 1

Bulked samples data

Area Ploughed	Sampling Period	Suspended Solids Concentrations (mg/l)	Percentage Organic Matter
A	4th July-8th July	180	67
B	10th July-12th July	52	54
C	13th July-14th July	16	75
D	17th July-21st July	28	71
E	24th July-28th July	32	50
F	31st July-4th Aug.	56	57
G	7th Aug.-11th Aug.	72	50

(Data presented in Davies, 1973).

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

During ploughing, water samples were bulked for seven sub-periods (generally comprising five weekdays each), when a known part of the catchment was being ditched (Table 1). 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 involved the assumption 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-ditch study and the pattern of sediment layering noted in the stilling basin. However, after careful examination of the data the results of these bulked samples were considered to be suspect and were rejected. There were two main reasons:

a) Each bulked sample comprised all the samples collected at the basin outlet over that particular period. For several periods, in addition to the 8-hourly samples, other samples taken during specific studies (e.g. the 6-ditch study) were also included, when samples were taken hourly over usually a 24 hour period. The resulting bulk sample would thus be heavily weighted towards conditions on that particular day (24 samples) rather than towards the week as a whole (only 12 samples for the other 4 days).

b) The suspended sediment concentrations appeared anomolously low compared with the individual samples. If, for example, we examine records for the week when area E was ploughed (24-28 July), the bulked sample had a concentration of only 32 mg/l whilst the fourteen individual samples had concentrations ranging between 10 and 344 mg/l with a mean value of 94 mg/l. In fact only four of the samples had values under 32 mg/l.

The deficit between the bulked sample concentrations and the mean value for the corresponding 8 hourly samples ranged from -4 mg/l (within measurement errors) to + 60 mg/l, and strongly implied a loss of sediment during the bulking procedure.

The ditching period was therefore 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 ditches.

The results have been summarised in Table 2. It was also possible to analyse other periods in the same way, when different types of ditching operations were in progress.

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

a) Phase 1: Predominantly ploughing ditches (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: Predominantly connecting the ditches already ploughed to the stream system by cutting link and cross drains, and the clearing of 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 (average of 4.1 gm/s compared to 3 gm/s for the first phase).

TABLE 2

	AREA	PERIOD	SIZE (ha)	MEAN LAND SLOPE (deg)	MEAN FLOW (l/s)	TOTAL RAIN (mm)	RANGE OF FLOW (l/s)	MEAN SED CONC mg/l	SOIL TYPE	TYPE OF WORK
PHASE I	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
	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										
PHASE 2		29- 1 Sept	-	-	5.3	0	4.2-7.2	142	-	LC
		4-7 Sept	-	-	8.3	8.6	4.6-39.2	1 667	-	LC,H
		8-11 Sept	-	-	7.5	0	5.5-8	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	5-9.3	354	BC	D,H

NB Land slope may be very different to the slope of the ditches.

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

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 (average rainfall 2.4 mm per day) there was a fairly good correlation (r^2 = 58%) since much of the sediment was brought out by storms or the release of water from the cutting of new ditches, whilst for the second phase there was a much lower correlation (r^2 = 22%) with some of the highest concentrations being recorded during the start of ditch clearing at a time when there was no rain and relatively low stream discharge.

I) PHASE I

Taking the ditch cutting phase first, we may examine seven sub-periods based upon the divisions of the ditching schedule. The average 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 ditches in areas H and I coincided with ditch clearing 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 sediment yield 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 ditching operations.

Areas A and G had the highest mean concentrations, and this would appear to be related to the prevailing hydrological conditions. The times when they were being ploughed covered the highest discharges in Phase I, and their mean flows were greater than the peak flows while some of the other areas were being ploughed. The fact that area A exhibits the higher mean concentration of the two, whilst having the lower mean and peak discharge, is due to the occurrence of a very high concentration (995 mg/l) recorded soon after the start of ditching, and, given the relatively small

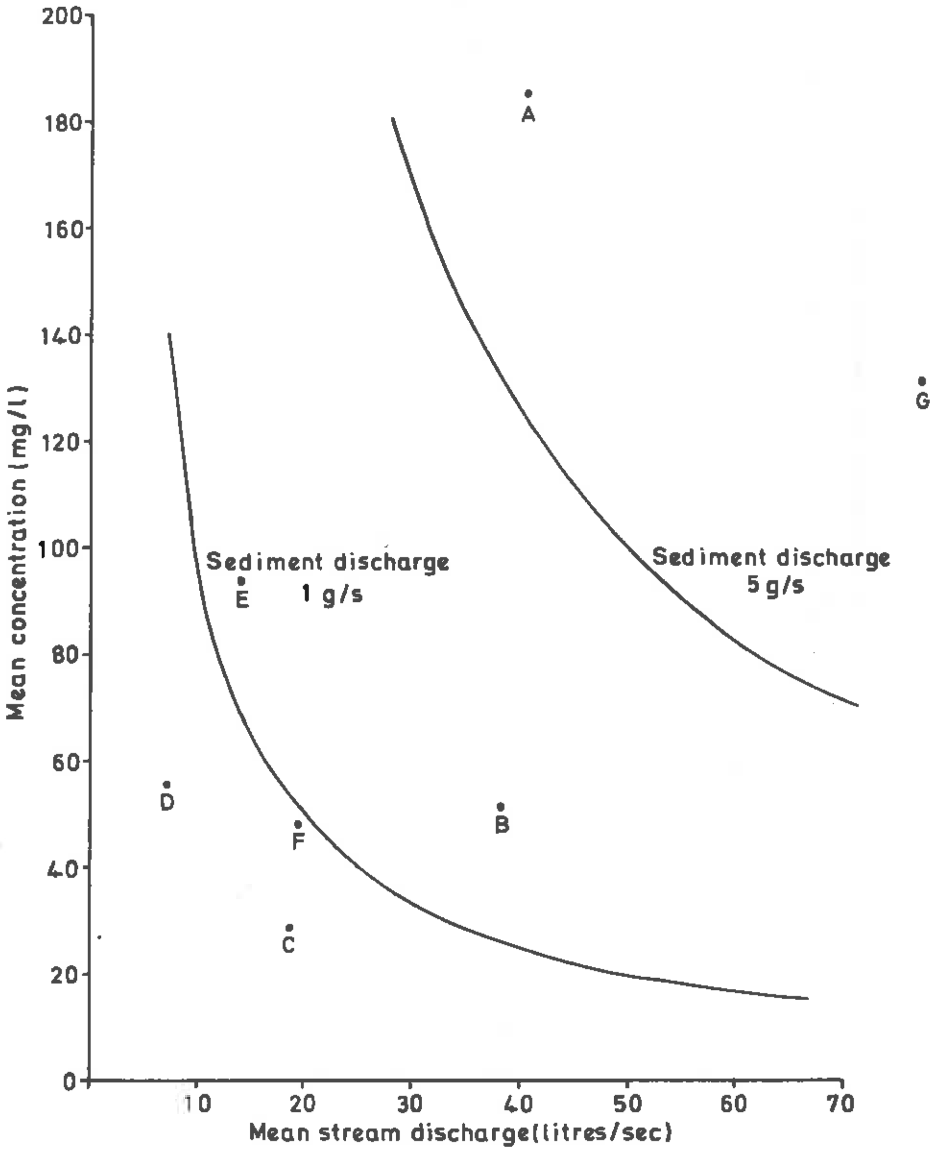


FIGURE 5. Streamflow and sediment concentrations for the sub-areas

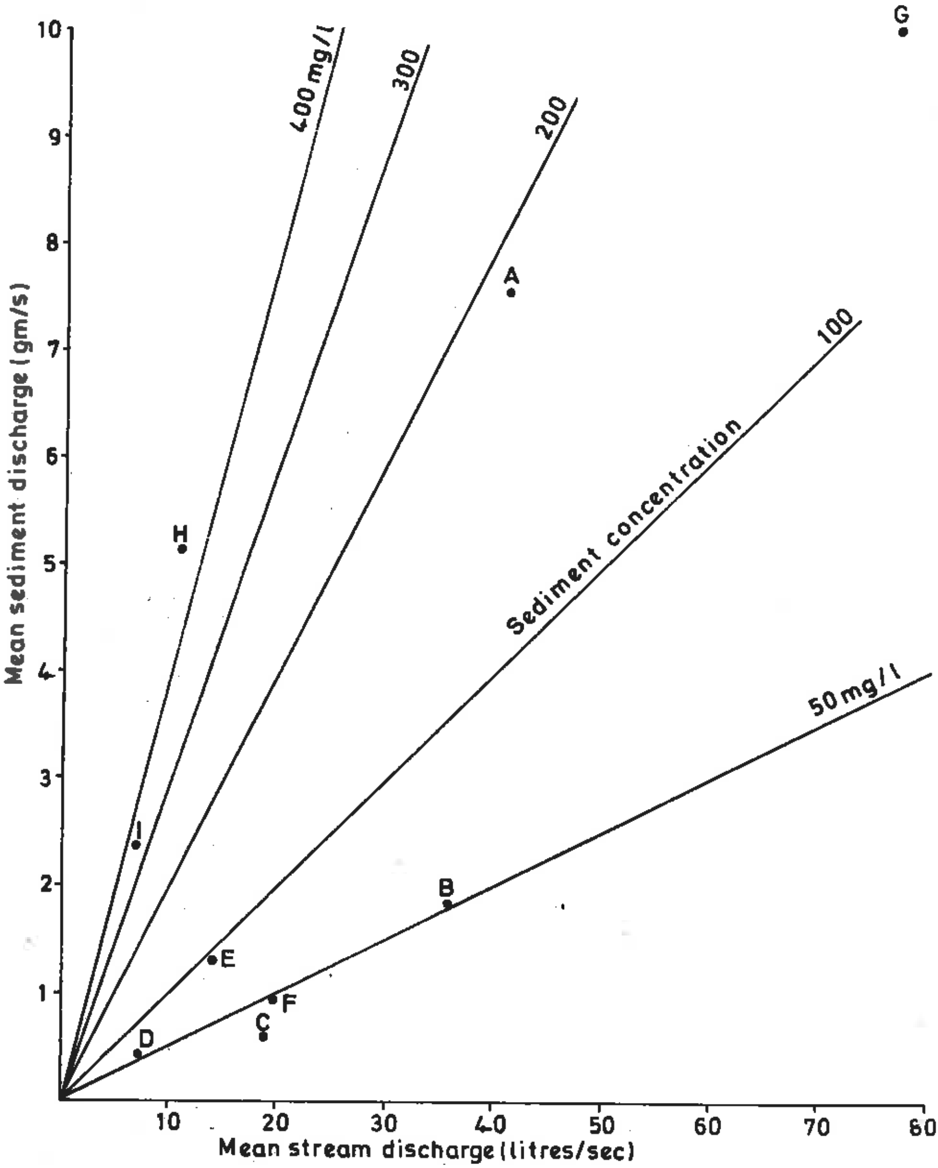


FIGURE 6. Streamflow and sediment loads for the sub-areas

number of samples in any sub-period (3 per day) this one extreme value 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 ditch draining 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 6-ditches discussed earlier).

Areas B and F exhibit very similar average concentrations and appear to have experienced similar hydrologic conditions, especially with regard to the range of streamflow and the average daily rainfall (about 4 mm). Each period included one large hydrograph, but that occurring during the ditching 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 ditching of Coalburn may therefore be approximated

150 mg/l - ditching in a period of relatively high stream discharge
50 mg/l - ditching during a period of moderate flow
30 mg/l - ditching 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 ditching. 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) PHASE II

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 ditches 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 during the holidays 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 7 000 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 over the intervening weekend. In the last two weeks, areas H and I were ditched 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 would depend 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 tend to have a greater quantity of sediment available to be flushed out during the next storm. It was also observed that sediment concentrations during ditch clearing remained high over the intervening weekends, indicating a 'carry-over' from one week to the next.

Given these qualifications we can suggest 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 ditches
200 - 300 "	1 000 "	Bucket drainer widening channels
5 - 150 "	1 000 "	Link and cross drains cut

2.3 Post-ditching period (September 1972 to October 1973)

It is interesting to note the immediate effect upon sediment yields of the cessation of ditching before turning to consider the longer term effects. The ditching operations were suspended for the annual holiday in August, by which time most of the ditches had been cut, but before they had been cleared of debris. This allowed the immediate response after the two very different ditching 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 ditching, namely 20-30 mg/l rising 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 250 mg/l to 50 mg/l in an eight hour period, though concentrations remained at a higher level than in the August holiday in the succeeding dry month, with concentrations of about 30-50 mg/l rising to 720 mg/l in the only storm (5.7 mm rainfall).

General maintenance work on the weir commenced at the end of October and continued over a total period of about nine months, during which streamflow data was recorded only intermittently. Although it was not considered to be accurate enough for the archiving of hourly values it was used to make estimates of total daily runoff (K. Blyth, personal communication). In addition some sediment data was lost, due mainly to problems of a shortage of personnel resulting in the sampler bottles not being changed on a number of occasions.

