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Dynamics of river sediments in forested headwater streams: Plynlimon

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Abstract

Long term studies of fluvial sediment processes in the Plynlimon catchments have contributed to the assessment and quantification of plantation forestry impacts in British upland catchments, at all stages of the forest cycle. The results from the Plynlimon studies are placed in the context of the observed impacts of particular forest practices and studies of forestry effects on sediment transport elsewhere in the world. The effects associated with drain excavation, ploughing, track construction, ground and channel disruption are outlined for both bedload and, particularly, for suspended load.

Finally, recent data on sediment yields from 1995 to 1997 at Plynlimon are reported and discussed in the light of longer-term sediment yield estimates. This paper also provides background information relevant to other sediment process studies which use data from the main Plynlimon sediment monitoring network.

Introduction

Where land use practice causes direct mechanical disturbance of easily erodible soils, a common consequence is soil erosion. At the world-scale, British upland soils are very stable (Newson 1980). However, where surface vegetation and soils are disrupted, as is commonly the case during forestry operations, there is the potential to mobilise large quantities of material. This can be significant in the upland areas of Great Britain where superficial deposits of weakly-cohesive glacial and fluvio-glacial deposits remain from the Pleistocene period. Once material is mobilised, plough furrows, drains, ditches and steep slopes leading down to river headwater channels, can facilitate the delivery of sediment to water courses and increase rates of sediment transport. Long-term studies of fluvial sediment processes in the Plynlimon catchments have contributed to the assessment and quantification of these impacts. Reviews by Maitland *et al.* (1990), Moffat (1988) and Soutar (1989) indicate that particulate inputs to fresh waters can be an important impact of British forestry practice. This has been widely recognised by forestry operators, conservationists and the water industry.

Due to the extensive planting that occurred during the twenty years after the Second World War, many British forests are now reaching the felling stage. Total wood production in Great Britain (conifers and broadleaves) was 8, 630, 000 m^3 in 1996, and is expected almost to double over the following two decades (Forestry Commission, 1997).

This paper places the results from the Plynlimon studies in the context of particular forest practices and of studies of forestry effects on sediment transport elsewhere in the world. Recent data on sediment yields from 1995 to 1997 at Plynlimon are also reported and discussed. This provides background information to other sediment process studies in this volume (Lawler *et al.*, 1997, Marks and Rutt 1997 and Collins *et al.* 1997).

Enhanced sediment delivery to fluvial systems has been associated with all stages of the forest rotation (Newson and Leeks, 1987; Soutar, 1989; Leeks, 1992). Although this can include fine and coarse material, and both size fractions are monitored at Plynlimon, the majority of research on physical sediment pollution has been undertaken on the impacts of fine material outputs. However, changes in coarse sediment inputs can cause channel instability, resulting in geomorphological change which may also, in turn, affect the channel biota (Marks and Rutt, 1997).

Fluvial particulate inputs associated with forestry

Most of the British work on fluvial sediment dynamics in forested catchments has been concentrated upon the afforestation and mature forest stages of forest development. Research on these phases is relevant to sediment dynamics during felling; firstly, it provides the baseline data by which to judge the impacts of felling; secondly, some of the forestry practices carried out during the felling phase are also common to other stages. For example, track construction or modification occurs during both afforestation and felling.

The enhanced throughputs of fluvial sediment during forestry operations tend to be associated with one or more of the following activities:

a) Construction and erosion of plough furrows and drains.
b) Track and road construction or modification.
c) Mechanical disturbance of the catchment surface.
d) Mechanical disruption of stream channel bed and bank.
e) Inappropriate management of wood debris within the river channel.

These activities may occur at a number of stages during the forest rotation. They are, however, most apparent during the afforestation and harvesting phases. As they tend to take place simultaneously, it is difficult to determine their individual impacts on downstream particulate loads. Some examples of these effects reported in the literature are detailed below. The impacts of particulate outputs on the ecology of freshwater ecosystems is reviewed in Marks and Rutt (1997).

PLOUGH FURROWS AND DRAINS

The main focus of concern in British studies of the impacts of forestry on the sediment loads of rivers and reservoirs has been the ploughing and drain construction during the afforestation stage (eg. Burt *et al.*, 1984). Increased particulate outputs have been reported, associated with the construction and erosion of plough furrows and drains.

