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The effects of forestry on upland streams—with special reference to water quality and sediment transport

G J L LEEKS and G ROBERTS
Institute of Hydrology (Plynlimon), Staylittle, Llanbrynmair, Powys SY19 7DB

Summary
The Institute of Hydrology (IH) has been carrying out studies of the interaction between forestry and grassland practices and upland streams since 1968. Experiments using a twinned-catchment approach are described and the results of 2 current projects in mid-Wales are reported. The effects of afforestation and clearfelling on water and sediment yields, water chemistry, temperature and flow responses are discussed within the broader context of other studies. Methods to reduce the sediment outputs of forested catchments are also listed.

1 Introduction
Traditionally, water supply undertakers have favoured forestry as a cover for water gathering catchments in upland areas of Britain. Forestry was regarded as a productive use of land which otherwise would have been, at best, marginal agriculture. Also, it was thought that forestry would act as a barrier against the public and cattle around reservoirs and along feeder streams, would provide a natural filter for holding up silt and removing pollution from surface runoff, would act as a sponge to even out the flow from varying rainfall and would provide a windbreak as an aid to further land development.

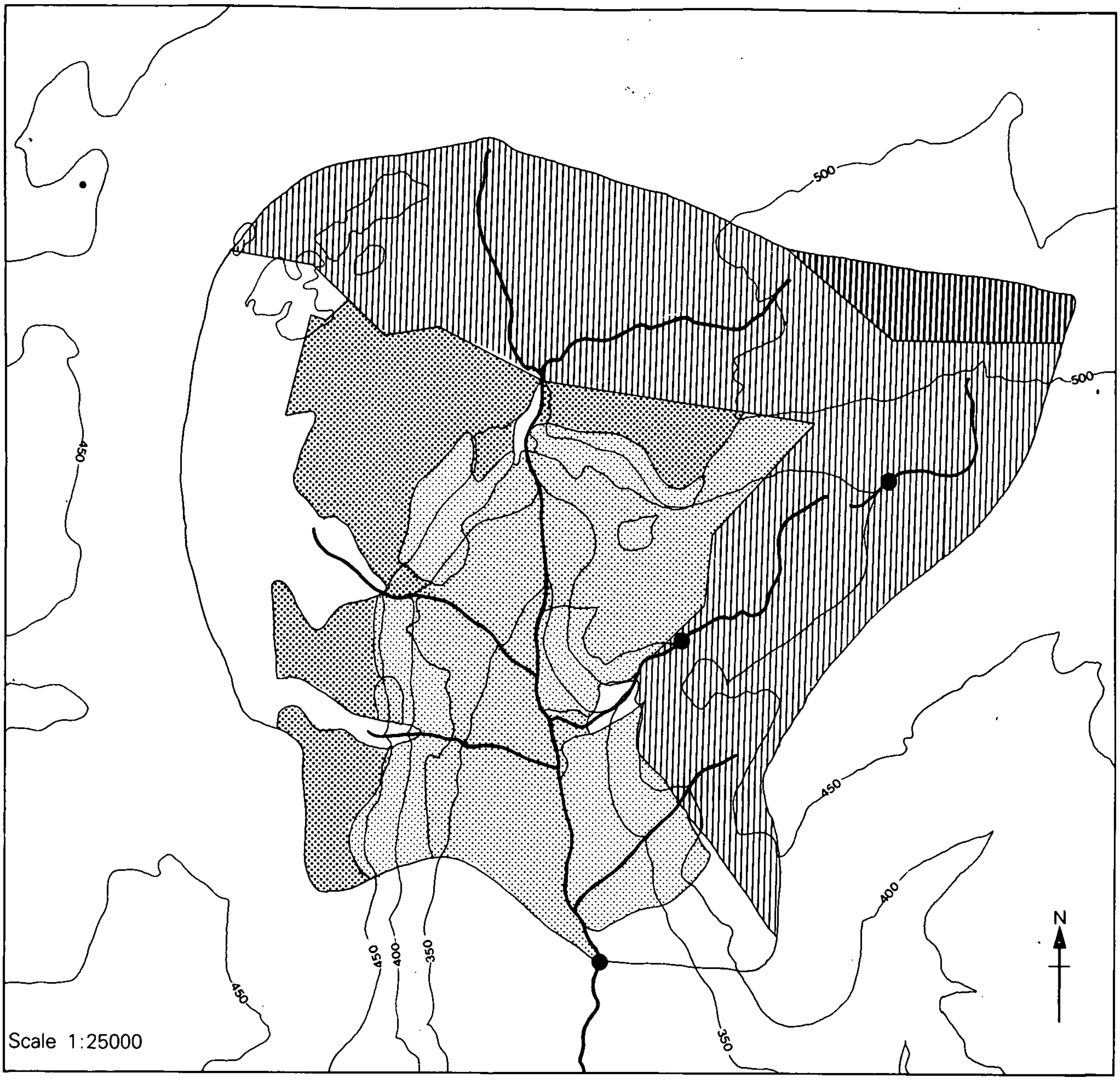
The Institute of Hydrology has been investigating the interaction between upland land use and stream processes since 1968. Details of some of the current experiments are given below. In the following sections, results from these experiments, with regard to water and sediment yields, water chemistry and stream temperature, are outlined in relation to work on other forested streams.

2 Institute of Hydrology upland catchment studies
The Institute of Hydrology began catchment studies at Plynlimon in 1968 to compare the water use of established forestry and rough pasture. Other associated studies include plot-scale studies to explain the results from the catchments (Calder 1976), the comparison of nutrient losses from the 2 land uses (Roberts *et al.* 1983) and the effect of pre-afforestation ditching on sediment losses (Newson 1980b; Arkell *et al.* 1983).

As a sequel to Plynlimon, a similar study, with the same objectives, is being carried out in Balquhidder in the central Highlands of Scotland, an area receiving a greater proportion of precipitation in the form of snow than is the case at Plynlimon. A detailed description of the Balquhidder catchments and an initial appraisal of the results have been given in Blackie *et al.* (1986). More recently, the Institute has initiated a series of 3 studies in mid-Wales into the effects of upland land use change. These studies are: afforestation at Llanbrynmair, clearfelling in the Hafren Forest at Plynlimon; and upland pasture improvement at Nant-y-Moch. Each study adopts a twin-catchment approach, one being undisturbed and acting as a control and the other being subjected to the land use change following a suitable calibration period. The need to calculate nutrient losses in the streamflows as a product of streamflow total and concentration meant that reliable flow measuring structures had to be installed. As a result, the studies could be extended to look at the effects of the changes on water use and streamflow responses to storm events. Subsequently, the experiments have been further extended to study a wider range of chemical determinands, sediment losses and fish populations. More detailed descriptions are given below of the background to 2 of these current research projects as they are illustrative of the possible effects of afforestation and the end of the first rotation upon upland streams.

2.1 The afforestation study
At Llanbrynmair moor, 24 km north of the Institute of Hydrology's mid-Wales station, the Economic Forestry Group purchased a considerable amount of land for afforestation purposes, the operation being scheduled to begin in 1982. In all, a total area of 1200 ha was involved. Shortly following completion of the purchase, 2 catchments were identified, one partly within the afforestation scheme and the other totally unaffected. The catchment within the afforestation scheme, the Cwm, is about 300 ha in area, approximately 40% of which was scheduled for afforestation. The unaffected catchment, the Delyn, is approximately 100 ha in area and is used as a control. Instrumenting the 2 catchments began in the spring of 1982 and was completed in the autumn. During 1983, Fountain Forestry Limited completed the purchase of a further 150 ha of the moor for afforestation. Virtually all of this land lies within the Cwm, resulting in approximately 90% of the catchment being affected on completion of the 2 schemes.