However, in all it was possible to extract data coverage for about half of this period(predominantly December 1972 - April 1973). This was the first time since ditching that an appreciable quantity of rain had fallen, and the mean flow was 45 l/s and the mean concentration 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 an average streamflow over a 24 hour period of from 200 to 400 l/s (representing peak flows probably in the order of up to 900 l/s). It was estimated that these storms probably carried in the order of 10000 kg of sediment on their peak days, and probably a total of about 15000 kg in all. This may be compared with peak daily loads of about 3000 kg during ditching (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 the peak values mentioned, with over 70% of the readings under 50 mg/l and nearly 90% under 100 mg/l. Only 2% were above 400 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 flow and sediment data together for only a few days, but nearly a hundred sediment readings were taken, and ranged from 1 to 380 mg/l with a mean concentration of 35 mg/l. Rainfall over the period was close to the seasonal average.

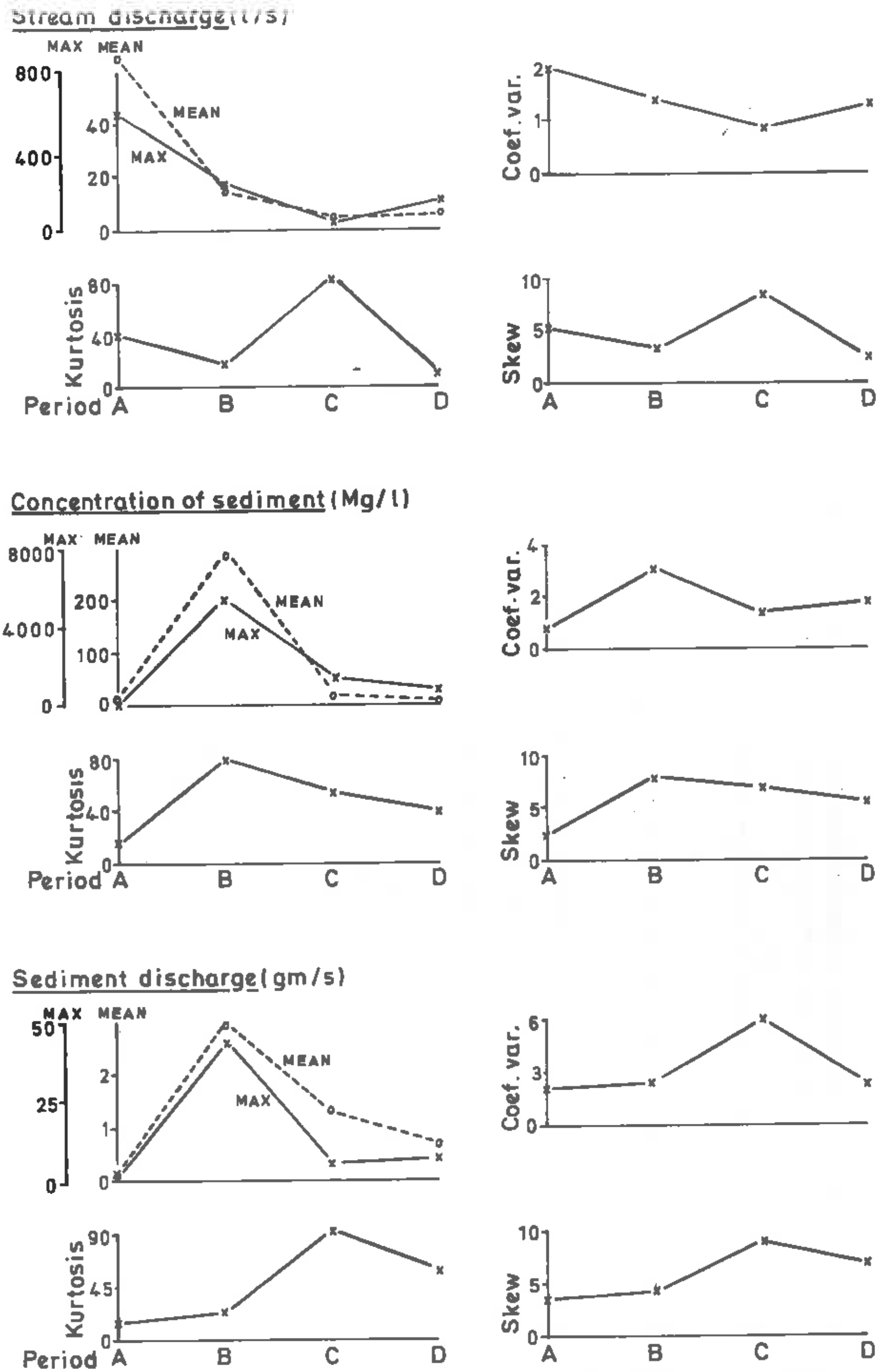
The following period (September-October 1973) when sediment samples were taken and the weir was fully operational again, was unfortunately a period with less than average rainfall. Discharge averaged only 11 l/s with a peak of 74 l/s. Sediment concentrations had a mean value of 35 mg/l and, apart from a reading of 574 mg/l which did not appear to be related to either rainfall or runoff the highest concentration was 320 mg/l.

2.4 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 main elements of sediment output (sediment discharge and concentration) together with the streamflow for comparison, and secondly, the rating curves between sediment and streamflow.

2.4.1 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 coefficient of variation, skewness (zero for the Normal distribution), and kurtosis (a measure of peakedness of the frequency distribution). The latter three statistical parameters 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 3, and are summarised graphically in Figure 7, for the 1972 and 1973 data.



COALBURN Analysis of the 8 hourly sample data for different periods:-
Period: A = calibration period - B = ditching period
C = post ditching 1972 D = post ditching 1973

FIGURE 7. Statistical description of catchment output before/after ditching

Table 3. General features of the catchment water and sediment output 1972–8

Period	$\overline{Q}$	Q_{max}	$\overline{C}$	C_{max}	$\overline{S}$	S_{max}		Coef. of variation	Kurtosis	Skew
Calibration	43	830	3.6 (3.9)	28	0.17	24.7	Q	2.0	4.3	5.6
							C	0.9	16.8	2.7
							S	2.1	18.3	3.8
Whole ditching period	17.8	191	207 (157)	7720	2.8	49.6	Q	1.4	19.4	3.7
							C	3.2	82	8.1
							S	2.3	25.4	4.3
1972 Post ditching	3.5	33	51.5 (120)	724	0.42	24.2	Q	0.9	83	8.7
							C	1.5	57	7.0
							S	6.0	92	9.6
Partial data Dec 1972 –April 1973	.45	N/A	67 (133)	1240	6.0	N/A	Q			
							C		N/A	
							S			
1973 Post ditching	10.7	74	35 (43)	574	0.46	12.8	Q	1.3	10.4	2.7
							C	1.9	42	5.9
							S	2.8	60	7.0
1978 Post ditching	57.5	374	9.0 (15.8)	40	0.91	14.7	Q	1.3	9.7	2.6
							C	2.3	5.9	1.8
							S	0.9	19.6	3.9

Units and abbreviations: Q = stream discharge (l/s)

C = sediment concentrations (mg/l)

$\overline{X}$ = mean value

X_{max} = maximum value

N/A = data not available.

The discharge-weighted mean sediment concentrations are given parentheses.

In the calibration period the 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 streamflow varied much more than the concentration, and the coefficient of variation of the sediment load readings 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 ditching, and then declined greatly after its completion. This was despite the discharge variation being almost the antithesis, with streamflow falling greatly in the ditching period and remaining at a low level in the two post-ditching periods (Figure 7). Sediment concentrations rose only slightly in the wetter period of winter 1972-3, when streamflow was equivalent to that in the calibration period (Table 3). In the 1978 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 ditching and in fact were only about treble those in the calibration period. Sediment loads followed broadly the same pattern as the concentration, although the highest loads were not carried in the ditching 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 differences in streamflow, together with effect of one brief storm in the otherwise rainless first post-ditching 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 for the sediment load have high values in this period. The higher moments of the sediment concentration were 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 ditching, 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 ditching when the range of sediment concentration had been so limited.

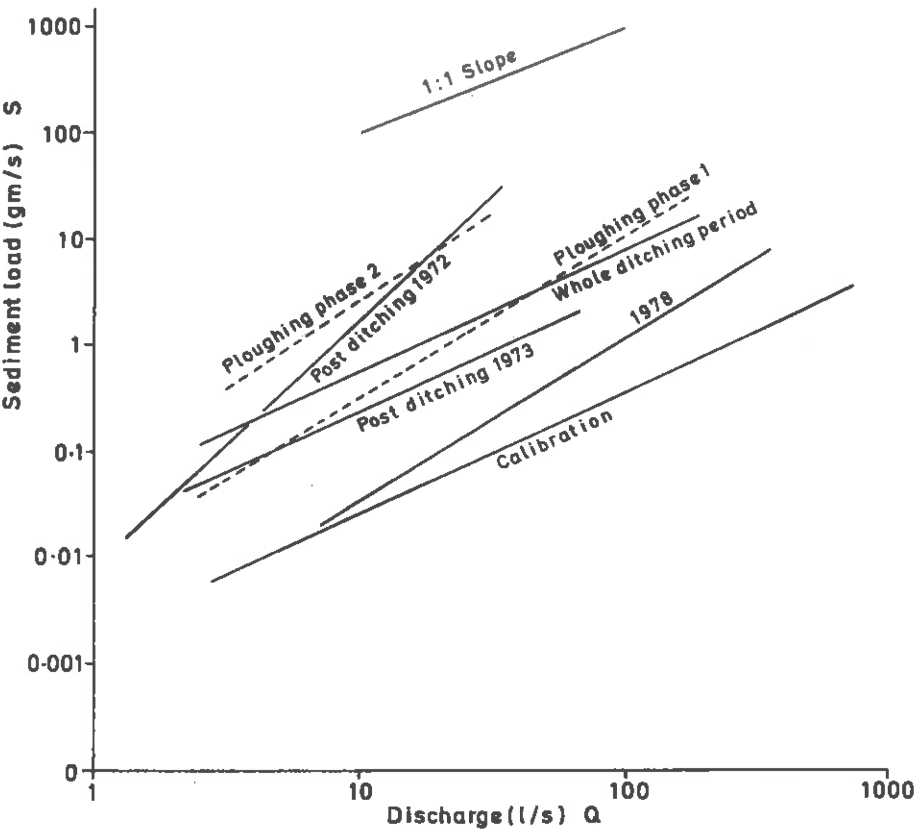
2.4.2 Sediment rating curves for the different periods

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, together with that for data collected nearly 7 years after the ditching and described in Section 2.5.3.

Not surprisingly the curve for the calibration period exhibits 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 ditching 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 ditching 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 ditching period. The very steep curve for post-ditching values in 1972 was largely due to one extreme point.

The pattern of decline in sediment yeilds 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 levels in the pre-ditching period.



Sediment discharge rating curves

FIGURE 8. Sediment-discharge rating curves before/after ditching

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 made in order to study the changing level of sediment yield through time (Table 4). This was the approach adopted by Painter et al (1974), but note that their graph is in error, with weekly totals from week 38, ten-times too large, and from week 74 a hundred-times too large. The correct weekly estimates are given in Figure 9.