Research by IH at Coalburn, Balquhidder and Plynlimon, however, has indicated that, although the large increase in fluvial particulates does diminish with time following the construction of plough furrows and drains (Robinson, 1980; Newson, 1980; Leeks and Roberts, 1987), concentrations remain well above pre-afforestation levels. For example, at Plynlimon, a comparison of mature forested catchments with mature grassland catchments has found 3–6 times higher annual suspended and bed-load yields per unit catchment area from forests. Therefore, drain erosion persists throughout the forest rotation. If erosion and catchment sediment yields in forests are to be reduced to similar levels to those observed in adjacent grassland catchments, some modification of the existing drain networks is required.

TRACKS AND ROADS

Arnold Arnold *et al.* (1975) state that 'of all the silvicultural activities, logging roads are the principal source of man-caused sediment.' New tracks may be constructed or old tracks modified during the felling phase. Results from the IH Balquhidder experimental catchments in upland Scotland linked forest road erosion to vehicle use (Johnson and Bronsdon, 1995). In a previous study of the effects of forestry on suspended sediment and bed-load yields in Balquhidder streams, Ferguson and Stott (1987) concluded that the main sediment sources were timber loading areas and logging roads.

The afforestation of the Cwm catchment, Llanbrynmair, near Plynlimon, provided an opportunity to monitor fluvial bed-load inputs associated with new track construction (Leeks and Roberts, 1987). The Cwm experimental catchment was 1.2 km^2 in area. A nearby control catchment, which remained as rough grassland, was also monitored. For 4 years, following track construction in 1986, yields remained at a uniformly low level in the control catchment, while gradually increasing in the Cwm. The principal source of the enhanced bed-load was one site on a track which had to be constructed from the bottom of the catchment to give access to higher parts of the afforested area. At a point where the track traversed the main channel, large amounts of loose gravel were eroded from an embankment and delivered to the stream via gullies. Peak bed-load yields occurred 3–4 years after track construction. Consequently, the particulate yield from this catchment was effectively doubled as a result of man-induced inputs from just one point source. A less common example of enhanced fluvial particulate levels associated with forest road construction, however, is provided by the occasional use of explosives. The blasting of foundations for new road crossings can lead to waves of sediments moving downstream in suspension, associated with both channel disruption and fine materials deposited in the river after being blown into the atmosphere (Leeks 1986).

A further example of the potential impact of forest road construction on the acceleration of erosion, and therefore of the input of particulates to watercourses, is represented by the construction of an unmetalled road at Glen Ogle in the Scottish Highlands (Duck, 1985), where particulate inputs to the Ogle Burn, one of the main influents to Loch Earn, increased by an order of magnitude; at least 1824 tonnes of sediment were deposited over an area of 4.6 ha of loch bed in less than two months. This was over 20 times as much material by weight as had passed a temporary gauging station, near the confluence with the loch, during an earlier 12 month monitoring period. It was estimated that the mean thickness of the resultant deposit would, without the road construction, have taken some 20–25 years to accumulate.

To facilitate the intensive use of modern articulated vehicles and felling machinery during contemporary timber harvesting operations, it is also common practice in British forests to modify old tracks to improve their accessibility, and to construct timber stacking areas, turning, processing and loading bays. At the beginning of the felling operation in the Hore catchment at Plynlimon, roads were widened and turning and loading bays created. As the material mobilised by these activities was carried directly to the stream network via road drains, Leeks

(1992) observed immediate increases in suspended sediment concentrations at all rates of discharge. Similarly, results from sediment monitoring during timber harvesting at Balquhidder indicated a 20% increase in suspended sediment yield following the construction of a timber loading bay (Ferguson *et al.*, 1987).

The renewal or clearance of road drains and culverts can also lead to large increases in suspended sediment concentrations. Leeks (1992) attributed concentrations approaching 200 mg/l, during periods of low discharge, to drain clearance in the Hore catchment prior to clearfelling.

Studies in the U.S.A. have also attributed high fluvial particulate levels to forest track and road construction or modification. For example, the effects of forest roads built during the summer of 1967 in the Caspar Creek watersheds, northern California, were monitored between 1967 and 1971 by Krammes and Burns (1973); the suspended sediment yields during the first winter were more than four times the preconstruction levels. Consequently, the United States Department of Agriculture recognised that forest roads represent one of the major sources of fluvial particulate inputs from afforested areas (Swift, 1988).