A map of the Cwm catchment showing the timing and extent of afforestation is given in Figure 1. Air photographs of the area confirmed that the 2 areas to be afforested by the Economic Forestry Group were, in fact, completed by April 1984. Some burning of the



Unchanged (rough pasture)

Economic Forestry Group 1983

Economic Forestry Group 1985

Fountain Forestry 1984

Fountain Forestry 1985

Fountain Forestry 1986

Streamflow sampling points ●

Figure 1. Llanbrynmair Cwm catchment: afforestation sequence

indigenous vegetation was involved and the whole area was ditched prior to planting. A phosphorus fertilizer was applied to all the planted areas at a rate of 181 kg ha^{-1} of P_2O_5. The area designated to be planted by Fountain Forestry in 1984 (see Figure 1) was completed during the spring of that year. This planting was mainly on steep slopes, the major species being Sitka spruce (*Picea sitchensis*), with smaller amounts of Douglas fir (*Pseudotsuga menziesii*), Japanese larch (*Larix leptolepis*) and noble fir (*Abies nobilis*), and the method used was screef planting with minimal ground disturbance. The bottom of the valley was contour ploughed in November 1984 and planted with Sitka spruce in April 1986. The only areas of the Fountain Forestry holding to receive a fertilizer dressing were 2 sites, adding up to some 10 ha, in the north-east and north-west of the plantation. These areas received an NPK dressing by hand during the spring of 1986 at a rate of 580 kg ha^{-1}. As part of their agreement with the Severn-Trent Water Authority, buffer strips, approximately 20 m wide, were left on either side of perennial streams. It was also agreed that approximately 15% of these strips were to be planted with a mixture of alder (*Alnus* spp.), birch (*Betula* spp.), oak (*Quercus* spp.) and ash (*Fraxinus excelsior*). Also, some areas above steep gullies on the western side of the catchment (see Figure 1) were left unplanted so as to minimize erosion. A number of roads to access both the top of the catchment and also the valley bottom have been constructed.

Routine monitoring at the outfalls of the 2 catchments began in July 1982. Streamflow from the Cwm catchment is measured by means of a Crump weir and from the Delyn by means of a sharp-crested weir with a V-notch.

2.2 The clearfelling study

This study is being carried out in the IH Plynlimon catchments in mid-Wales. The forested catchment, the upper Severn, has been described in some detail elsewhere (IH 1976; Newson 1976). Two subcatchments are involved: the Hafren of 358 ha which is to act as a control, and the Hore of 317 ha. Agreement was reached with the Forestry Commission that approximately 157 ha of the Hore subcatchment, amounting to almost 50% of the catchment area, would be felled over a 2 year period beginning in 1985. Two areas were to be felled, both in the lower portion of the catchment, consisting of a 90 ha area containing Norway spruce (*Picea abies*) and Sitka spruce planted in 1937–38 and a 67 ha area containing mainly Sitka spruce but also Japanese larch, Norway spruce and lodgepole pine (*Pinus contorta*) planted in 1948–50. Some thinning and clearing of windblown areas of trees had been taking place for several years, and it was agreed that this practice would be terminated in the spring of 1984, so as to allow a 12 month 'settling down' period. At this time, approximately 16% of the Hafren had been affected, and 13% of the Hore, all in the lower portion of the catchment. Figure 2 shows the areas that have already been clearfelled in the first year of operation, indicating the techniques used. The rest of the enclosed area is scheduled to be felled over the next 18 months or so. Because of the uncertainties about the effects of thinning and felling already carried out, it was decided to use the upper portion, above the areas to be felled, of the Hore subcatchment to act as an additional control. Therefore, a steep streamflow measuring structure was constructed mid-way up the Hore subcatchment (Figure 2) to supplement the ones in existence at the outfalls of the Hore and Hafren. This structure was completed during the autumn of 1985 and flow recording began in October. Flow records are available from the other 2 sites since 1973.

3 Water yields

Recent research has shown that the afforestation of upland catchments is not necessarily beneficial with regard to water resources. The first experiment was conducted by the late Frank Law who, using a lysimeter situated within the forested part of the Stocks Reservoir catchment, showed that, of the 990 mm rainfall that fell during an annual study period, the loss from the forest was 290 mm greater than that from grassland (Law 1956, 1957). However, the validity of Law's results was not universally accepted. In particular, because of the small surface area of the lysimeter used (0.045 ha), doubts were expressed concerning the replicability of the experiment. More recently, the Plynlimon study conducted by the Institute of Hydrology in mid-Wales has verified Law's results for upland, high-rainfall areas. It has been found that, of the 2300 mm or so annual rainfall, approximately 17% is lost by transpiration from the Wye, grassland, catchment whilst 38% is lost from the Severn, established forestry, catchment (adjusted for 100% forest cover) (Newson 1979). Process studies have shown that the difference is due to the interception and subsequent evaporation of the incoming rainfall within the forest canopy (Calder 1976). Calder and Newson (1979), using the data from the Plynlimon study, calculated the likely losses in water supply that would occur in the major upland catchments following increased afforestation up to 50% canopy coverage. The figures vary from area to area depending on the climatological conditions, with a predicted average reduction in yield of about 10%. In contrast to the upland situation, Gash and Stewart (1977) predicted that evaporative losses from Scots pine (*Pinus sylvestris*) in Thetford Forest, a low rainfall area, would be very similar to the potential evaporation from short grass, plentifully supplied with water. The difference between the 2 situations has been attributed to differences in interception loss, this varying by a factor of more than 3 across Great Britain and in many cases being the largest component of the total evaporation (Gash *et al.* 1980). The results for Plynlimon and Thetford were obtained for established forestry. No results are available at present on the effect of plantation age on water use.