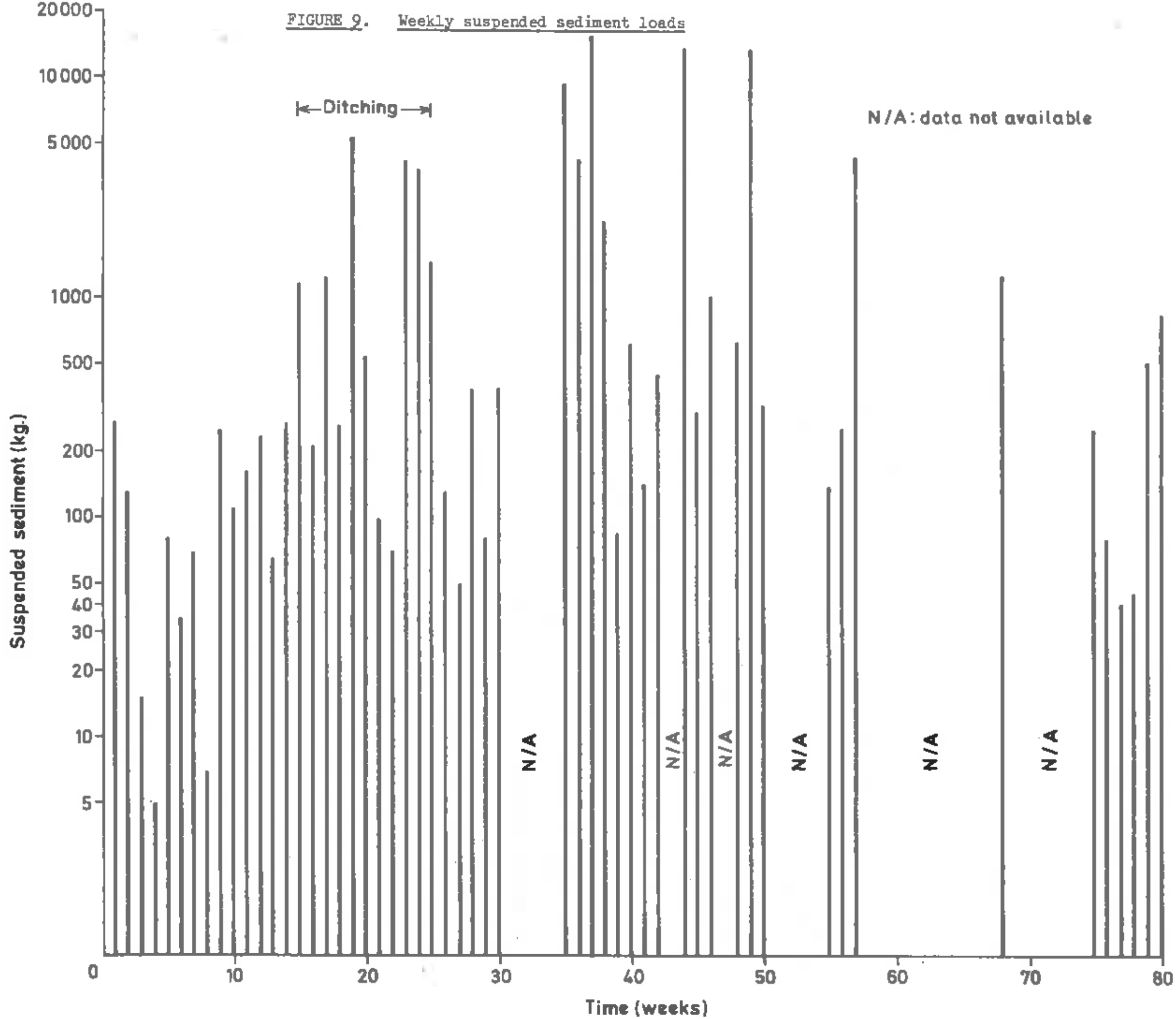
Table 4 COALBURN WEEKLY SUSPENDED SEDIMENT LOADS (kg)

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	160	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

* Ditching in progress N/A - Break in sediment or discharge record.

However, as can be seen from the figure, the general trend of the data is severely distorted by the very irregular pattern of rainfall during the period. Thus, the wet calibration period which had very low sediment concentrations produced weekly sediment yields similar to those occuring immediately after ditching, when, although concentrations were much greater, stream discharges were very much lower.

FIGURE 9. Weekly suspended sediment loads



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 much water and sediment was 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 ditching there was a very stable relationship. At the start of ditching, sediment loads increased dramatically, and the two phases of ditching can be readily identified, with the intervening holiday period when little sediment was carried from the catchment. After ditching, 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 little sediment was carried. As we have already seen, the post-ditching pattern was one of generally higher baseflow concentrations than before ditching (about 30 mg/l cp. about 3 mg/l) and with a greatly increased sediment response to storm flows. In the largest winter storms after ditching, quantities of sediment were carried in a single day equivalent to the yearly output prior to ditching.

The broad trend of the catchment sediment yield may be studied by fitting a smooth curve through the double mass plot in order 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.

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

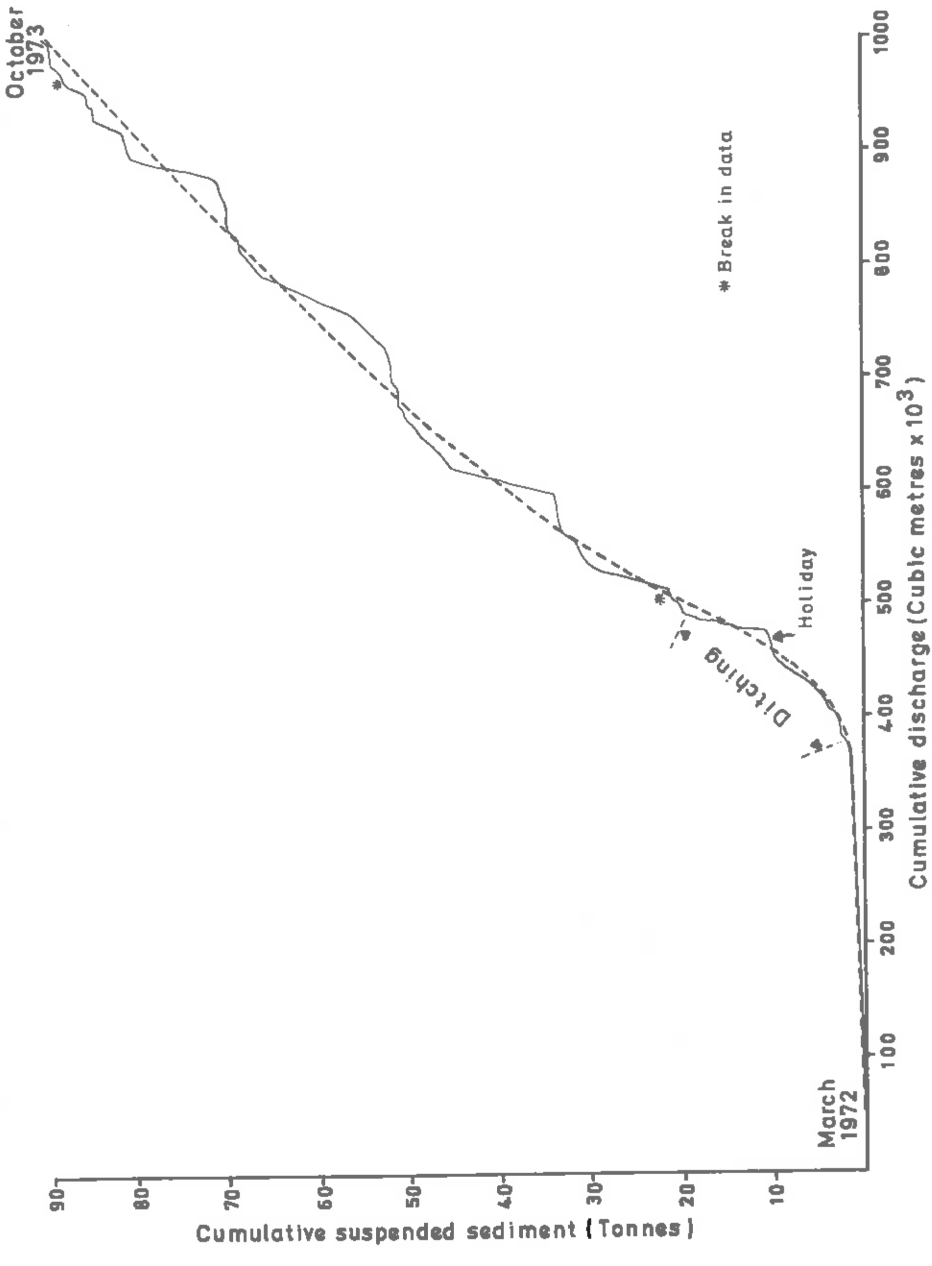


FIGURE 10. Double mass curve of discharge and sediment

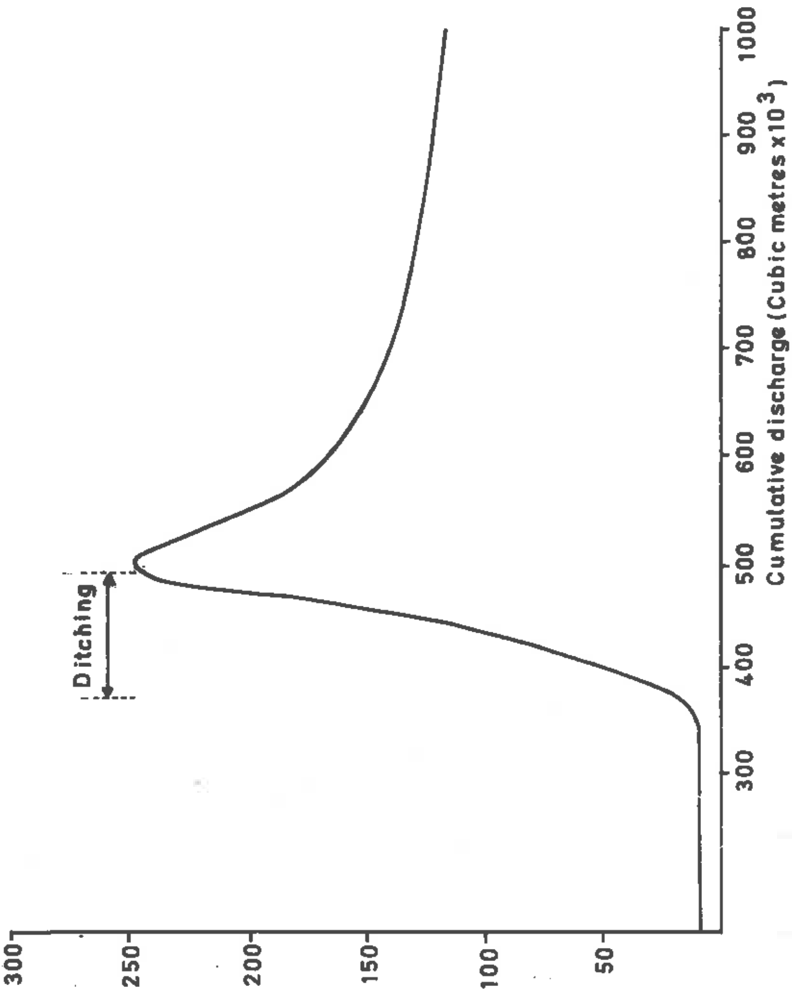


FIGURE 11. Averaged sediment concentrations

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.

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 hydrologic behaviour.

The direct mechanical changes to the catchment were clearly evident. Over 250 km of ditches 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 to erosion. However, both of these effects would be largely transient as vegetation began to cover and bind the bare soil and as sediment was flushed from the catchment. In Spring 1974 it was estimated that there was still about 100 m^3 of loose mineral soil in the drainage system (Painter et al, 1974)*. If we assume a bulk density value of 1.3 as being fairly representative of clay soils (e.g. Brady, 1974) this would represent about 130 tonnes of sediment, and constitute a store equivalent to several years sediment yield at post-ditching levels.

The indirect changes resulted from the altered hydrologic regime created by the dramatic increase in drainage density. The effect this had on the evacuation of storm water from the catchment has been described in some detail in section 5 and involved a much more 'peaky' runoff response. Even if all other factors were to have remained unchanged, the increase in storm peaks might be expected to have resulted in increased level of sediment yields.

*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 include fresh erosion.

Examination of contemporary photographs and visits to newly ditched sites indicates that sediment losses were probably derived almost entirely from within the ditches, 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 ditch edge. Furthermore, these ridges would have contained the surface vegetation mat dug from the ditch 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 ditches 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 ditching (S.R. Eyre, personal communication). Some seven years after the ditching the main plant types observed in the ditches included grasses, mosses and rushes, with species including *Eriophorum*, *Sphagnum*, *Juncus*, *Vaccinium*, *Plantago*, *Ranunculus* and *Cirsium*, though some of the smaller ditches did not contain vegetation due to shading by the Molinia grass on the ditch tops.

A study of erosion of material from the drainage ditches was carried out in the 18 month period after ditching (Painter, *et 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 ditch 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 ditches 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 ditches in peat than in glacial material, a phenomenon which has been noted recently in Scotland (Graesser, 1979) and in mid-Wales (Newson, 1979), 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, from the person involved, further details of the 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 ditches carried water down a steep (30^0) slope to join the main channel, the majority of the ditches 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 Current rates of sediment output

In order to determine the long term effects of the ditching on sediment yields, further suspended sediment measurements were taken in 1978. This was nearly seven years after the ploughing, by which time it was anticipated that the direct effects of the ditching would have ended, and a new equilibrium state would have been attained.

The original sampling point was located in the field and a North Hants 1B automatic vacuum sampler, similar to that used before, was installed. Care was taken to ensure that as far as possible the same point in the channel cross-section was sampled. An 8-hour sampling interval was adopted as before and over one hundred samples were taken in a period covering nearly a 40-fold range in streamflow from 10 to 370 l/s, and with a mean flow of 58 l/s.

Sediment concentrations were about 1 to 5 mg/l during low flows, and increased to at least 40 mg/l during floods. The arithmetic mean concentration for the whole period was about 9 mg/l which when compared with values for the other periods summarised in Table 3 demonstrates that sediment levels had declined still further from those in the year after ditching (which had generally had much lower flows), but were still greater than double those observed in the calibration period (which had comparable discharges). The greater availability of sediment was also shown by the increased response to higher streamflows, with a sediment rating curve now of the form:

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

The rating curves for all periods are described in section 2.4.2.