Fluvial particulate inputs should therefore be considered when assessing the suitability of all roads and tracks for harvesting operations. Borg *et al.* (1988) stated that 'if possible, tracks should be adequately drained and located away from watercourses.' More detailed guidelines on forest road design and construction have resulted from the research conducted by the Coweeta Hydrologic Laboratory, United States Department of Agriculture Forest Service (Swift, 1984a; 1984b; 1985; 1988).

MECHANICAL DISTURBANCE OF THE CATCHMENT SURFACE

Mechanical disturbance of the catchment surface is apparent mainly during the harvesting phase of the forest rotation, when the use of heavy plant to remove trees often makes the soil surface more vulnerable to erosion. For example, the 'wheelings' produced by the movement of felling machinery provide flow pathways which concentrate the flow of water, which in turn encourages the entrainment and rapid conveyance of sediment to watercourses.

A previous example of this effect came from the Hore clearfell experiment in the IH Plynlimon experimental catchments. From 1983 the Hore subcatchment was instrumented extensively to provide background sediment transport data for the two years leading up to clearfelling, and to identify post-felling impacts. Considerable ground disruption by machinery during the felling work, including forwarders and skidders, made large amounts of material available to the streams. Rating curves were plotted of suspended sediment concentration against discharge for the pre-felling period and for the first two years of the felling operation; sediment concentrations increased by an order of magnitude for moderate to high flows. Hence, annual total catchment yields of suspended sediment rose from 24.4 t km^{-2} pre-felling to 141.0 t km^{-2} in 1986. Volumes of bed-load were also calculated; these increased twenty-fold in a recently felled ditch system, but recovered to a four-fold increase after log and debris jams formed across the channel (Leeks and Roberts, 1987).

In Great Britain, notwithstanding the substantial success of minimum disturbance harvesting techniques, such as cable crane extraction or skylining (Maitland *et al.*, 1990), it is important to recognise that these low-impact techniques also demand a higher level of road construction and improvement, the effects of which were discussed above. However, on an international scale, cable logging is likely to encourage surface erosion, leading to particulate inputs to watercourses and a degradation in water quality. For example, Ursic (1991) monitored the hydrological effects of harvesting mature pine by cable logging in north Mississippi, U.S.A; suspended sediment concentrations in felled catchment watercourses were three and 50 times greater than those observed in an adjacent control catchment during the first and second year after harvesting respectively. There is, however, little evidence for this effect in British upland forestry. The evidence from Plynlimon is that when aerial cable techniques are used, as in 1980–81 (Leeks and Roberts 1987), the removal of tree cover did not, in itself, enhance sediment loads in headwater streams. This suggests that post-felling soil exposure is not as significant in British forests, indicating that it is the mechanical disturbance of the catchment surface which is the dominant cause of fluvial particulate inputs associated with timber harvesting. Most British commercial forests were planted from the 1930s onwards, before which, although vegetated, soils had been unafforested, and therefore more exposed to rainfall, than the soils of natural forests which have been protected from rain impacts and ground surface flow by canopy interception. On an international scale, however, there are many examples of surface erosion associated solely with the removal of natural tree cover. In such cases exposure of the bare unconsolidated soil surface leads to increased erosion through rain-drop impact processes, resulting in an increase in fluvial particulate inputs by up to three orders of magnitude.

MECHANICAL DISRUPTION OF STREAM CHANNEL BED AND BANK

Although it has rarely been quantified, the unbridged crossing of streams by heavy plant can result in considerable particulate mobilisation. Leeks and Roberts (1987) noted suspended sediment concentrations of up to 380 mg l^{-1} in Mid-Wales following heavy plant movements through a stream under low flow conditions, when pre-plant crossing background levels would have been below 1 mg l^{-1}. It is recommended in all three editions of Forests and Water Guidelines, that machines should not be allowed to work in streams (Forestry Authority, 1993; Forestry Commission, 1988, 1991).

Research in the U.S.A. has also identified the mechanical disruption of stream channel bed and bank as a significant source of particulate inputs to watercourses during forestry operations. Consequently, Ursic (1991) reported that the importance of maintaining the integrity of channels cannot be overemphasized, and stated that forestry machinery should be prevented from working in stream channels.