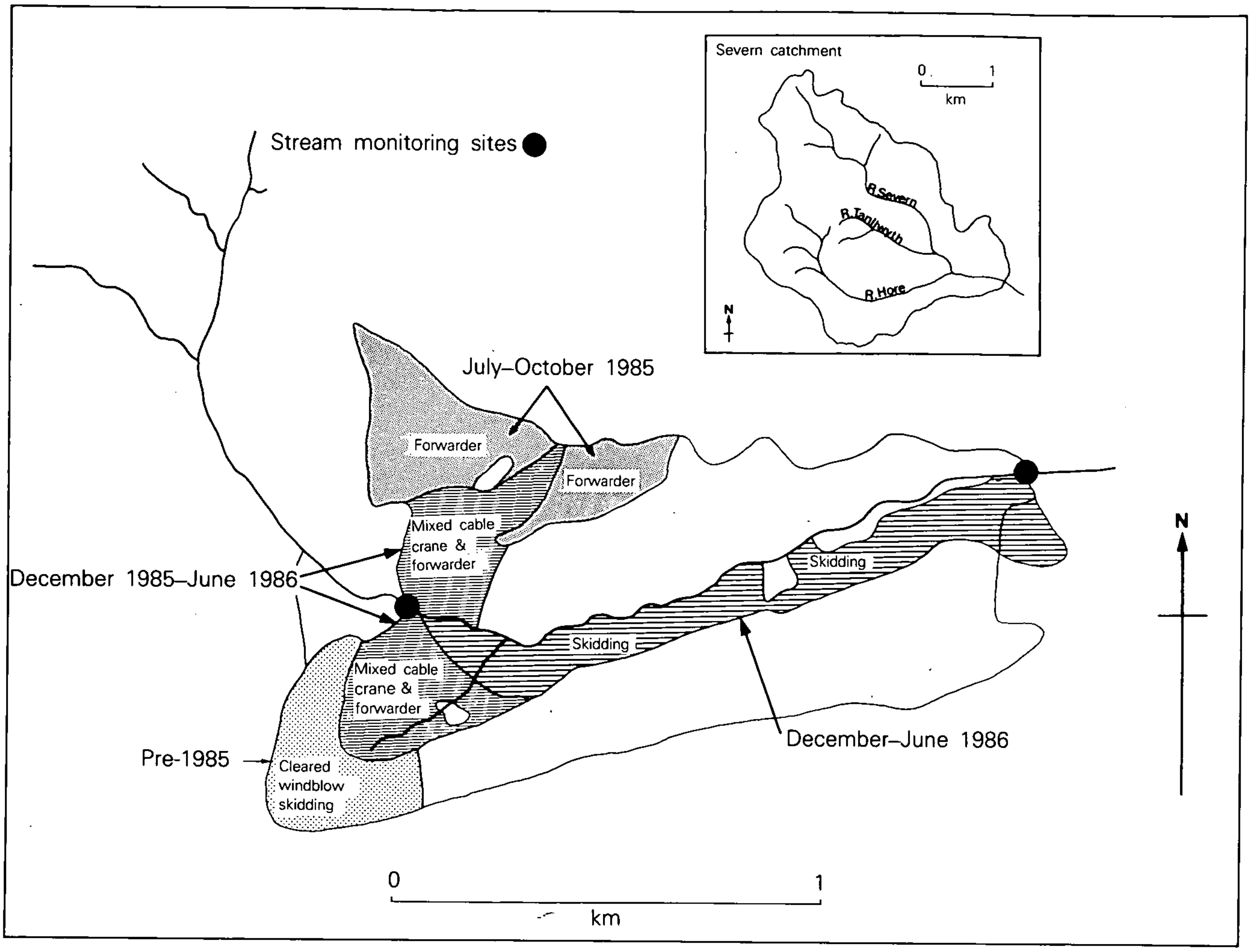


Figure 2. Hore felling project: techniques and dates

4 Flow response

The effect of forestry on stream response to rainfall, particularly the initial drainage required to produce conditions conducive for sapling development (Taylor 1970), on the timing and magnitude of peak flows has been of interest. Robinson (1980), in his study of the afforestation of the 152 ha Coalburn catchment, found that pre-afforestation drainage produced a much peakier storm response, with higher flood flows and a reduction of 50% in the time to peak. Similar results were found by Conway and Millar (1960), at Moor House in the northern Pennines, where a burnt and drained catchment exhibited earlier peak flows and higher peaks than a nearby undrained catchment. It was found that severe burning of the peat surface increased peak flows by reducing the storage capacity of the soil, although this effect was much smaller than the change due to drainage. On the other hand, Burke (1968) at Glenamoy, southern Ireland, showed that drainage increases the storage capacity above the water table, thus ensuring a less rapid response to rainfall in drained than undrained areas. It has been suggested (McDonald 1973) that soil type is the major factor in determining the effect of drainage on peak flows, but parameters such as type of drainage, topography and the amount and intensity of rainfall are also of relevance. In general, though, the majority of studies (see, for example, Burke 1968; Robinson 1980) suggest an increase in low flows following drainage.

At Llanbrynmair, a detailed investigation of the timing of peak flows from the Cwm catchment using a unit hydrograph approach has revealed that the drainage carried out by the Economic Forestry Group at the top end of the catchment (see Figure 1) has resulted in a significant increase in peak flows (see Plates 1 & 2). The increase for an individual rainfall event depends on its duration, ranging from 5% for a 10 hour duration rain storm to 20% for a 5 hour one. The average measured lag time between the centroid of storm rainfall and the resultant peak flow was cut from 2.7 hours to 1.8 hours after drainage.

The studies quoted above show the effects of initial drainage on the patterns of streamflow losses. These effects, however, may be only temporary because, after canopy closure, the infilling of drains by vegetation, the deep ground layer of leaves and needles and the higher interception losses may result in a smaller response than in the original upland pasture (Binns 1979). This was originally thought to be the case for

Plate 1. One of the steep stream flumes in the forested Severn catchment at Plynlimon during a flood event (Photograph G J L Leeks)

the established forest at Plynlimon, where a reduction in peak flows was found in the forested compared with the grassland catchment. Times to peak were slightly longer for the forested catchment although, when the analysis was restricted to identical rainstorm inputs, the reverse was true (Newson 1979). A more recent analysis of a larger data set suggests, however, that the response difference of the 2 catchments is small. G A Cole (pers. comm.) concludes 'it would appear that the mature closed forest canopy of the Severn, despite drainage, ameliorates floods sufficiently to give a comparable response, though a lower volume of runoff, compared with the neighbouring grassland Wye catchment'. Again, there is no indication at what stage in the forest development this will happen.

5 Temperature

Forestry will also affect stream temperatures because of the shading effect of the tree canopy. Roberts and James (1972) reported that at Plynlimon monthly mean streamwater temperatures in the forested catchment were generally 2°C cooler in the summer and up to 1°C warmer in the winter. Similar trends were obtained by Gray and Edington (1969), who found that the felling of a woodland bordering a small tributary of the River Coquet in Northumberland increased the summer maximum stream temperature by up to 6.5°C.

6 Chemistry

6.1 Afforestation

Substantial nutrient losses, particularly nitrogen, have been reported as a result of draining organic soils (Duxbury & Peverly 1978) and wet sloping land (Benoit 1973). Roberts *et al.* (1986), in their study of the effects of upland pasture improvement on nutrient losses, found enhanced nitrate concentrations (up to 16 mg l^{-1} of NO_3-N) following tile drainage at 10 m intervals, whilst the concentration of other forms of nitrogen and of phosphorus and potassium seemed unaffected. The draining of the Coalburn catchment prior to afforestation produced noticeable increases in the concentration of calcium and, to a lesser extent, magnesium, whilst the concentration of sodium and potassium showed little evidence of change (Robinson 1980). It was suggested that this represented a change in water chemistry from a predominantly peat catchment to a boulder clay type, as the influence of the inorganic soil was increased through its exposure by the drains. Stretton (1984) reported massive increases in total iron, manganese and aluminium following the draining of the Cray catchment. It has been suggested that road construction is also likely to have a considerable effect on water quality (Binns 1979), presumably as a result of the increased sediment losses referred to in Section 7.

In the Llanbrynmair experiment, as well as monitoring the outfalls of the 2 catchments using composite water samplers, spot samples are taken at 2-weekly intervals, beginning in February 1984, at 3 points in the Cwm catchment (see Figure 1).

The uppermost site represents an area of early ditching and planting by the Economic Forestry Group; the middle point is similar but separated from the upper point by a mire area, whereas the outfall represents contributions from the whole catchment including a later planting schedule for the lower basin. A rainfall sample is collected at the outfall of the Cwm catchment. All the samples are analysed for the various forms of nitrogen, phosphorus, potassium, silica, organic carbon, conductivity, and pH at the Severn-Trent Water Authority Laboratories at Shelton, Shrewsbury.