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

2.5.4 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 ditching would have resulted predominantly from the loss of available loose material in the ditches. After some time this supply of sediment would have been exhausted and further sediment yields would result solely from the erosion of new material.

A simple two component model may thus be suggested to described the level of sediment concentration, and is shown in Figure 12. There is a large rapidly declining component representing the flushing out of the losse material from the ditches, and a much smaller and possible more slowly declining component representing the loss of material by erosion of the bare soil surfaces.

We would 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 ($m^3 \times 10^3$)

K is the supply of fresh material by erosion; here taken as a constant value of 10 mg/l.

This equation was derived by fitting the central portion of the curve between 100 and 400 $m^3 \times 10^3$ in Figure 11, which was considered to be the most representative section, thus avoiding both the immediate effects of the ditch clearing and the uncertainties of the final part of the curve (due 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 (Figure 13). Values of cumulative discharge were calculated from the available discharge records together with estimates of flow generated by the Institute of Hydrology's catchment model for the period when the weir was inoperative. Using this curve suggests, for instance, that the material loosened by the ditching would have been largely removed within the first four years.

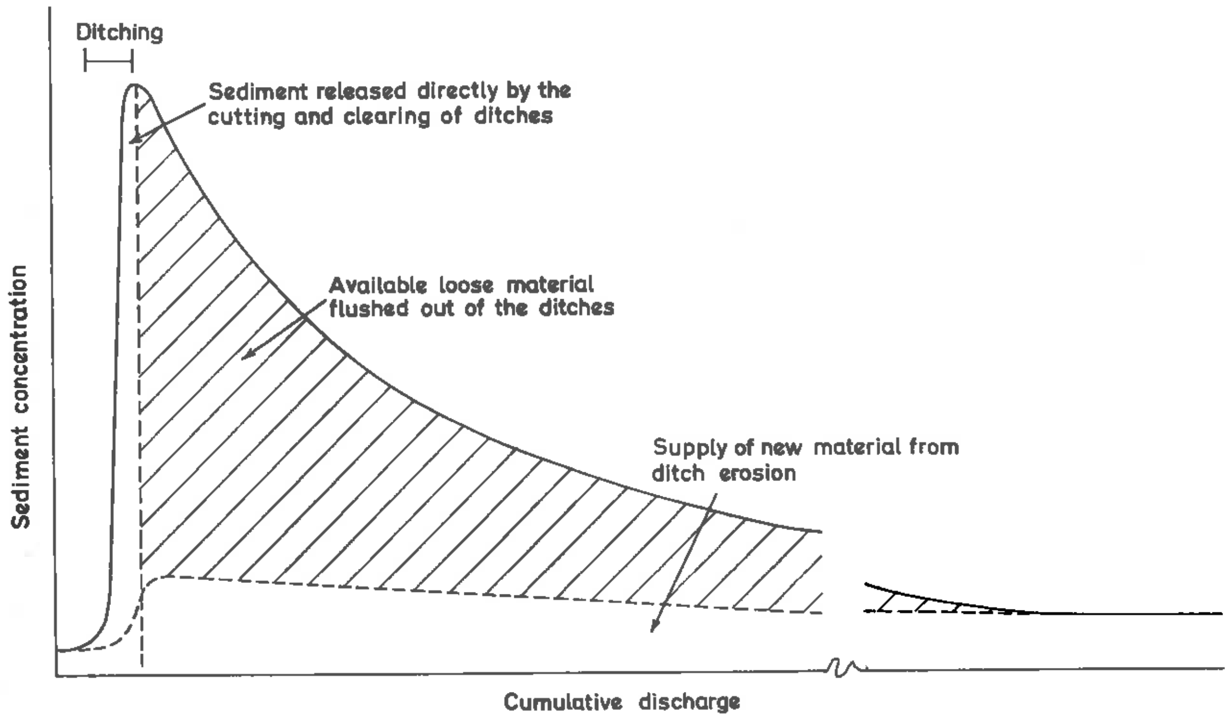


FIGURE 12. Generalised model of sediment output after ditching

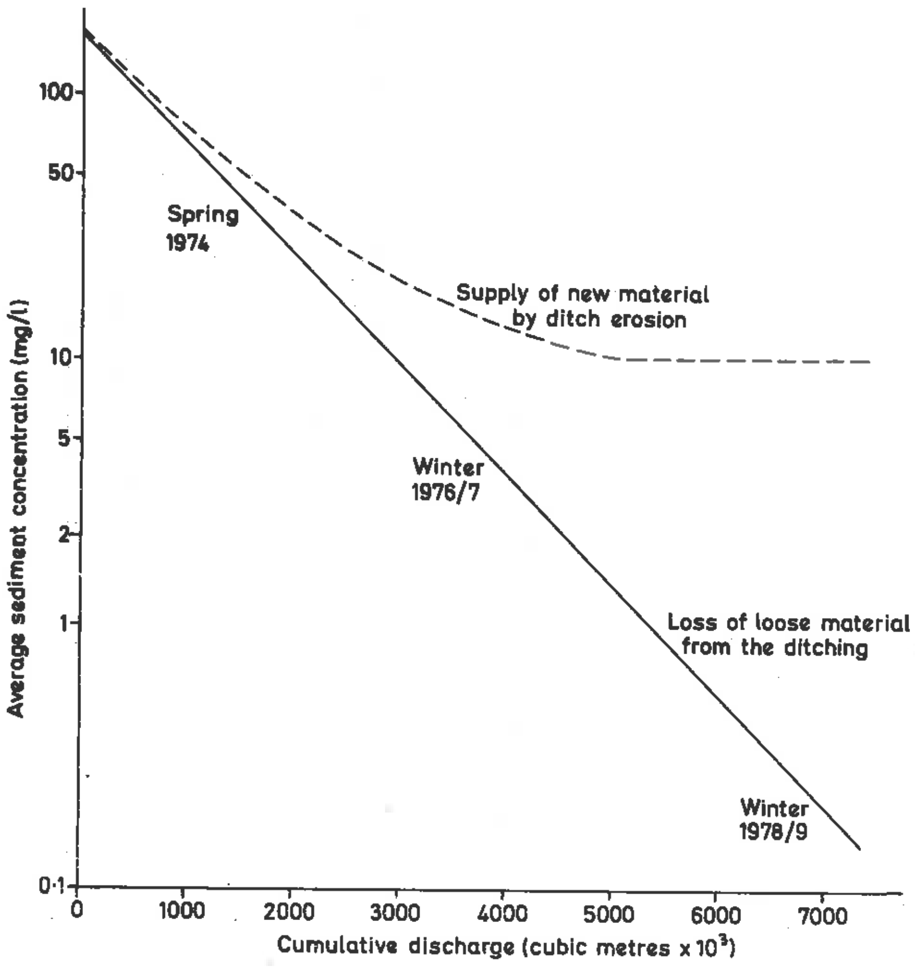


FIGURE 13. Model predictions of sediment loads

The decline in 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 as:

$$\frac{\ln 2}{b}$$

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 660×10^3 m^3 of runoff, or about 7 months duration given the mean annual flow of 1170×10^3 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 ditching would be equivalent to nearly half a century of sediment loads at pre-ditching 'natural' erosion rates. This helps to underline both the enormous effect of the ditching upon the catchment system and also the dramatic rate of recovery to a new equilibrium.

2.5.5 Verification of the model

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.

Much of the sediment carried from the catchment is deposited in the stilling basin of the weir, and this provided an opportunity to make an estimate of sediment loss independently of estimates based upon measurements of suspended sediment. The stilling basin was drained for the maintenance work in 1973 and in May the accumulated sediment was excavated. Several problems had to be overcome in the interpretation of the data. Firstly, an unknown quantity of sediment had accumulated in the five years from the construction of the weir up to the ditching. However, sediment loads before ditching were low, and even if all the sediment was trapped would probably only represent about 25 tonnes.

Secondly, the accumulated sediment was estimated by surveying the bottom of the stilling basin at about 230 grid points before and after excavation and it was not possible to be certain the new base coincided exactly with the original level. Since the stilling basin was cut into bedrock any difference should however be small. Thirdly, the stilling basin may not retain all the sediment, some being carried over the weir and the quantity accumulated therefore represents a lower bound to the amount lost from the catchment.

The average difference in bed elevation at the grid points was 43.1 cms., giving a total volume of about 77 m^3 of sediment. Samples taken from the basin in 1979 had densities of between 1.36 and 1.44 gm/cm^3, and taking a 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 ditching this would suggest about 85 tonnes of sediment had accumulated during ditching and up to May 1973.

The measured sediment loss over this period comprised 19 tonnes during ditching and another 66 tonnes afterwards. However this included only about 465000 m^3 of flow after ditching, and the Institute of Hydrology has estimated that a further 256000 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 ditching of 102 tonnes and a total since the start of ditching of 121 tonnes.

The cumulative discharge since ditching was about 720000 m^3 by May 1973, and from the exponential decay curve we can estimate a sediment load of 95 tonnes, which, together with the 19 tonnes measured during ditching and 8 months new erosion*(say 12 tonnes), would give a total of 127 tonnes.

The agreement between the measured suspended sediment yield and that derived from the exponential decay model was very close (under 5% difference) and suggests that the gaps in the data record would have had little effect upon the fitting of the decay curve, and the estimates derived from it.

The estimated quantity of sediment in the stilling basin was much less than these values and gave an overall trap efficiency of 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.

Five years later at the end of 1978 the North West Water Authority planned to carry out maintenance work on the weir again, and at the same time to drain and clear the stilling basin of accumulated sediment. It was hoped that this would have provided another estimate of sediment yield for comparison

*October 1972 - May 1973.

with the model, but unfortunately the work had to be postponed due to bad weather and staff shortages (A. Johnstone, N.W.W.A., personal communication). The author therefore made an estimate of the volume of sediment in situ in summer 1979, though it should be recognised that this would have been much less accurate than the 1973 survey. The mean depth of sediment in the stilling basin was about 40 cms which would represent about 70 m^3 of material and a weight of approximately 100 tonnes, ie. very similar to the quantity measured in 1973.

The exponential decay model predicted that about 65 tonnes of loose sediment would have been lost from the catchment since May 1973, and if an allowance is made for an additional loss of about 18.5 tonnes per annum due to new erosion, this would give a total sediment load over the period of 175 tonnes. Assuming that the trap efficiency of 70% calculated in 1973 would be valid, the quantity of trapped sediment would suggest that the total load was about 145 tonnes which gives a difference between the estimated six-year sediment load totals of about 19%. This represents a very reasonable agreement for a catchment in disequilibrium, and considering the great extrapolation of the decay curve gives considerable support to its validity. Furthermore, it might well have been expected that the trap efficiency would have been lower than in 1973 due to the greater sediment loads, and thus the value of 60% for this period does not 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 data collected at the end of 1973 was not used in the fitting of the curve (see Section 2.5.4), and could be used to test the predicted levels at a time over a year after the end of the ditching. The sediment concentration predicted by the model for this period was 39-37 mg/l which was close to be observed discharge-weighted mean concentration of 43 mg/l.

The satisfactory agreement between the model predictions and independent estimates gives support to the model proposed and to the conclusions derived from it.

2.6 Measurement of bed load

In order to determine the total mechanical removal of sediment from the catchment it was necessary to measure the quantities of bed load discharged. This represents the material which tends to be transported in almost continuous contact with the stream bed in contrast to the suspended sediment which tends to be kept by turbulence within the water flow, and would therefore have been sampled by the North Hants Water sampler. Most studies have shown bed load quantities to be small in comparison with suspended loads (eg. Gregory and Walling, 1973), but in some situations bed load may be far more important than suspended sediment (Newson, 1979).

A review of the available techniques for measuring bed load concluded that a trench across the stream was the most satisfactory and accurate method (Painter, 1972). In late summer 1972 such a trap was constructed, comprising a large concrete sump about 85 cms long by 25 cms wide, and with a depth of about one metre. At approximately fortnightly intervals the sediment in the trap was measured and the trap was emptied. A sample of sediment was retained for density measurement although unfortunately these density values were not available to the author and consequently the value of 1.4 gm/cm^3 measured for the stilling basin sediment was assumed. Due to a possible difference in density values and errors in the estimation of sediment volumes is the data for the 3 month study period it is simply listed below rather than being presented as a formal table.

Period	Sediment Volume (cm^3)	Total Streamflow (m^3)	Sediment weight (Kg)		Sediment concentration (gm/m^3)	
			Bed	Susp.	Bed	Susp.
13/ 9/72 → 26/ 9/72	54500	5925	77	1550	13	262
26/ 9/72 → 18/10/72	21000	6095	29	504	4.8	83
18/10/72 → 29/11/72	75250	135000*	105	9170*	0.78	68
29/11/72 → 20/12/72	10600	155630	15	21594	0.01	139

*Estimated value due to the weir being inoperative for part of this period.