WOOD DEBRIS IN CHANNELS

In the U.K., new interest in the use of 'dead' wood for environmentally sensitive engineering approaches to river management (Brookes, 1988) has led to new research on the links between channel dynamics and vegetation (Gurnell and Gregory 1987, Gregory, 1992). The majority of research results refer to coarse woody debris (CWD). This is likely to be associated with any timber harvesting activity within a catchment, and may influence the impact of fluvial particulate inputs associated with such operations.

Accumulations of CWD can have major geomorphological effects through its influence on the storage and transport of particulates and organic matter, channel form and stability (Gregory *et al.*, 1994).

In-channel storage provides a buffer, reducing the impacts of any episodic particulate inputs and regulating their transmission downstream. The role of CWD in particulate storage is illustrated by Gregory *et al.* (1994). Keller and Tally (1979) identified two creeks in the U.S.A. where storage zones, controlled by CWD accumulations, each accounted for 30% and 40% of the channel area. Megahan (1982), cited in Bilby (1985), estimated that 49% of the total particulates were associated with CWD in seven catchments in Idaho, U.S.A. Keller and Swanson (1979) noted the importance of mid-channel bars downstream of debris-controlled plunge pools as sites of in-channel storage on low-gradient, meandering streams; whereas on steep-gradient streams, the stepped long-profile reflects particulate accumulations upstream of debris dams.

Mosley (1981) identified the importance of debris-dam collapse in governing the transfer of particulates downstream and emphasised that such collapse is associated only with a small proportion of run-off events, and the material released moves only a short distance before being redeposited. Since woody debris provides abundant storage sites in forest streams, annual yields from small forested catchments are frequently less than 10% of the particulates stored (Sullivan *et al.*, 1987). However, if debris accumulations are removed, there are major increases in transport and yield, as material previously lodged behind debris rapidly comes out of storage (Gregory *et al.*, 1994). Hedin *et al.* (1988) noted a similar effect three years after deforestation, consequent upon the natural breakdown and removal of debris dams. It also plays an important role in woodland river ecology which has been reviewed by Gregory, Gurnell and Petts (1994).

There can, therefore, be no doubt that CWD has an important influence on the geomorphology and ecology of woodland river channels. Massive accumulations of debris can restrict the upstream migration of anadromous fish (Chapman, 1962; Beschta, 1979; Bilby, 1984). Bacterial decomposition of CWD may also reduce dissolved oxygen levels (Hall and Lantz, 1969). Furthermore, debris torrents (which in themselves can cause serious channel scour, thus having a negative impact on habitat), can follow the dislodgement of CWD accumulations by high flows (Swanson and Lienkamper, 1978; Everest and Meehan, 1981). Accumulations of CWD associated with timber harvesting play an important role in slowing the movement of particulates in drains and river channels which have been damaged by felling operations. For example, before clear felling, the Hore (Plynlimon) was yielding lower mean annual bed-load outputs per unit catchment area than the adjacent Tanllwyth forested catchment (11.8 t km^{-2} compared with 38.4 t km^{-2} respectively). The initial impact of the clearfell was a decline in bed-load trapped at the downstream end of the catchment (8.3 t km^{-2} in 1986) due to the build up of material behind timber debris within the channel and drains. However, as debris dams broke down or reached capacity, the bed-load yield rose gradually up to 54.5 t km^{-2} in 1988. Further up the catchment, the effects of timber debris build up were slightly delayed. In one tributary in which windblow problems caused the trees to be removed earlier than the rest (using skidding techniques), the yield increased from 2.16 t km^{-2} in 1983 to 44.28 t km^{-2} in 1984. However, as the felling continued, timber debris built up in the channel, thereby creating a number of debris dams and bed-load yield declined to 9 t km^{-2} in 1985. Hence, where there is no danger of stream diversion and additional erosion, there may be advantages in delaying or phasing channel clearance work to reduce peaks in enhanced bed-load outputs following felling.