An initial analysis of the chemical data shows that, whilst nitrogen concentrations at the outfall of the 2 catchments were similar during the first 3 years of the study, those in the Cwm catchment were higher than those in the Delyn following the autumn of 1985. This trend is consistent up to the present time and is mainly due to differences in nitrate-N and, to a lesser extent, organic N concentrations, though the peak values are still less than 0.6 mg l^{-1} NO_3-N and 1 mg l^{-1} of total N. During the autumn of 1983, a massive flush of ammoniacal-N, with peaks in excess of 1.5 mg l^{-1} $NH4^+N$, were experienced at the outfalls of both catchments. Also observed were small, but significant, flushes of nitrate-N and organic N.

Nitrogen concentrations at the 3 sampling points within the Cwm catchment were very similar prior to autumn 1984. However, at this time and up to the present, ammoniacal-N concentrations in the upper basin (see Figure 1) have been much higher, with a peak value of 1.6 mg l^{-1} NH_4^+N, than those in the lower basin which, in turn, are higher than those at the outfall (see Figure 3). A similar, but much smaller, trend is also found for organic N. Nitrate-N concentrations, however, are consistently higher, but not to such an extent as ammoniacal-N, in the lower basin than at the outfall which, in turn, are higher than those in the upper basin.

In brief, therefore, what is being observed is a substantial release of ammoniacal-N in the upper basin following the autumn of 1984. This release is then manifest as nitrate-N lower down the basin, though it is obvious that total nitrogen concentrations are less in the lower basin, possibly due to denitrification effects or dilution. If the latter, it will be interesting to observe what effects, if any, will be identified following planting of the lower reaches.

Ortho-phosphate and organic phosphorus concentrations at the outfalls of the 2 catchments are usually below the limit of detection.

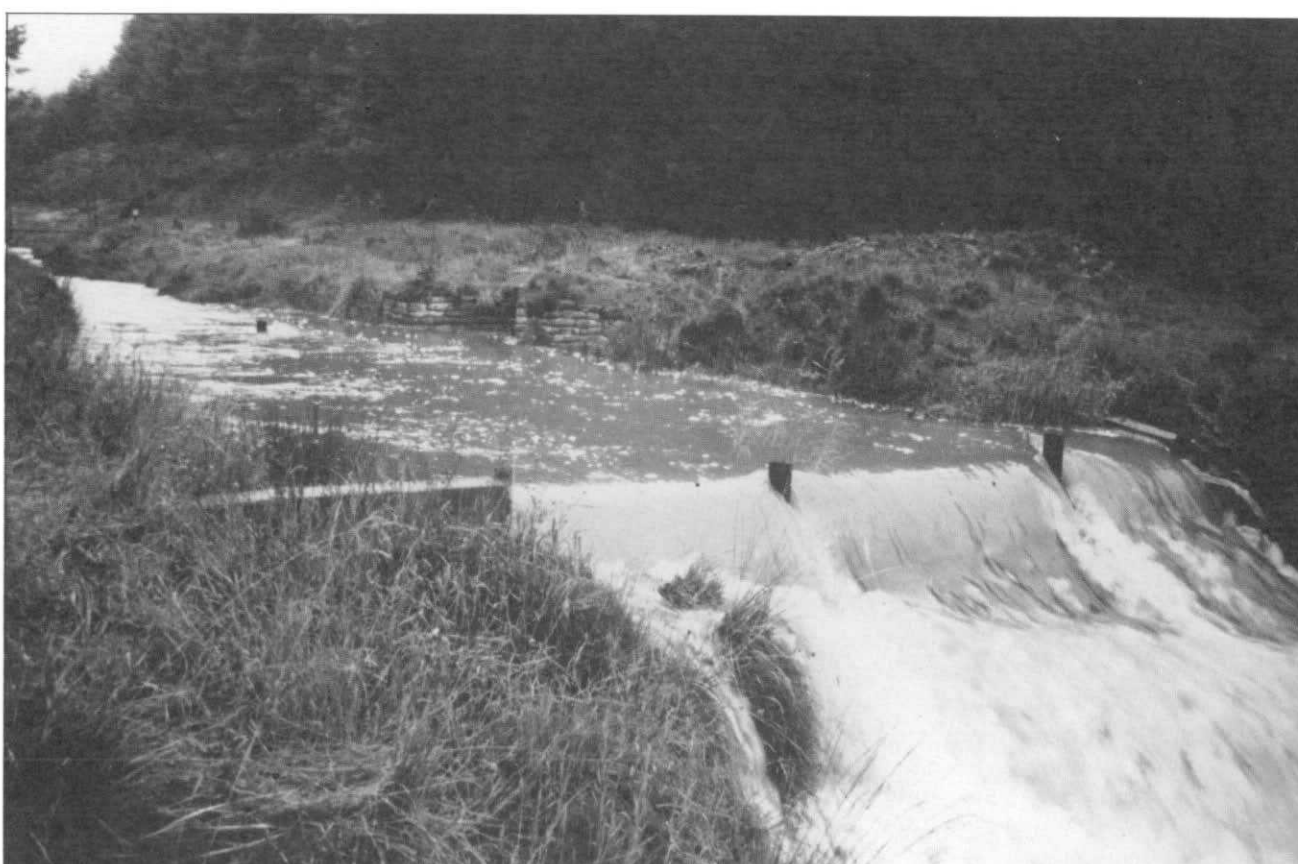


Plate 2. A bed-load trap in the forested Hore subcatchment at Plynlimon during a flood event (Photograph G J L Leeks)