It is clear that the quantities of bed load were minor in comparison to the susepended sediment loads, and in fact accounted for less than 1% of the total sediment load. Even if a density value double that assumed above were to be adopted, bed load would make an insignificant difference to total loads. The suspended sediment measurements may therefore be taken as a good approximation of the total particulate loss of sediment.

The measurement period extended from shortly before the cessation of ditching 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 ditching, but increased again in the large 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 of bed load may be shown to follow an exponential decline through time after ditching, and had a relationship of the form:

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

where C is the bed load concentration (gm/m^3)

e is the base of natural logarithms

Q is the cumulative discharge (m^3)

The 'half-life' of the decay may be calculated as about 13500 m^3, which represents a time of about four days assuming the long period average daily flow.

The small quantities 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 are then left to line the channel bed.

3. NATURAL WATER CHEMISTRY

In parallel to the study of the mechanical removal of material from the catchment a study was undertaken as an undergraduate project (Davis, 1973) of the solute concentrations in the stream water. This was to determine if the ditching 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 (4.2 to 853.2 l/s). 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	Discharge (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
Ditching	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-ditching (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	40-70
	152	4.7	0.8	3.6	0.7	50

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;

TABLE 6

Solute discharge rating relations prior to ditching

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

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

namely calcium concentrations were fairly strongly 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 potassium with streamflow is related to the manner in which potassium ions are held in the micaceous-clay colloid structure of the soil.

During the period of ditching, water chemistry analyses were made of the bulked samples only. Since solute concentrations generally vary much less than suspended sediment with variations in streamflow, and since these were the only record of the level of solute concentrations during ditching, they are summarised in Table 5. However, they should be treated with caution due to the problems of unrepresentative sampling and the long storage time before analyses, already mentioned. The values refer to samples taken during the first ditching phase, and they are all near the upper end of the range in concentrations noted 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. Davies (1973) reported T.D.S. values of up to 260 mg/l for water draining from a freshly cut ditch.

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

3.2 Discussion of findings

There was an apparent increase in solute levels after ditching, and the relative abundance 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 ditches (Davies, 1973; NERC, 1973). This argument was largely based upon the fact that prior to ditching 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 4.20 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, this argument fails to take into account the fact that the stream discharge was very different in the periods immediately before and after ditching, both in terms of mean values and the flow range. In fact, the highest flow during sampling after ditching was less than the lowest flow prior to ditching. 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).

In order to examine whether a geniune change had occurred in the pattern of chemical denudation of the catchment, the pre-ditching solute rating curves for total dissolved solids and calcium were used to estimate the concentrations that might have been expected for the low flows after ditching. 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 ditching 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 and a coefficient of determination nearly 10% greater than before ($r^2 = 48\%$). The estimated calcium concentration for a discharge of 2.5 l/s was 12.2 mg/l 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 due to the fact that the errors involved (weighing and hygroscopic errors) would be at least in the order of ±5 mg/l, 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-ditching mean concentration of 95 mg/l and also suggests that no fundamental change in the chemical erosion of the catchment had occurred.

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

It is interesting to note that the total annual dissolved load would have probably been of the order of 40 tonnes/km^2, which is greatly in excess of the mechanical erosion, being about 12 times the pre-ditching load and about three times present levels. A similar picture has been shown for other humid temperate catchments (Oxley, 1974; Walling, 1971).

FIGURE 14. Relation between Calcium concentration and flow

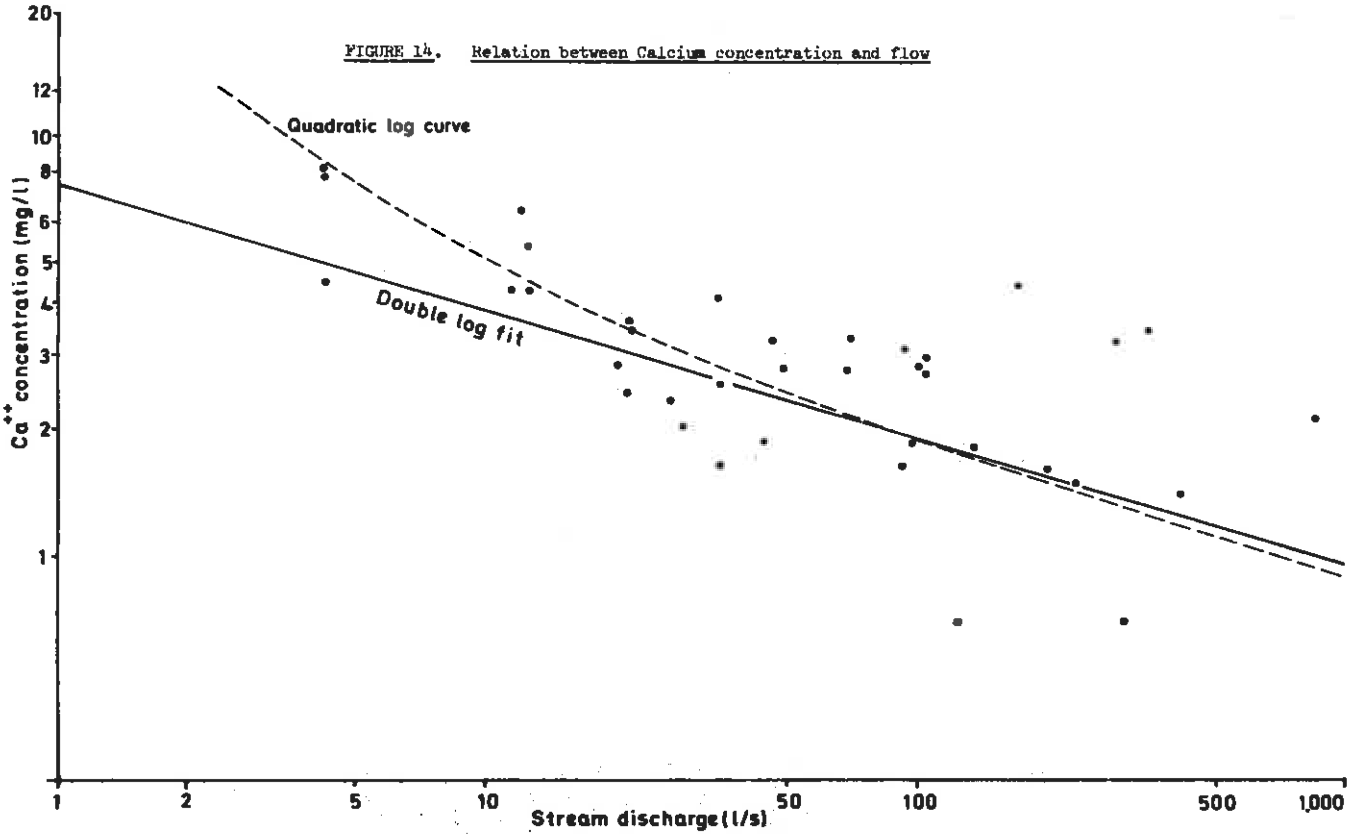
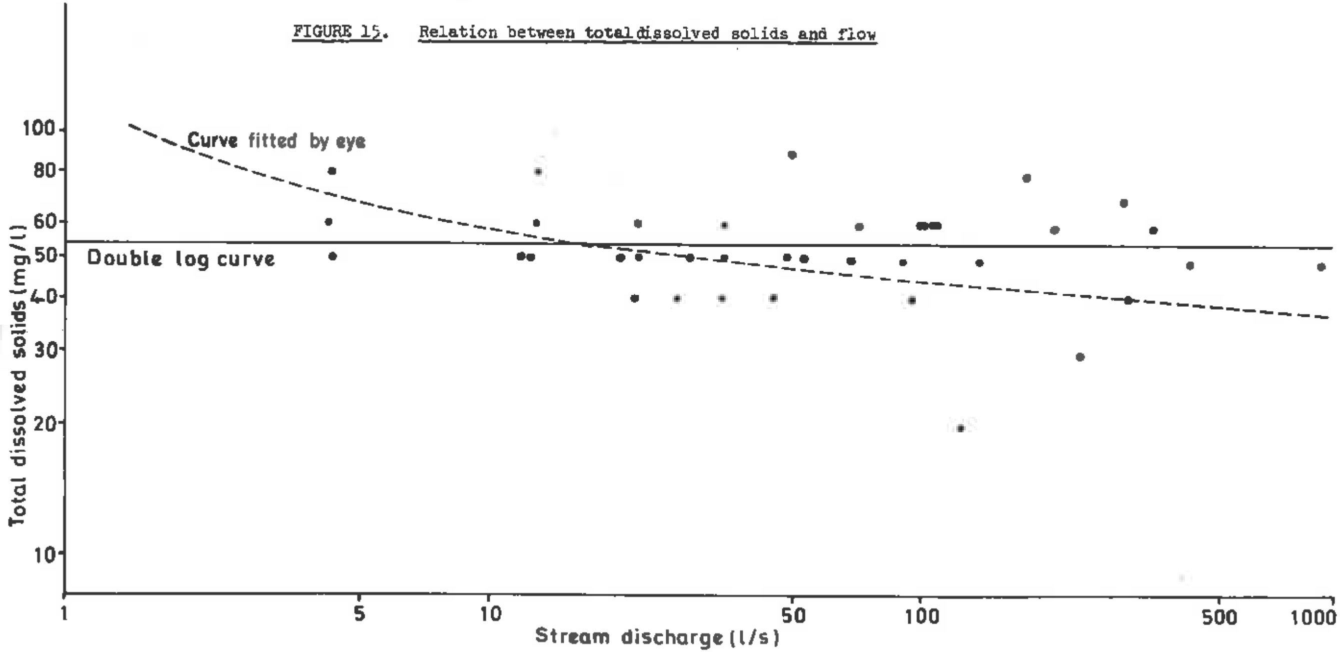


FIGURE 15. Relation between total dissolved solids and flow



Dissolved loads increased during ditching as water which had been in contact with the soil for some time was released, so that, only for a short period after ditching 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 ditching and laboratory analyses of particulate/dissolved phosphate concentrations in the stream runoff were carried out by the Cumberland River Authority. The particulate fertilizer would have dissolved readily and probably little phosphate would have been carried out in suspension.

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, in order 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 similar magnitude to the accuracy of the techniques used* (ie. the orthophosphate determined by colorimetry). The values are 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 representing the rock phosphate that had fallen directly into the natural stream channel network. In succeeding storms more phosphate was washed down the stream network and concentrations rose up to 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:

$$P \propto \sqrt{Q}$$

where P 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

*DoE (1972), p. 82.

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 again in the commencement of ditching operations, and during the first ditching phase ranged between 0.7 and 2.2 mg/l with a mean value double that prior to ditching. Concentrations were no longer simply related to discharge but fluctuated in an apparently random way as the ditching progressed.

During the two week annual holiday phosphate concentrations declined a little 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 ditch clearance period, with values up to 1.5 mg/l. Concentrations fluctuated little with discharge, being related rather to suspended sediment concentrations (ie. the pattern of the ditch clearance operations).

Unfortunately the analyses were only continued for a few weeks after the end of the ditching 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 available phosphate remaining.

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

$$P \propto Q^1$$

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). We must therefore reject the claim made at the time that

> "... 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." (NERC, 1973).

4.2 Quantities of phosphorus lost from the catchment

The loss of phosphorus from the catchment may be estimated from the recorded concentrations of phosphate (PO_4), 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, flourine, iron and aluminium which occurred in the natural rock. The total weight of rock phosphate applied was thus 57000 kg, of which 8436 kg represented phosphorus.

The loss of phosphorus before fertilizer application was very low, amounting only about 0.094 kg/week or 0.032 kg/ha/year. This compares with the average loss in drainage waters 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 dtiching are given in Table 6 below.

Table 6. Phosphorus losses at Coalburn

Period	Average flow (l/s)	Period loss (kg)	Annual loss (kg/ha/year)
Pre-fertilizer	28	0.354	0.032
Post-fertilizer	40	75.8	2.9
Ditching phase 1	27	13.9	0.876
Holiday	10	2.1	0.297
Ditching phase 2	8.1	2.9	0.334
Post ditching	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. Whilst a lot more will have doubtless come off after that, the rate will be falling and this is an acceptably low figure (W.O. Binns, Forestry Commission, personal communication).

5. HYDROLOGICAL EFFECTS OF THE DITCHING

5.1 Introduction

The purpose of the ditching 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 at the time of the ditching, so this discussion must necessarily be restricted to changes in the hydrometeorological 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, known to the author, is that of Williams (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. However, since Williams' analyses were based upon largely the same data set, they are 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 ditches upon storm runoff patterns was studied by comparison of sets of simple single-peak hydrographs before and after ditching.