Beschta (1979) stated that the removal of large logging and road construction debris that had accumulated since 1965 in the Mill Creek catchment area, Oregon, U.S.A. in 1975, accelerated the scouring of previously stored sediments leading to increased suspended sediment concentrations and turbidity. During the first winter after debris removal, streamflow eroded over 5000 m^3 of sediment along a 250 m reach of the stream. Similarly, Bilby (1984) reported large changes in channel structure during the first high flow after debris removal from a small stream in Washington, U.S.A. Channel cross-sections were altered substantially by the movement of stored sediment, and the number, area and volume of pools decreased. Everest and Meehan (1981), therefore, state that the total removal of debris can result in a completely open channel, promoting stream-bed scour, stream-bank instability and loss of fish habitat productivity. Such observations support the conclusion of Benke *et al.* (1985) who state that 'although there are certain situations that may require wood removal to eliminate stream blockage, the wisest management practice is usually no management.'

Impacts of particulate outputs from forestry upon water resources

The costs of sediment pollution problems in the UK have rarely been quantified. However, some examples of the impacts of enhanced sediment loads associated with afforestation upon water supply are available. Impacts on potable water resources can include increased treatment costs or damage to distribution systems (Marks, 1994) and accelerated deposition within downstream storage areas (Duck, 1985) which may affect reservoir operations. Elevated concentrations of suspended sediments in reservoir water may be costly to remove (Stott, 1989). In September 1980 the excavation of forest ditches above the Holmestyles Reservoir in the Pennines resulted in high suspended sediment inputs to the reservoir. Consequently, the turbidity of the water at the reservoir's treatment works, which supplied 10,000 people, increased from an average of 2 formazin turbidity units (FTU) to up to 1000 FTU (Austin and Brown, 1982; Burt *et al.*, 1984). Although the total suspended solids concentration was not measured, it is likely that this increase in turbidity was due to the suspension of particulates eroded from the forest ditches. A new treatment plant had to be installed at a capital cost of £143,000 and an additional running cost of £20,000 per annum (Edwards, 1986).

During the afforestation of the Cray Reservoir catchment in the Brecon Beacons, Wales, work involving road construction, land drainage and ploughing also led to a deterioration in the quality of the water supply. Because of the high quality of this resource, sophisticated treatment had been unnecessary previously. Following afforestation, which commenced in March 1981, a number of rainfall-related discolouration events were reported culminating in late September 1982, when persistent heavy rainfall resulted in turbidity measurements in excess of 4 nephelometric turbidity units (NTU) persisting for a period of 15 days, peaking at 11 NTU. Again, although the total suspended solids concentration was not measured, it is likely that this increase in turbidity was due to the input of suspended particulates eroded from the afforested area. Consumer concern was widespread and alternative supplies had to be obtained. In 18 months, costs to the Welsh Water Authority were reported to be over £45,000 plus a financial penalty of £319,000 as the construction of an already proposed new treatment works had to be brought forward in the capital programme (Stretton 1984, Forestry Commission, 1991).

Sediment yields and forestry at Plynlimon 1995–97

Past papers have described results from the Plynlimon sediment monitoring networks through to the early 1990s (eg. Newson, 1980 and Leeks, 1992). It is therefore timely to consider more recent yields in comparison with the longer term results. Long-term monitoring programmes present the opportunity to study the effects of a range of land-use management practices. Since records began in 1972, the sediment monitoring network within the Plynlimon Experimental Catchments has been intensified to enable detailed reach studies associated with specific phases of the forest rotation.

CURRENT PLYNLIMON SEDIMENT MONITORING STUDIES

From 1993 to 1997 the Institute of Hydrology has been undertaking research to quantify the influence of current timber harvesting operations upon fluvial particulate loads throughout England and Wales, and to investigate methods to prevent or ameliorate sediment pollution associated with future harvesting operations.

Figure 1 shows the major monitoring sites employed to investigate the impacts of particulate outputs associated with current plot-scale harvesting operations. Previous harvesting studies at Plynlimon were based upon relatively large harvesting areas. For example, the Afon Hore clearfell experiment (Leeks, 1992) involved the felling of 91 ha, comprising 29% of the total catchment area (Roberts and Crane, 1997). Current Forestry Commission harvesting policy favours the phased felling of smaller plots, normally in the region of 10–20 ha.

The harvesting plot selected for this study is detailed in Figure 2. This site consisted of three separate areas, each felled using a specific technique appropriate to the site conditions. The total area harvested was 13 ha, comprising 15% of the Nant Tanllwyth catchment. Felling took place during January–June 1996.