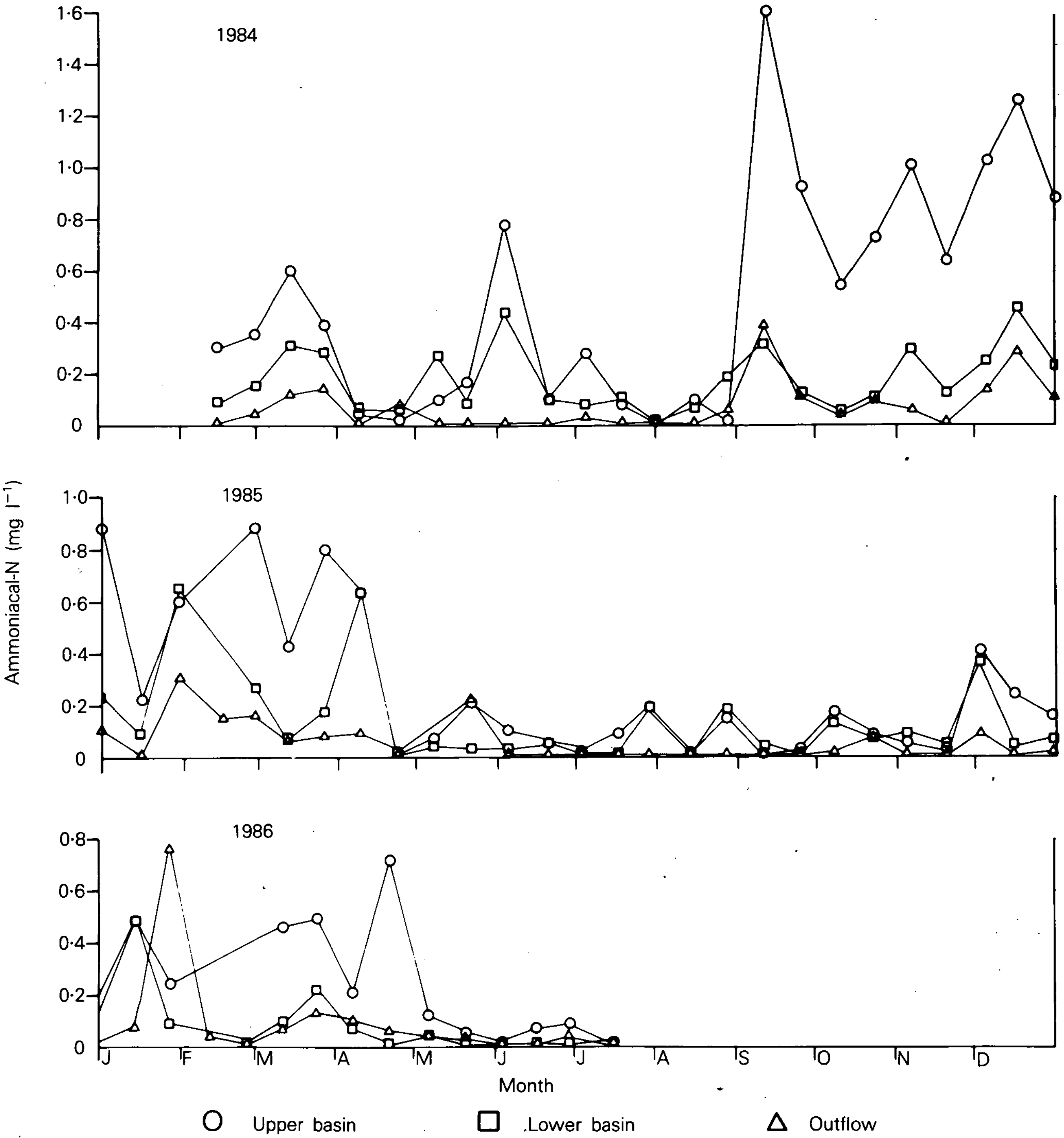


Figure 3. Ammoniacal-N concentrations at various points in the Afon Cwm catchment

Although some occasional high values have been observed, there is no consistent difference in the concentrations in the 2 streamflows. On the other hand, ortho-phosphate and, to a lesser extent, organic phosphorus concentrations have been consistently higher in the upper basin compared to the lower basin or the outfall of the Cwm catchment since the spot sampling began in February 1984. It remains to be seen whether these relatively high concentrations (peak of 0.44 mg l^{-1} ortho-P) will be manifest at the outfall of the catchment.

Potassium concentrations have generally been higher at the outfall of the Delyn catchment compared with the Cwm, although during 1986 the reverse is true. This pattern is confirmed by the results from the spot sampling within the Cwm catchment, which shows higher concentrations at all 3 sampling points in 1986 compared with 1984 and 1985.

Of the other determinands, higher concentrations of silica are found at the outfall of the Delyn compared with the Cwm, whilst the reverse is true for organic carbon. Conductivity and pH are higher in the Delyn.

For the spot sampling in the Cwm, organic carbon is much higher in the upper than in the lower basin, whilst the pH increases in a downstream direction.

In brief, an initial appraisal of the chemical data suggests that the afforestation is affecting concentrations within the upper basin of the Cwm catchment. With the possible exception of potassium, the increases have not yet been observed in the lower basin or at the outfall of the catchment. However, the currently observed increases in concentration within the upper basin do not constitute a problem for water supply purposes, though the ortho-phosphate concentrations may pose a threat as they are well above the value generally regarded as limiting for eutrophication.

No results are available from long-term studies of the effects of the planting and subsequent growth of young saplings on water chemistry.

6.2 Mature forest cover
Reliable chemical budgets for mature forest stands are few in number for British forests. Comparisons of nutrient concentrations in streamflows from land under rough pasture and established forestry at Plynlimon show very low concentrations and only minor differences between the 2 land uses (Roberts *et al.* 1983).

6.3 Felling phase
The part of the forestry rotation that has received the greatest attention, in terms of water quality, has been the clearfelling of established forestry. This emphasis follows the study at Hubbard Brook, in the White Mountains of New Hampshire (Likens *et al.* 1970), which showed a massive deterioration in water quality following the clearfelling of a 15.6 ha watershed. Nitrate-N losses of 104 kg ha^{-1} and 147 kg ha^{-1} were recorded, respectively, in the first and second year following felling. These figures compare with estimated losses of 1.3 kg ha^{-1} and 2.8 kg ha^{-1} from an undisturbed catchment. Post-felling nitrate-N concentrations in the streamflow exceeded for 2 years, almost continuously, the level of 11.3 mg l^{-1} recommended by the World Health Organisation for drinking water. Similar massive increases were found in the concentrations of other ions, notably potassium. Although this experiment was quite unlike a normal timber harvest (as all the cut timber was left on the catchment and vegetation regrowth suppressed by herbicides for 3 successive summers), nevertheless it did demonstrate potential losses and provoked a fear that conventional felling practices would result in similar rises in ionic concentration.

Since then, many studies, mostly in the USA, have been reported in the literature. These studies, as well as calculating nutrient losses from conventional felling techniques, have also looked at alternative harvesting and post-harvesting practices, which include logging road location and management, clear- and strip-felling, use of skyline cable systems, whole- or part-tree harvesting, slash burning and stream edge protection strips. Many study reviews have been given, including Sopper (1975), Stone *et al.* (1978) and Martin *et al.* (1984). The studies report a wide range of results reflecting the techniques adopted and showing the benefits of using various protection practices during felling operations. For example, O'Loughlin *et al.* (1980) found much smaller nitrate-N losses from a felled catchment where a riparian protection zone of intact forest nominally 20 m wide was left on each side of the stream. Similarly, Brown *et al.* (1973) demonstrated the benefits of patch-cutting as opposed to clearfelling. On the other hand, Neary *et al.* (1978) found higher concentrations of potassium in water draining a cut and burnt watershed in New Zealand than had previously been reported in the literature. The increase was attributed to the fact that most of the slash accumulated close to the stream. This material was burnt and converted to potassium-rich ash which was then leached into the stream by 2 subsequent storms.

In the Hore study, spot and composite samples have been taken at each site, with rainfall sampling at the head of the main Severn catchment. The only significant trend in the chemical data which has been observed to date has been in the nitrate-N and, to a much lesser extent, the potassium concentrations. Whereas samples collected during 1979-80 from the 3 sampling points gave very similar values (Roberts *et al.* 1983), nitrate-N concentrations from samples taken during this present study were significantly different. This difference was evident during the periods September 1983–February 1984 and September 1984–December 1984 when nitrate-N concentrations were consistently in the order Hafren>Hore>Upper Hore (see Figure 4), presumably as a result of prior thinning and felling practices. The differences were not large, however, with peak values less than 0.5 mg l^{-1} NO_3-N. Since then, a great deal of variation between the 3 sampling points is apparent, though no consistent trend can be observed. It seems, therefore, that to date there has been no increase in nutrient losses as a result of the clearfelling that has taken place since July 1985.