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 unit hydrograph analyses would be appropriate to provide non-dimensional runoff hydrographs for comparison.

The unit hydrograph has always posing theoretical problems, such as the definition of net rainfall and runoff, though 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 surprisingly elusive, and the mammoth Flood Study 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 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 period, and the relationship derived ignored most of the data points (Robinson, 1976).

It is not intended to discuss further the merits and 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 better.

Six storms were analysed for one period before ditching and for two periods afterwards. Certain criteria were applied in the selection of suitable storms. Only single-peak hydrographs were analysed, and care was taken to reject storm events which had rapidly declining antecedent flows since this would complicated baseflow separation. Winter storms in snow-free months were used, summer months being rejected so as to reduce the uncertainties of the distribution of the rainfall 'losses' (which are greater and more variable through time for drier ground conditions). Summer storms are also often more intense, and the runoff might be generated from an unrepresentative part of the catchment. A horizontal baseflow separation was adopted due to the small dry weather flow component.

Unit hydrographs were derived by the 'least-squares' technique adopted in the Flood Study Report (NERC, 1975) and the range of values for individual storms of some of the main parameters of the unit hydrographs are given in Table 7.

Table 7. 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 (.178)	13-26 (19.5)

Mean values are given in parentheses.

Mean unit hydrographs were derived by averaging the individual parameter values and are shown in Figure 16. This demonstrates clearly that the ditches have provided a much more 'peaky' response, with time to peak halved, and flood peaks increased by approximately 40%.

As mentioned, summer storms were not analysed, but these unit hydrographs may be compared with those derived for summer storms in Williams (1977). The pre-ditching unit hydrograph was a little more peaky than that for winter with a time to peak of four hours and a peak of .145. This may have been due to seasonal differences in runoff patterns (eg. Harvey, 1971) or to sampling differences. The post-ditching unit hydrograph was however very different to that derived here - having a much greater peak of 0.37 and a time to peak of only 1.5 hours. This was probably due to the fact that despite Williams' statement "it should be noted that extreme events have been ommitted from the unit hydrograph analysis", the sole post-ditching storm analysed had a rainfall intensity of about 10 mm/hour. It does not seem likely therefore that summer storm peaks would have increased appreciably over those in winter.

It is interesting to note that the mean unit hydrography derived 4-5 years after the ditching shows a slight decrease in flood peak and increase in time base which may be interpreted as due to the growth of vegetation in the ditches. This reduction in peak flows may continue, and once the trees have reached maturity may result in a more stable level of flow than even for 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 litte, 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)

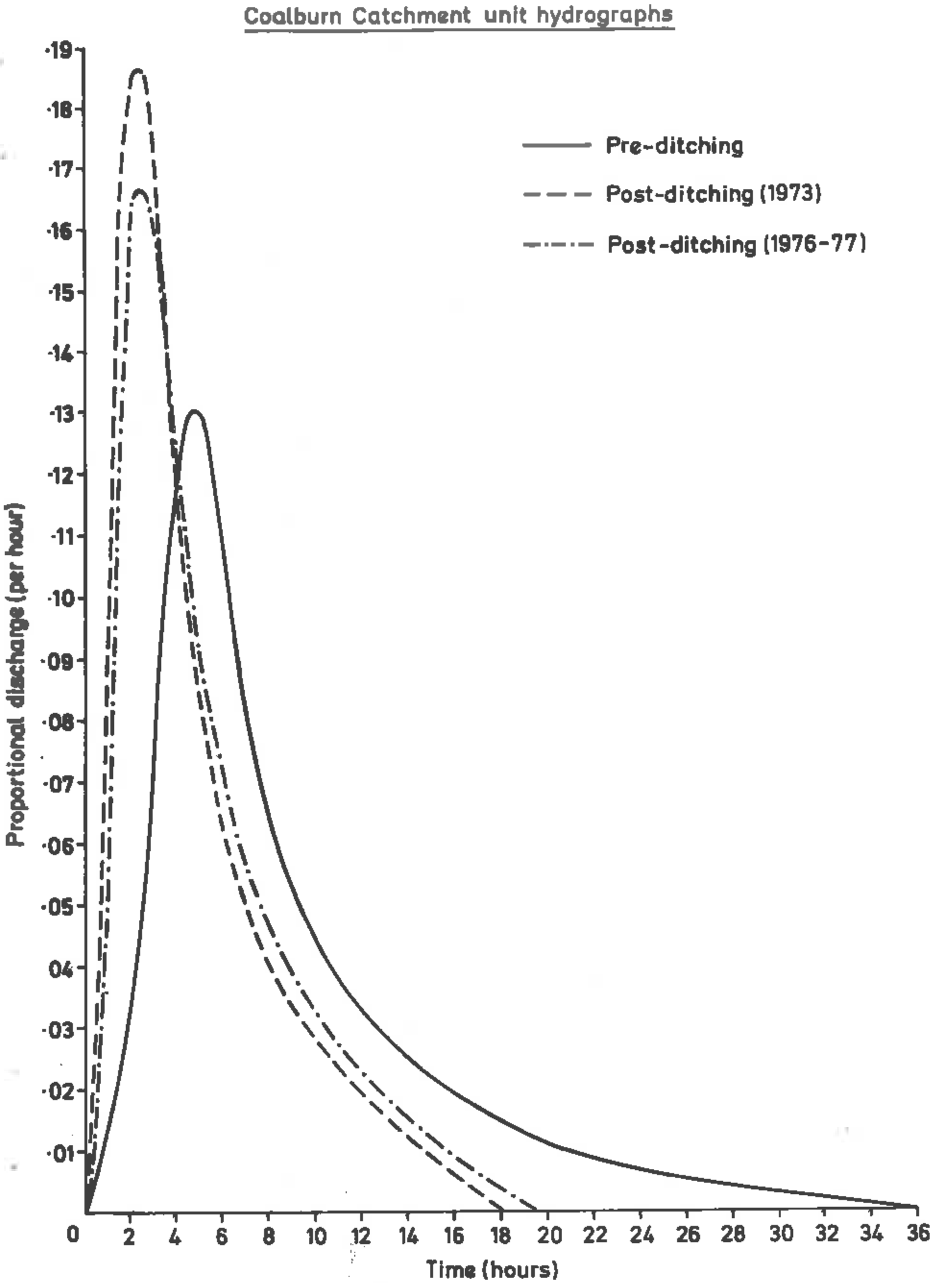


FIGURE 16. – Unit hydrographs before and after ditching

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.

5.2.2. Total storm runoff

About 15-20 storm events were sampled before and after the ditching to study the relation between storm rainfall and the percentage runoff. Storms were chosen to cover a range of storm magnitudes, and a horizontal baseflow separation was used, as in Section 5.2.1, to derive the net storm 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 in the sample prior to ditching, 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 yield equation of the form:

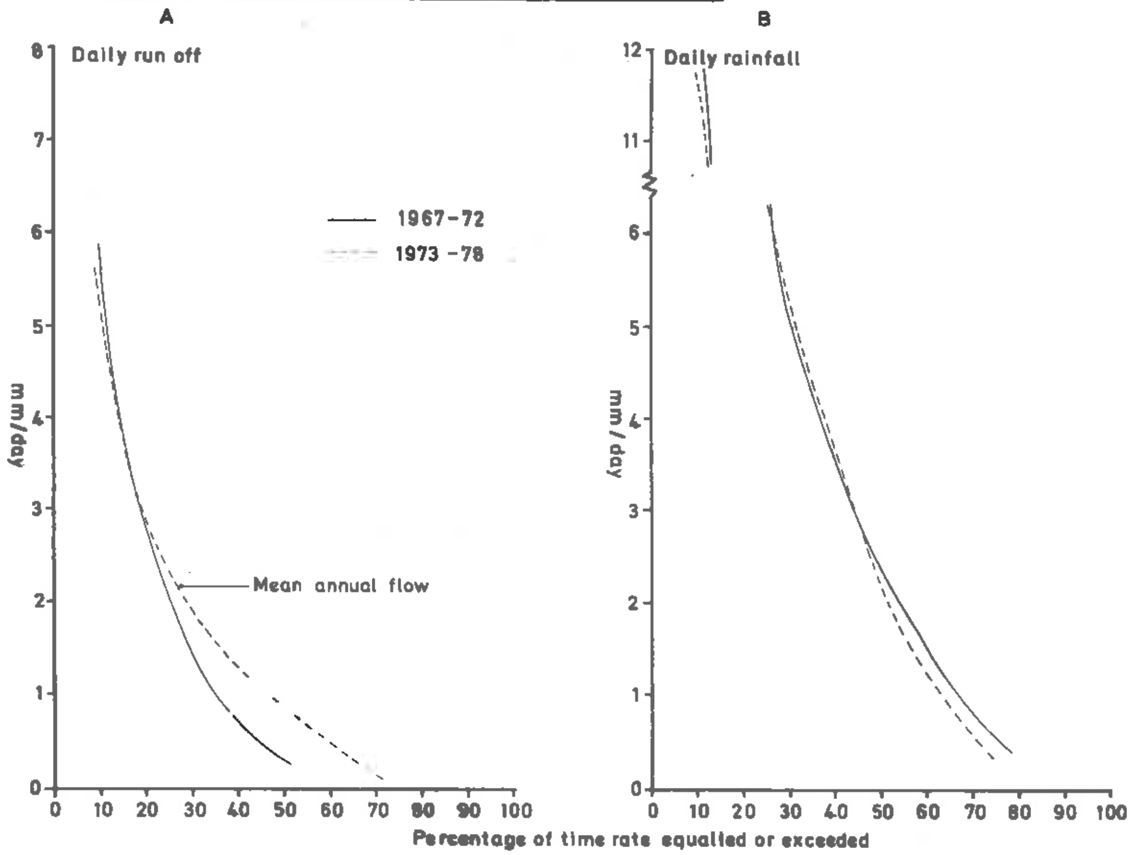
Before: $\%$ R.O. = 0.548 R + 22.9 $r = .29$

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

The relationship between storm rainfall and runoff were much stronger after the ditching, and this may indicate a decrease in the importance of antecedent conditions. The important 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 ditching, possibly due to the generally 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 ditches, 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 ditches on storm runoff yields would have been

FIGURE 17. **Cumulative frequency curves for rainfall and runoff**



limited to a modest increase. This conclusion appears to be confirmed by the daily flow duration curves for streamflow (Figure 17A), which shows little change in storm runoff patterns for days with greater than the mean annual flow.

An additional factor restricting any increase in storm runoff volumes may be the presence of the turf ridges on each side of the ditch. 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 ditching tended to have drier summers than before, and so it might be expected to have had a much greater proportion of time with low streamflows, and a lower flow rate for a given frequency of occurrence. The daily flow duration curve in fact shows that the opposite occurred, and the level of low flows at a given frequency were higher than before (Figure 17A). This also, at first, appears a surprising result, considering the greater rate of streamflow recession after the ditching, noted in the unit hydrograph study (Section 5.2.1).

In order to study the behaviour of low flows, master recession curves (eg. Wilson, 1974), were derived from a number of storms before and after ditching. Storms were selected with long uninterrupted recessions, and only winter events were analysed, so as to reduce any irregularities in the recession rate due to evaporation losses.

Master depletion curves before and after ditching are shown in Figure 18, and it may be seen that after an initially more rapid decline during storm discharges, the post-ditching recession rate becomes much lower and higher discharges are sustained longer than for the earlier period. This may be the result of seepage of water into the ditches between storms, partly from water 'ponded' between the ridges, and partly due to the greater drainage network reaching parts of the catchment which were previously rarely if ever drained of surplus soil moisture except in summer.

These results conflict with the findings of Williams (1977) who concluded that the ditching had had no effect at all on catchment drainage and baseflow levels between storms. A possible explanation to account for

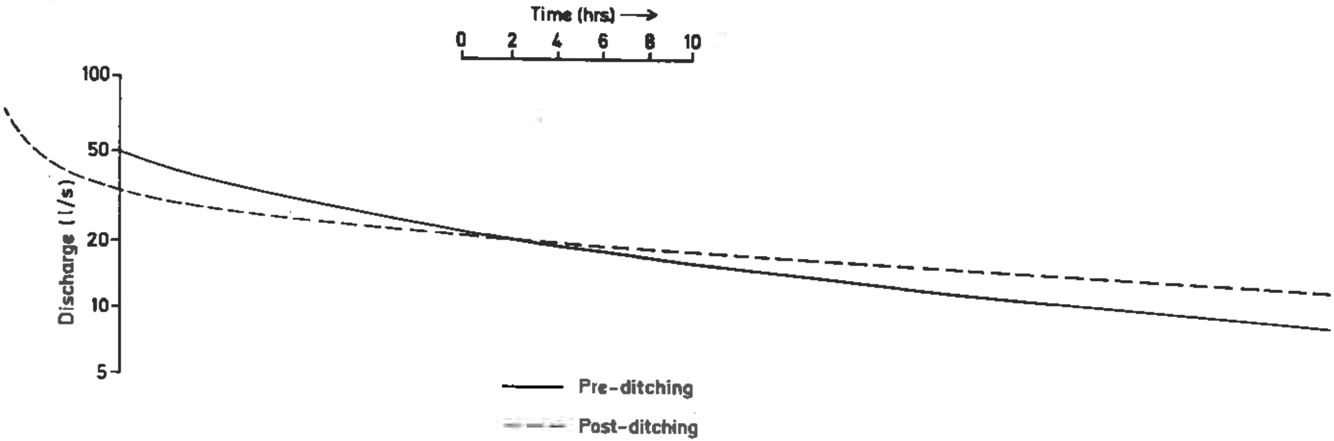


FIGURE 18. Master depletion curves before and after ditching

the different conclusions drawn from basically the same data, is that Williams may have mixed recessions from different seasons (and hence under differing evaporation rates). The recessions for the post-ditching may have been chosen from the two previous summers of 1975 and 1976, which had very high potential evaporation rates (up to 135 mm/month) and when soil moisture reserves would have been exceptionally low. These conditions may have led to steeper streamflow recessions (eg. Weisman, 1970).

5.4 Water yield

The presence of the ditches 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 ditching 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 ditching 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 8; all measurements are in mm.

Table 8. Major components of the annual water balance

	Rainfall (R)	Runoff (Q)	% Runoff	Loss (R-Q)	Ep	Loss/Ep	$\hat{Q}$
Pre-ditching:							
1967	1480	998	67.4	482	533	0.90	995
1968	1304	822	63.0	482	541	0.89	873
1969	1084	724	66.8	360	512	0.70	721
1970	1297	914	70.5	383	503	0.76	868
1971	990	655	66.2	335	471	0.71	655
Mean:	1231	823	66.9	408	512	0.79	822
Post-ditching:							
1974	1292	856	66.2	436	566	0.77	865
1975	1100	795	72.3	305	604	0.50	732
1976	1159	818	70.6	341	578	0.59	773
1977	1264	966	76.4	298	530	0.56	845
Mean:	1203	859	71.4	345	569	0.61	804

(Ep is the potential evaporation calculated by Penman's formulae, $\hat{Q}$ is the predicted runoff from a simple rainfall-runoff model described later.)

The percentage runoff increased by about 4.5% after drainage (3% for water year data), despite the fact that the annual rainfall was somewhat lower, and the potential evaporation was much higher. Flow duration curves for the two periods are given in Figure 17A and show an increase in flow levels below the mean annual flow. Since the slope of these curves represent the frequency of occurence of the daily flows we can see that the greatest change (represented by the greatest difference in slopes at a given runoff value) was for daily flows of between one and three mm (about 20-50 l/s average flow).

Several earlier studies have noted a higher water yield from a ditched catchment than from an undrained one (eg. Conway and Millar, 1960; Mustonen and Seuna, 1972; Green, 1970), although the mechanism was often unclear. It was therefore decidedto study the data in more detail in order 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, with a carefully maintained standard of instrumentation, and random errors should therefore be small. Possible systematic errors were then investigated.

(2) Revisions of a stage-discharge relationship without being applied to the 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 the 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 ditching (eg. Wilcox, 1979). Much of any change in velocities would probably have been lost in the stilling basin. The accumulation of sediment in the stilling basin would also have tended to lead to underestimates of runoff since ditching, rather than overestimates.

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

(3) No change was made in the method of calculation of potential evaporation. A theoretical albedo value of 0.25 was used over the whole period although measurements in the catchment indicated the ditching had lowered the albedo from 0.15 to 0.13 (NERC, 1973). This would have given rise to a slight increase in evaporation losses since ditching.

In short, there does not appear to have been any change in the data collection and processing themselves, which could account for the apparent increase in runoff (S.W. Smith, Institute of Hydrology, personal communication), and in fact, any changes that might have occurred would have acted to decrease the streamflow measured after ditching.

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

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

Pre-ditching: $Q = 0.693\ R - 29.8$ $r^2 = 92\%$

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

The pre-ditching 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 ditching. 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 may be estimated as 6.8% of the runoff (220 mm); 4.6% for water years.

We may compare the regression equations for the two periods to determine if they are significantly different. Cochrane and Cox (1964) provide a suitable test that does not require that the variances of the two sets of data are equal, and this test was also adopted in Green (1970).

A critical value of Student's t is calculated as:

$$t_{crit} = \frac{w_1 t_1 + w_2 t_2}{w_1 + w_2}$$

where the subscripts refer to the different periods t_1, t_2 are Student's t values for n-1 degrees of freedom. w for each period is given by:

$$w = \frac{s^2}{s_{xx}}$$

where s^2 is the mean sum of squares $\Sigma(Q-\hat{Q})^2$

s_{xx} is the corrected sum of squares $\Sigma(R-\overline{R})^2$

The t value for the difference between the regression slopes (b) is then given by:

$$t = \frac{b_1 - b_2}{\sqrt{\dfrac{s_1^2}{s_{1_{xx}}} + \dfrac{s_2^2}{s_{2_{xx}}}}}$$

(NB. This equation is incorrectly printed in Green, 1970.)

For the calendar year data this yielded:

$$t_{crit} = 4.232$$
$$t = 0.237$$

So the slopes are *not* significantly different. A similar conclusion holds for the water year data.

A comparison was then made of the main elements of the water balance to determine whether or not there were statistically significant differences between the two periods. A t-test indicated that the decrease in rainfall and increase in runoff between periods were not statistically significant. The increase in percentage runoff, however, was significant at the 95% level, and this goes some way to substantiating the apparent change in catchment yield.

5.4.2. Possible physical mechanisms causing a change in yields

Various possible physical causes of the small apparent increase in yields were investigated, and are listed below:

(1) The presence of the drains would lead to a lowering of the catchment water table. The period of decline would give rise to a temporary period of increased flow as the water was drained from above the new water table level. This would lead to an increase in low flows (as was observed) and we should expect the increase in flow to decrease with time (which was not observed). The release of significant quantities of water has generally been associated with much deeper and wetter peat bogs, such as raised bogs (eg. Wilcox, 1979) than the conditions at Coalburn. The release of such water is 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 ditching (D.A. Thompson, Forestry Commission, personal communication).

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

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

This would probably result in greater runoff in winter (due to the improved drainage) and lower runoff in summer (due to the drier soil conditions).

(3) The ditches account for about 10% of the catchment area, and if they returned 100% of the rainfall that fell into them, instead of 67% runoff as from the rest of the catchment, this could lead to an increase in water

yield of about 3.3% of the annual rainfall. This increase would however be largely confined to storm events, and would be greater in summer (when catchment losses are greatest).

(4) The increase 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 ditching 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 ditch 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.

Several possible mechanisms to account for the apparent increase in water yield have been outlined above. Since different mechanisms would have had different effects on the seasonal pattern of runoff as well as on peak and low flows, the seasonal water balance was examined to help determine which process was most likely to have been the cause of the increase.

5.4.3. 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 9.

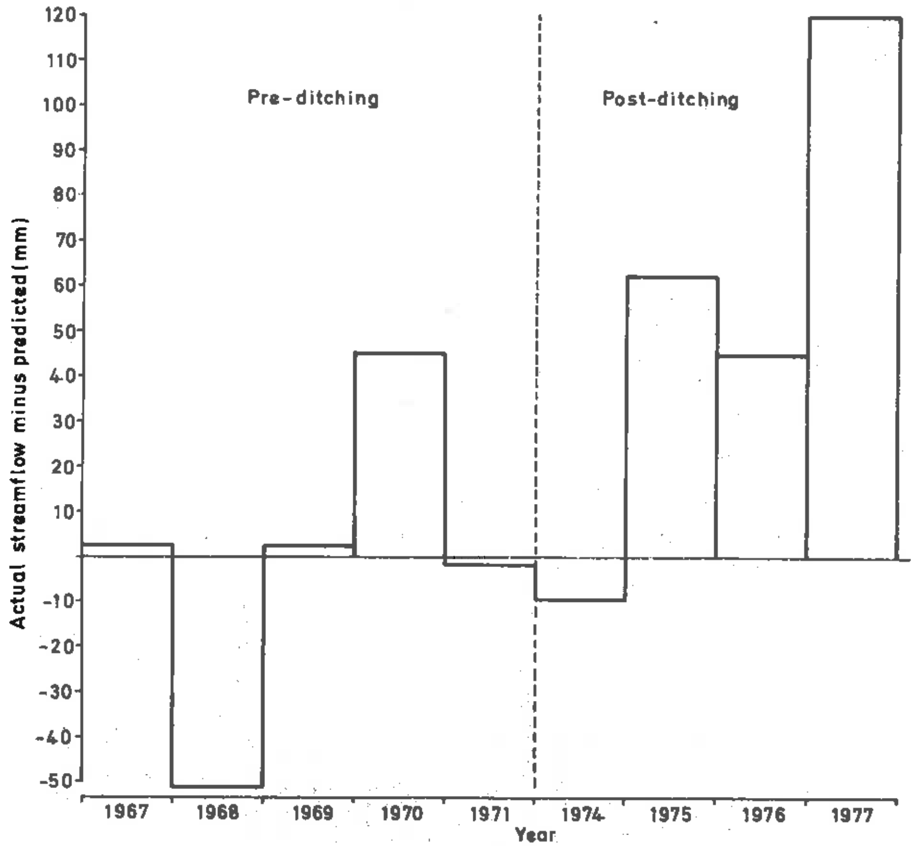


FIGURE 19. Deviations of actual streamflow from predicted values

Table 9. Major components of the seasonal water balance

PRE-DITCHING

Period	Winter R	Winter Q	% Runoff	Period	Summer R	Summer 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
1970-1	652	599	91.9	1970	575	305	53.0
1971-2	542	465	85.8	1971	457	196	42.8
Mean	638	539	84.5	Mean	582	283	48.6

POST-DITCHING

Period	Winter R	Winter Q	% Runoff	Period	Summer R	Summer Q	% Runoff
1973-4	542	480	88.6	1974	497	235	47.3
1974-5	794	636	80.1	1975	642	370	57.6
1975-6	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

(NB. Values have been rounded to the nearest mm.)

There was obviously a great deal of variation between individual periods, but overall these results show little evidence of a change in the seasonal runoff balance, with an increase in percentage runoff after ditching, for 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 for winters to have more rainfall and summer to have less, from about the same time as the ditching.

This contrasts with the study of Williams which concluded 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 efficiency; andleading 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 ditching 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 may be of a similar magnitude to the precipitation or runoff of a given month, due to factors such as snowfall, snowmelt, the timing of the rainfall, or very dry ground conditions. There are, for instance, a number of months with over 100% runoff, clearly reflecting the release of water from a previous period. Secondly, months which lag 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 incidently indicated that only the winter increase was significant (no level was given). Nevertheless, Williams assumed that there had been an equivalent decreased in summer runoff, since a double mass curve analysis of runoff at Coalburn and nearby Kielder Burn had indicated no change in the relation before and after ditching (and hence no change in the total annual runoff).

Kielder Burn was however rejected as a 'control' catchment in this study, and for a variety of reasons the evidence for no change in water yield at Coalburn was not accepted. The period of common data was very short, with only two years of records prior to ditching. 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, tending 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 ditching), 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 (Mike Storey, Northumbrian Water Authority, personal communication). Unfortunately no other sutiable gauge could be located to act as a 'control' catchment.

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 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 susggested in Section 5.4.1.

It is therefore proposed by the author that the evidence indicates there was a real increase in the water yield, and that this was not confined to a particular season, but represented an increase in flow over the whole year. The mechanism suggested to account for this increase was (4) in section 5.4.1, 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. CONTEXT AND CONCLUSIONS

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

With the likely continued expansion of British forestry, and an increasing concentration in upland areas, much greater portions of upland catchments will in future be forested. 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 catchment 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 180 tonnes (130 m^3) of material was carried from the catchment in the streamflow as a direct result of the ditching. This represents a loss of only about 0.2% of the total 60000 m^3 of material that was excavated to create the ditches.

The study provided a rare opportunity to observe sediment levels *during* the ditching 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^3), limiting these variations.

There was a dramatic increase in sediment levels during and after ditching, with concentrations rising from a previous level of generally under 10 mg/l, to greater than 7000 mg/l. Whilst much greater yields would probably have resulted from a catchment with steeper slopes and a more suitable soil grain size distribution, it is thought that the fairly rapid rate of decline to a new equilibrium level observed, would probably be a general feature, and the fact that this was reached without any influence from the young saplings indicates that it would be a feature of moorland drainage schemes too. The most important conclusion regarding sediment yields is therefore that on a regional scale the effect of the ditching 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 "there are serious implications for the afforestation of catchments containing reservoirs" (Richard Hey, University of East Anglia, personal communication). However, the reaction from members of Water Authorities contacted, was generally that the increase in yields would probably not have any serious consequences on reservoir storage, since rates of sedimentation in U.K. reservoirs are usually small - eg.