7 Sediment
7.1 Afforestation
In terms of water quality, the biggest effect of afforestation and its associated practices has been an increase in sediment losses and, again, drainage has been implicated as the main cause. Robinson and Blyth (1982) found that the pre-afforestation drainage of the Coalburn catchment referred to earlier increased sediment concentrations by over 2 orders of magnitude. It was calculated that the sediment yields over the following 5 years were equivalent to nearly half a century's load at pre-drainage rates. Subsequent sediment yields did not decline to pre-drainage levels, but remained about 4 times higher, as a result of the erosion of the drains. Most of the sediment, accounting for more than 99% of the total load, was in suspended form. There was no change in sediment concentration when the trees were planted. Burt *et al.*

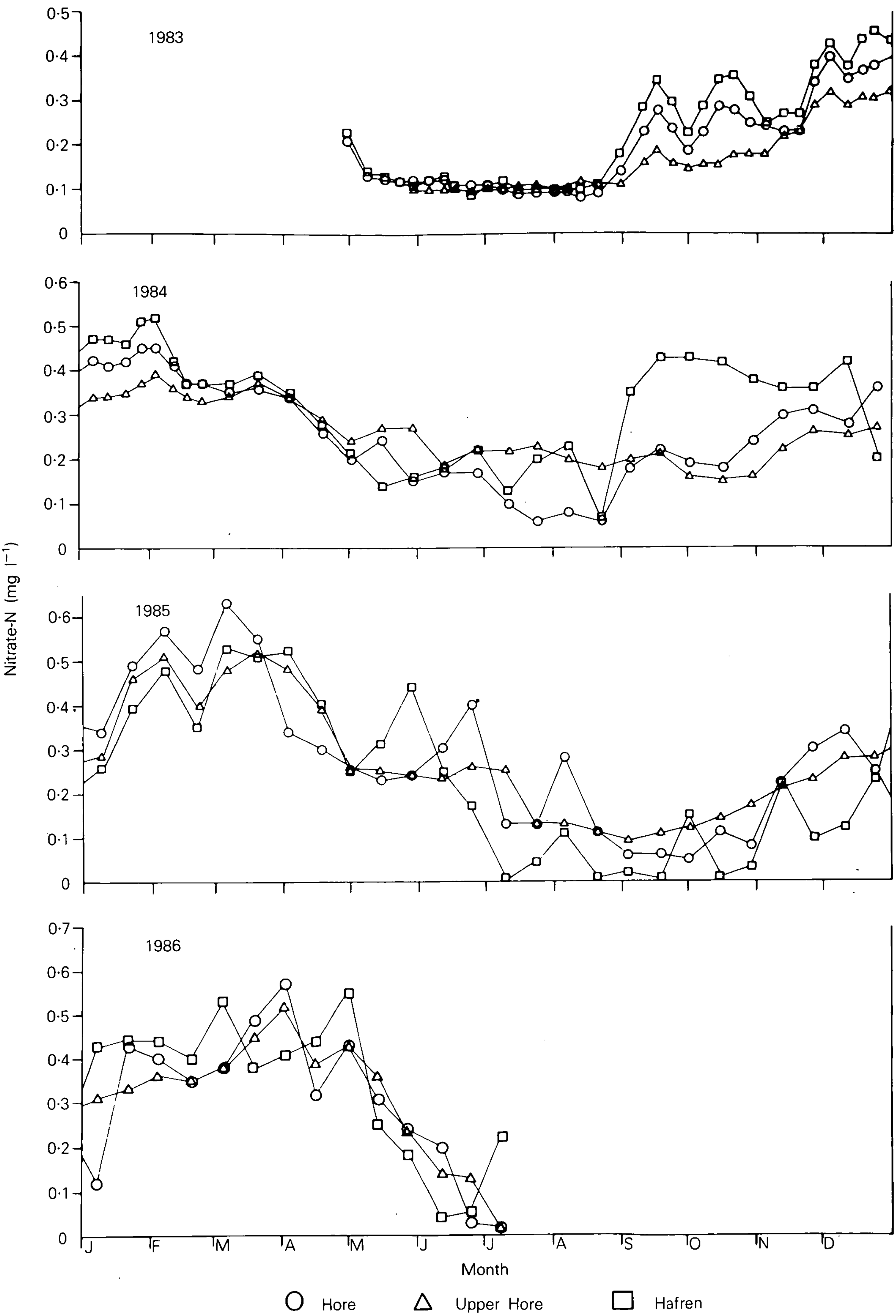


Figure 4. Nitrate-N concentrations in streamflows within the Hafren Forest

(1984) reported large suspended sediment yields following the open ditching of 2 small upland catchments for afforestation above Holmestyles Reservoir in the southern Pennines. These yields caused a major pollution problem at the reservoir, and a new treatment works had to be constructed to provide potable water (Austin & Brown 1982). Similar problems were caused for the water industry by the ploughing of 11.5% of the land in the Cray Reservoir catchment in south Wales for forestry in 1981 (Stretton 1984), and resulted in serious pollution incidents in 1982, involving discoloration and high turbidity of water treated for public supply.

In the IH Llanbrynmair catchments study, the land practices associated with the afforestation of the Afon Cwm have led to the mobilization of sediment from previously stable areas of the catchment. This increase in sediment availability has, in turn, led to increased sediment transport and yields.

In addition to natural erosion scars and stream banks, a number of new sediment sources have become active. The dense drain network in the upper basin has been subject to varying degrees of erosion. As might be anticipated, steep downslope drains and 2nd order drains appear to be most affected. The enhanced sediment load transported through the upper basin channel is demonstrated by in-channel shoals, blockages and over-bank deposits composed mainly of gravel-sized material.

Contour ploughing has reduced the initial outputs of fine sediment from the lower parts of the catchment to the stream channel (see Plate 3). However, road cutting has made a considerable amount of gravel material available to the stream from areas which were previously covered by thin, but relatively stable, soil and grasses. Loose gravels, exposed on steep road embankments, are readily transported by gravity and gully erosion into the stream channel (see Plate 4).

The annual bed-load yields and typical size analyses are shown in Figure 5. Bed-load yields will vary in accordance with a variety of factors, some of which do not relate directly to land use. For example, during the early parts of this study, an unusually high snowmelt flood led to high bed-load yields. This flood yielded sufficient sediment to overtop the weirs in both catchments (see Plate 5). Therefore, the bed-load trapped behind the weirs represented only the minimum values for yield.