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

Nevertheless, increased sediment loads may cause a number of local problems due to the larger quantities of sediment that will be deposited where flow velocities are reduced. This may lead to changes 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 1880's 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 sediment that were being carried down into the reservoir (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. Facts here are, therefore, very valuable and we would be most grateful to receive the results of your work." (Ian 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 (eg. 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 survvial 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 Kelly, 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 ditched 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 popùlations 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 ditching of Coalburn amounted to of the order of nearly half a century's load (120 tonnes/ha) and was carried from the catchment in under 10% of that time. Present loads remain at about 4-times pre-ditching 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 ben 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. It is not thereforepossible to be as confident about the accuracy of the measurements as for, say, a Water Authority laboratory, and only a small number of samples were taken. However, it would appear that no great change occurred in the general levels of these solutes as a result of the ditching, though a temporary increase may have occurred as soil water drained from the catchment. It is not clear what effect, if any, the phosphate application may have had on the solute levels.

6.2.2 Fertilizer losses

Rock phosphate fertilizer was applied to the catchment a short time before the ditching 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 the principal nutrient often found 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 during daylight in photosynthesis. Fish mortalities may then occur during the night or if the overproduction of algae leads to a shortage of food, and large quantities start to 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 ditching averaging 0.5 mg/l, and increasing to 1.0 mg/l during ditching. 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 saplings. One possible means is through altering the timing of the application. If fertilizer is added prior to ditching the plough will overturn the surface mat to create a ridge for tree establishment, and the phosphorus is lost during the ditching. This probably amounted to under 2% of the applied phosphorus during and shortly after ditching, though more phosphorus would undoubtedly have been lost during the succeeding wet winter (phosphate concentrations were observed to increase with streamflow). An alternative method is to apply the phosphate after the ditches are cut, but a large amount will then fall directly into the ditches 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 ditches. 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 taken into acount 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 saplings' root system to reach the phosphorus rich sandwich layer at the base of the ridge, whilst if it was applied to the surface after ditching it would be available sooner to the surface root).

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". It was unable, for instance, to determine the effect of ditching 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 after drainage (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 comprised 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 oversimplification, for several reasons. Firstly, the *effect* of the drainage is measured by reference to conditions prior to ditching (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 hydrologyic 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 ditches 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 4-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 ditch networks have been described above, and may be compared. At Glenamoy, the purpose of the ditching 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 3.6m the water table was kept more than 40cms below the surface throughout the growing season.

In contrast, the ditching 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 that has often been thought, and that drier soil conditions are generally restricted to a small distance either side of the ditch. Field measurements at Moor House itself, indicated that the lowering of the water table was restricted to at most 2-3 metres each side of a ditch, and that mid-way between ditches the water table depth below the surface varied between 0 - 15cms, and was *not* appreciably different to depths on adjacent undrained areas (A. Stewart, personal communication).

Clearly, the effect of the ditching at Moor House has been much less than that at Glenamoy, and it is suggested that this was largely due to different drainage techniques (although this is not to dismiss the importance of differences in peat type).

The increase in hydrograph peaks following the drainage at Coalburn may now be viewed in terms of the proposed framework above. The catchment had a fairly high natural drainage density of 3.5 km/km^2, which was increased 60-fold by the ditching to give a ditch spacing of 4.8 m. The peat comprises predominantly Eriophorum and *Sphagnum*. Thus the catchment is intermediate between Moor House and Glenamoy, having similar peat to the former, and a similar ditch spacing to the latter. Unfortunately there was insufficient time to study water table depths, though it would appear likely that any lowering of the water table is very limited, since local experience is that the ground does not seem any drier than undrained areas (T. Johnstone, Chief Forester, Wark, personal communication), and the *purpose* of the ditching 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 ditches 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 water table and the likely unimportance of peat compaction, together with the enormous increase in drainage density provided the great increase on 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 this work would generally result in an increase in flood flows.

The data after ditching suggests that there may have been 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 tend to *underestimate* flows after ditching (and hence underestimate an *increase*), and also since an increase in runoff after ditching has been noted in other studies. Green (1970) noted a 10% increase after the drainage of the Brenig catchment and Mustonen and Seuna (1972) noted a 30% 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 *Carex* bog in central Finland noted a 100% increase in runoff as the distance between ditches was reduced from 60 m to 5 m (Huikari, 1968).

An increase in annual runoff of 5% would be of interest to reservoir managers, and especially if much of it occurred in times of low flows (M. Storey, Northumbria Water Authority, personal communication). Further data from Coalburn will necessarily be limited as the saplings grow to maturity, and begin to affect the water balance (eg Institute of Hydrology, 1976). It may therefore 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. And indeed a similar call was made for an investigation of the effects of land drainage, by Dr. H.L. Penman on the opening of the new headquarters of the Institute of Hydrology in 1973 (Institute of Hydrology Report No 20 p 9). Drained moorland may represent the 'optimum' land use around an upland reservoir.

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 ditching, 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 although silting may cause a number of localised problems and may be important in small reservoirs when a large part of their adjoining catchment area is drained.

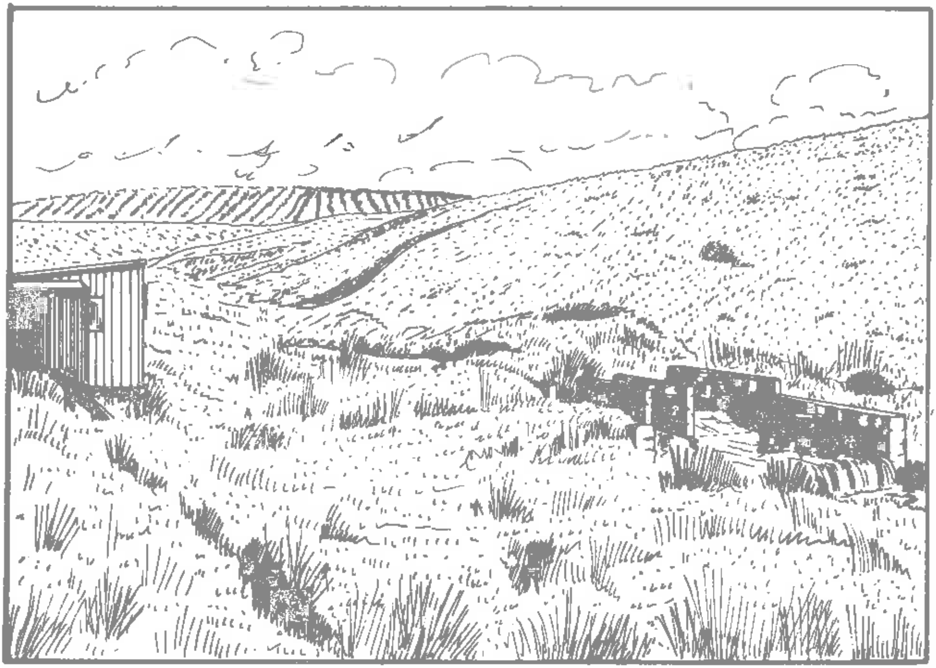
Of more importance may be the effect of the larger sediment loads on fish stocks. Healthy fish may withstand enormous concentrations of sediment, but even a shallow covering of silt (eg 2 mm) on spawning grounds may be sufficient to kill most of the eggs, since it impairs the circulation of water around 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 be released by ditching schemes to affect breeding grounds downstream, and in particular the spawning success in the autumn and spring following the drainage. The increased sediment levels will continue for a number of years, and probably always remain above pre-ditching levels - even under mature forest (Newson, 1979) - 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 hydrograph peaks at Coalburn increased by about 40% and it would appear likely that upland ditching usually leads to an increase in flooding. This may be especially significant since "The effects of agricultural 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 also be a benificial effect of an increase in water yields.

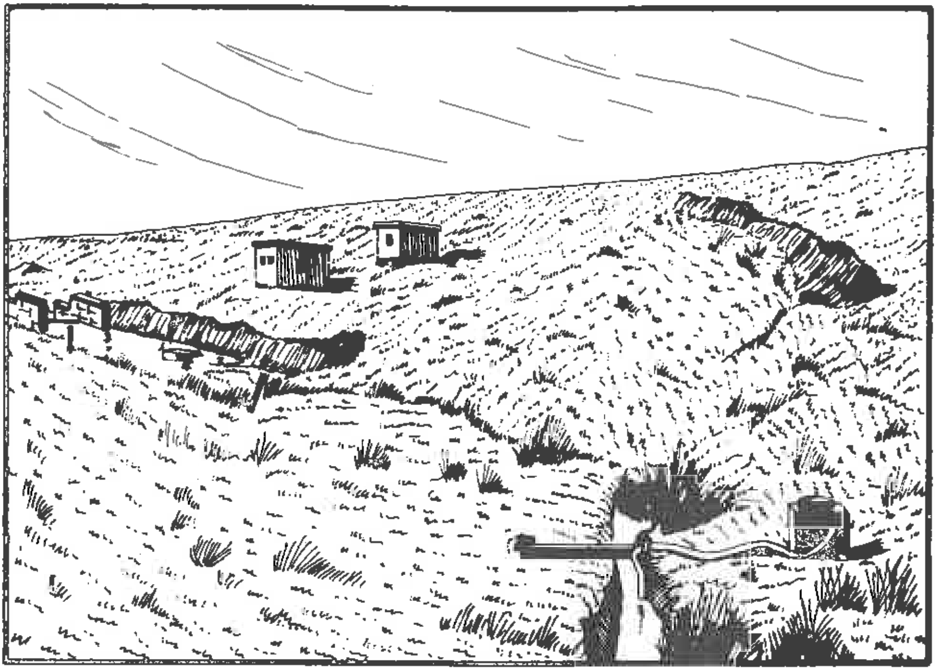
The work has highlighted three main groups of problems which may be caused by upland drainage schemes (both for forestry and for grazing land). All the groups have a common feature in that their effects are, to some degree, temporary. Thus, the bulk of the sediment released by drainage works will have been removed, and a new equilibrium level of sediment loss reached within, say 5 years; phosphate losses will probably continue for no longer than 10 years; and in increased risk of flooding will probably be removed after canopy closure of the trees - say 20 years (although the concept of a mature forest being able to reduce 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 undergoind 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.



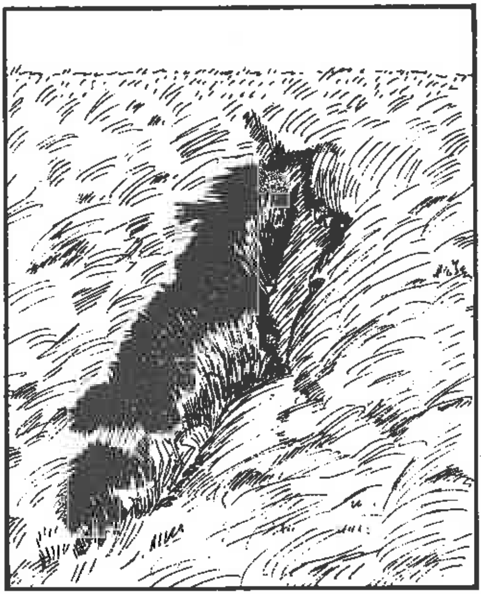
General view of the catchment, showing the Crump weir and stage recorder hut in the foreground. Rows of young saplings can be seen in the distance.

(Sketches drawn by Mr Gordon Bryant from photographs)



View looking downstream to the weir and stilling basin.
The North Hants vacuum sampler can be seen in the foreground.

View of the young saplings, showing their height in relation to the Molinia grass (Spring, 1979). The irregular spacing of the trees is due to mortalities.



Large gully that formed from a ditch on a 30^{0} slope (dimensions about 10 m long, average width 2 m and depth 1 m).

Acknowledgements

The author is indebted to many organisations and individuals for their help in the preparation of this paper.

Special thanks are due to the Institute of Hydrology for the provision of much of the data, and in particular to Ken Blyth and Malcolm Newson.

The Coalburn catchment is part of the Wark forest, and I am grateful to the Chief Forester, Tom Johnstone for permission to carry out the necessary fieldwork, and for all his help.

The work has also benefitted from conversation and correspondence with many individuals, including W.O. Binns (Forestry Commission), S.R. Eyre (Leeds University), M.J. Green (Water Research Centre), R. Halliday (North West Water Authority), R. Hey (University of East Anglia), I.G. Littlewood (Welsh National Water Development Authority), I.R. Smith (Institute of Terrestrial Ecology), S.W. Smith (Institute of Hydrology), A. Stewart (Nature Conservancy Council), M. Storey (Northumbria Water Authority), D.A. Thompson (Forestry Commission) and R. Wood (Severn-Trent Water Authority).

Kind thanks to Gordon Bryant and John Dixon for drawing the figures.

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