The Delyn is relatively steep, with coarse sediment supply in the lower basin and finer gravel screes higher up. These screes contribute sediment directly to the stream channel. As a result, the Delyn bed-load yields are high relative to other mid-Wales grassland catch-

Plate 3. High outputs of fine sediment following drain excavation have been prevented by contour ploughing in the lower parts of the Afon Cwm catchment (Photograph G J L Leeks)

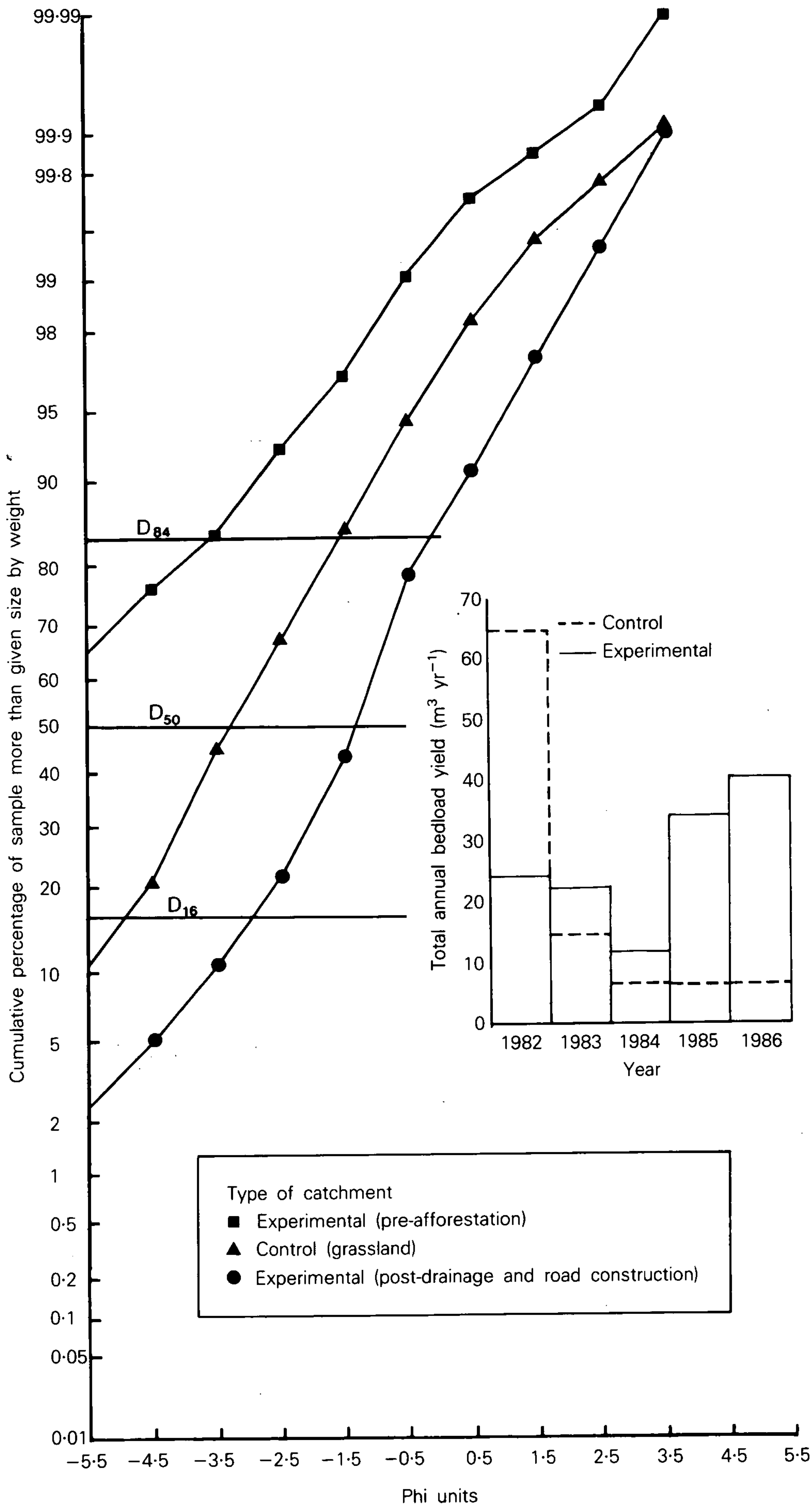


Figure 5. Bed-load size analysis and yields at Llanbrynmair experimental catchments

Plate 4. Loose gravels, exposed on steep road embankments, are readily transported by gravity and gully erosion into the stream channel. Afon Cwm catchment, Llanbrynmair (Photograph G J L Leeks)

ments, and throughout the pre-afforestation period yields are higher per unit catchment area than those from the Afon Cwm. Hence, in terms of the river sediment study, the Delyn yields cannot be regarded as representative of an ideal 'control' catchment.

The size analyses of the bed-load sediments also reveal a contrast between the 2 catchments before the afforestation. The size distributions of the Delyn bed-load tend to be finer than the Afon Cwm pre-afforestation samples (typical samples are shown in Figure 5). The most probable reason for this difference is again the supply of gravel from screes to the Delyn.

Despite the reservations expressed above with regard to the relative bed-load transport response of the 2 catchments, the data collected over the last 5 years do exhibit a number of interesting trends which can be related to land use change. In 1983 and 1984, yields were higher from the Afon Cwm. However, if the catchment areas are taken into account, the yield per square kilometre remains higher in the Delyn. Subsequent to road construction in the lower Afon Cwm catchment during 1984, there was a considerable rise in bed-load yield at the Cwm weir from the beginning of 1985. The supply of loose gravel from road cuttings and embankments is also indicated in the size distribution of bed-load from post-afforestation flood events, with an overall decrease in sediment size yield.

The results for 1986 show no sign of a decrease in yields from the Afon Cwm, and many sediment sources are still undergoing active erosion.

With regard to suspended sediment load, concentrations from 0.001 g l^{-1} up to 0.100 g l^{-1} have been measured at the Afon Cwm weir during natural flows.

These levels have been exceeded during short-lived pulses of sediment following machinery moving through the river (ie up to 0.380 g l^{-1}). However, the overall concentrations do not appear excessive relative to other mid-Wales rivers.

7.2 Mature forest cover

The long-term effects of open ditches have been demonstrated at Plynlimon. Yields of bed-load from sediment traps suggest that mature forested subcatchments are still yielding 3–5 times the volume of bed-load discharged from grassland subcatchments (Newson 1980b; Arkell *et al.* 1983). Similar ratios have been found between drained and undrained areas at Lake Vyrnwy, Nant-y-Moch and the Clywedog Reservoir. Forested streams may also experience increased stream bank erosion, as observed by Murgatroyd and Ternan (1983) in Narrator Brook at the south-western margin of Dartmoor. Bank erosion rates were observed to be higher along forested reaches relative to non-forested. This increased erosion was attributed to suppression by the forest cover of the development of thick grass turf and its associated dense root networks and, secondly, to the river attempting to

Plate 5. Flood events can result in considerable transport of bed-load sediments. Emptying trapped bed-load sediment from the Crump weir at the lower end of the Afon Cwm, Llanbrynmair (Photograph G J L Leeks)

by-pass log jams and debris dams in the stream channel.

The erosion of forestry roads has also been implicated in causing increased streamflow sediment loads (Mills 1980; Graesser 1979), though quantitative evidence is lacking, particularly in upland Britain. However, research carried out in the United States of America (see, for example, Swanson *et al.* 1982) has quantified losses from forestry roads and has identified factors such as means of construction, gradient, maintenance and traffic intensity as being important in determining the magnitude of the increased sediment losses.

The increased outputs of sediment from the uplands may also affect river stability in downstream reaches, as suggested in a regional study of mid-Wales rivers by Newson and Leeks (1987).

7.3 Felling phase

An extensive network of instrumentation has been installed in the Hore catchment. This network is designed to provide a range of data, from overall total sediment yields for whole subcatchments using bed-load traps, down to continuous records of suspended-load discharges, derived from the use of absorptiometric turbidity meters (Thorn & Burt 1975; HMSO 1981) and depth-integrated bulk samplers (Guy & Norman 1970; Leeks 1983). In addition to yield calculations, these data are being used to investigate thresholds in sediment movement and any change in such thresholds and sediment availability as a result of practices associated with tree harvesting.

Although the felling operation is still in progress and many data remain to be analysed, some preliminary results are worthy of mention. The suspended sediment concentrations, derived from vacuum filtration of bulk samples, have been regressed on water discharge to produce a rating curve for the Hore (see Figure 6). This curve can be combined with flow duration data to calculate average annual suspended sediment yields. The yields (shown in Table 1) are also divided by catchment area in square kilometres to permit comparison between the different sizes of catchment.

It is evident from Figure 6 that there is a considerable spread in the relationship between concentration and discharge. This spread is typical of many upland channels and contrasts with published rating curves for many lowland rivers. During the felling operations, there has been a significant increase in the suspended sediment yields of the Hore. Regression lines of concentration *vs* water discharge show higher concentrations for most discharges in comparison with pre-felling samples. The rating curves indicate an increase in concentration by up to an order of magnitude for moderate to high flows. This increase, in turn, is reflected in higher annual yields of suspended sediment (see Table 1), from 24.4 tonnes km^{-2} yr^{-1} up to 57.1 tonnes km^{-2} yr^{-1}.

Table 1. Average annual bed-load and suspended load yields in forested and unforested catchments in mid-Wales. The figures for the Hore catchment indicate the effect of felling operations on suspended load

Catchment	Area (km^2)	Bed-load yield (t km^{-2} yr^{-1})	Suspended load (t km^{-2} yr^{-1})	Land use
Hore	3.08	11.8	24.4 (57.1)	Mature forest (First year of felling operations)
Hafren	3.67	NA	35.3	Mature forest
Tanllwyth	0.89	38.4	12.1	Mature forest
Cyff	3.13	6.4	6.1	Pasture

NA-not available

In the case of bed-load, the catches have been accumulated, and then divided by the period of measurement in years and catchment size to facilitate similar comparisons between the yields of different catchments. Before the felling operation, the Hore catchment was discharging fairly low yields of bed-load relative to other nearby forested catchments (see Table 1). However, since the felling operations began, bed-load yield has increased 5-fold at the downstream end of the catchment. In addition, a network of traps on drains and small tributary streams is also being monitored. Following the felling and removal of trees using skidding techniques in one tributary, annual yield of bed-load increased from 1.2 m^3 km^{-2} yr^{-1} during 1983 up to 23.4 m^3 km^{-2} yr^{-1} during 1984. However, as felling continued, tree debris build-up in the channel has led to a decrease in annual yield to 5 m^3 km^{-2} yr^{-1}. It would therefore appear that, in the short term at least, leaving tree debris within the channel may have benefits in reducing bed-load discharge peaks.

It is to be expected that the bed-load response to the felling operations would be much slower than the suspended load, because bed-load tends to move gradually downstream through a number of within-channel stores. In the case of suspended sediment (mostly of clay, silt and fine sand grades), once entrainment has occurred much of the material is transported out of the uplands and into lowland alluvial sections of the river. The main 'wave' of bed-load transport may, therefore, still be upstream of the lower Hore flume.

7.4 Reduction of forested catchment sediment outputs

A number of guidelines to reduce the sediment yields from forests are listed below. These guidelines are based upon the Institute of Hydrology catchment studies, other authors and observed good forest practice.

i. The most appropriate time to plough is spring and early summer as some revegetation is possible,

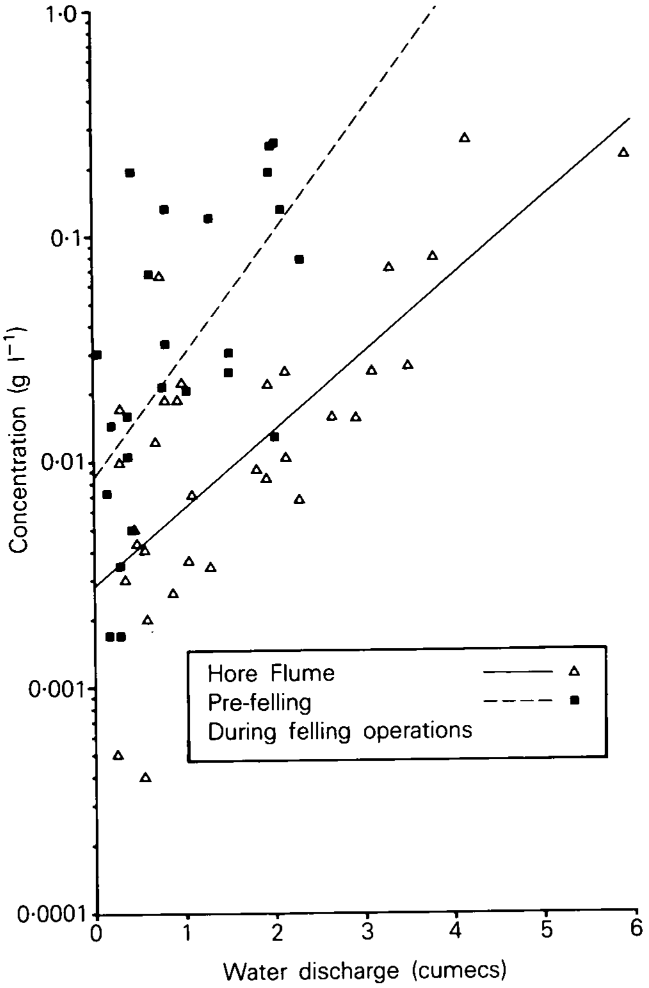


Figure 6. Suspended sediments rating curves for the Afon Hore subcatchment, Plynlimon

thereby reducing the likely suspended sediment outputs over the following year (Burt *et al.* 1984).

ii. When possible, contour ploughing may reduce initial sediment losses. The use of ripping techniques also shows promise.

iii. When excavating ditches through highly erodable materials, gradients of less than 2° are desirable to prevent scour (Newson 1980b).

iv. New forest ditches should be stopped short of the stream channel. Thompson (1979) makes a similar suggestion with regard to lakes and reservoirs. Drains which have suffered erosion during the first rotation could be modified for the second rotation by blocking off outlets to streams or dispersal of flow along new-cross drains. This practice might also be worthwhile during the first rotation, as significant erosion can persist in a drain for several decades unless remedial action is taken.

v. Following felling operations, it is usually considered desirable to clear drains of debris. However, while major blockages are not apparent, small debris dams can reduce peak sediment outputs and therefore reduce the downstream effects of felling operations. In such cases, some delay in drain clearance may be advantageous.

vi. The output of road drains directly into streams should be avoided.

vii. The erodability of road embankments in close proximity to streams can be reduced by protecting the toe with boulder-sized material or gabion baskets.

viii. The quick repair of road embankments in which incipient gullying is discovered near streams, with plastic netting or similar stabilizing material, is worthwhile.

ix. The movement of machinery through streams should be minimized, eg by detours to road bridges, whenever possible.

8 Conclusions from current work

It should be emphasized that the results of the afforestation and felling experiments reported in this paper are preliminary. The felling operations in the Hore have enhanced sediment yields, which were already higher than in comparable grassland catchments. However, to date no consistent trend has been apparent in data on nutrient losses.

In the Cwm, afforestation has led to a rise in chemical concentrations, mainly in the upper basin (notably in ammoniacal-N, ortho-phosphate and potassium). Road construction and drain erosion have led to continuing increases in bed-load yields. The adoption of contour ploughing techniques in the lower basin has effectively reduced the rise in suspended load often associated with open ditching.

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