SUBCATCHMENT SEDIMENT YIELDS

Fig. 3 shows an example of the continuous suspended sediment concentration data collected by the Wallingford Integrated System for Environmental monitoring in Rivers (WISER) instrumentation (see Wass *et al.*, 1997) employed at all turbidity monitoring sites. The combination of total suspended sediment concentrations (SSC) time series with flow records in Fig. 3 illustrates the response of SSC to peaks in water discharge. This demonstrates the importance of discharge in controlling suspended sediment concentration and, in turn, transport. Flux estimates are based upon the 15 minute data for water discharge and calibrated SSC. Rating curves for 1995, 1996 and 1997 for the main turbidity monitoring and flow gauging sites are shown in

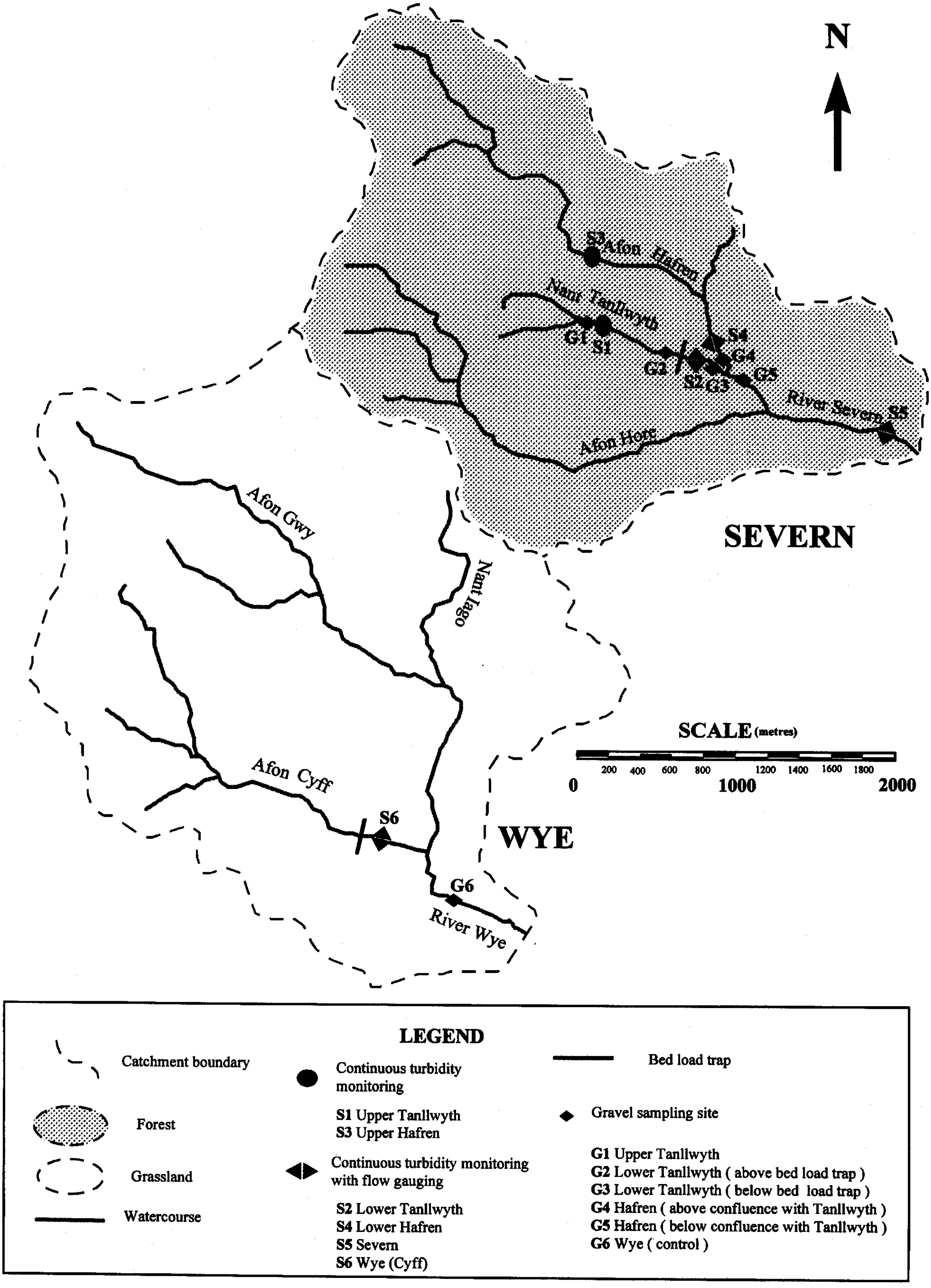


Fig. 1 *Sediment monitoring network within Plynlimon Experimental Catchments*

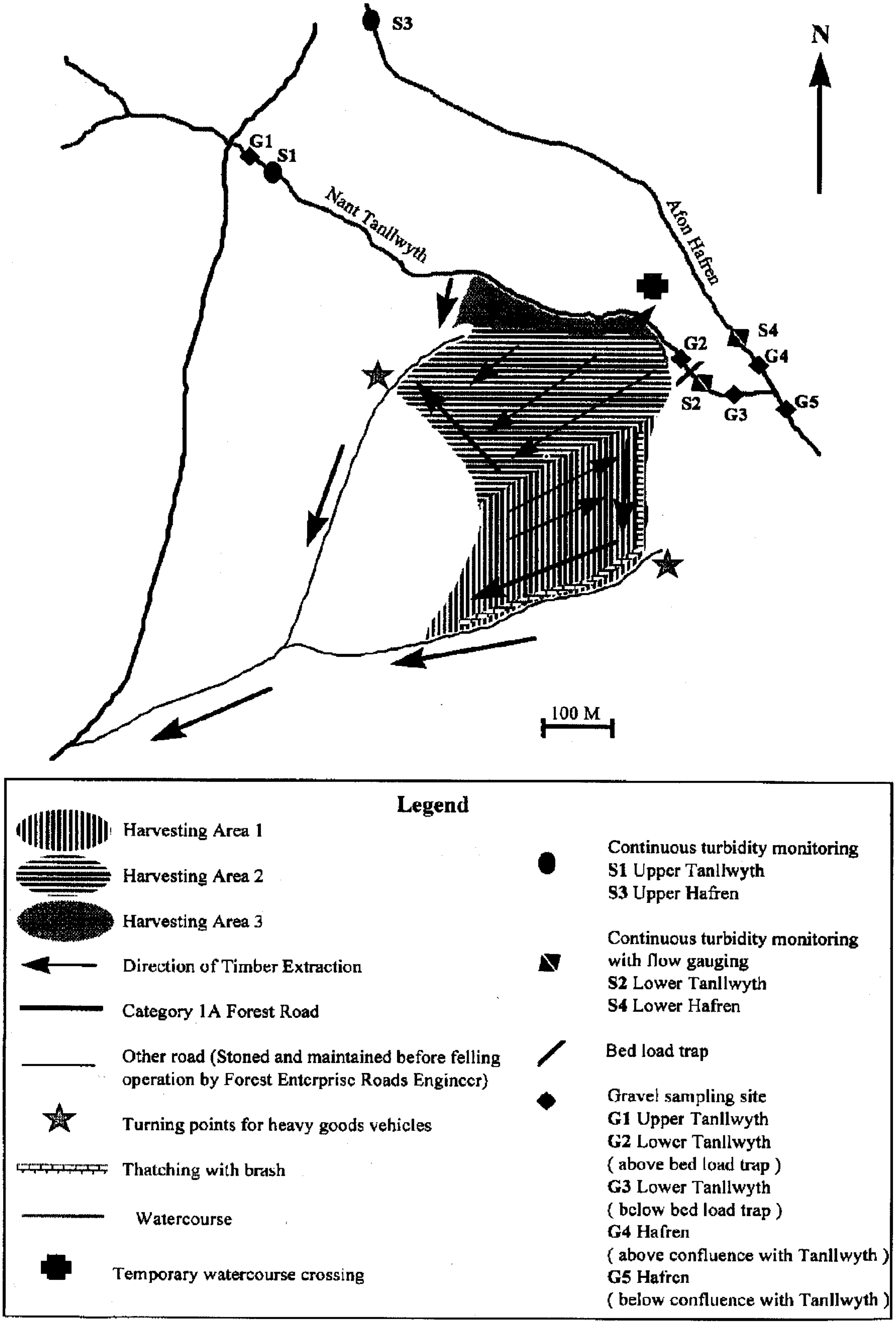


Fig. 2 *Details of harvesting operation in Nant Tanllwyth catchment*

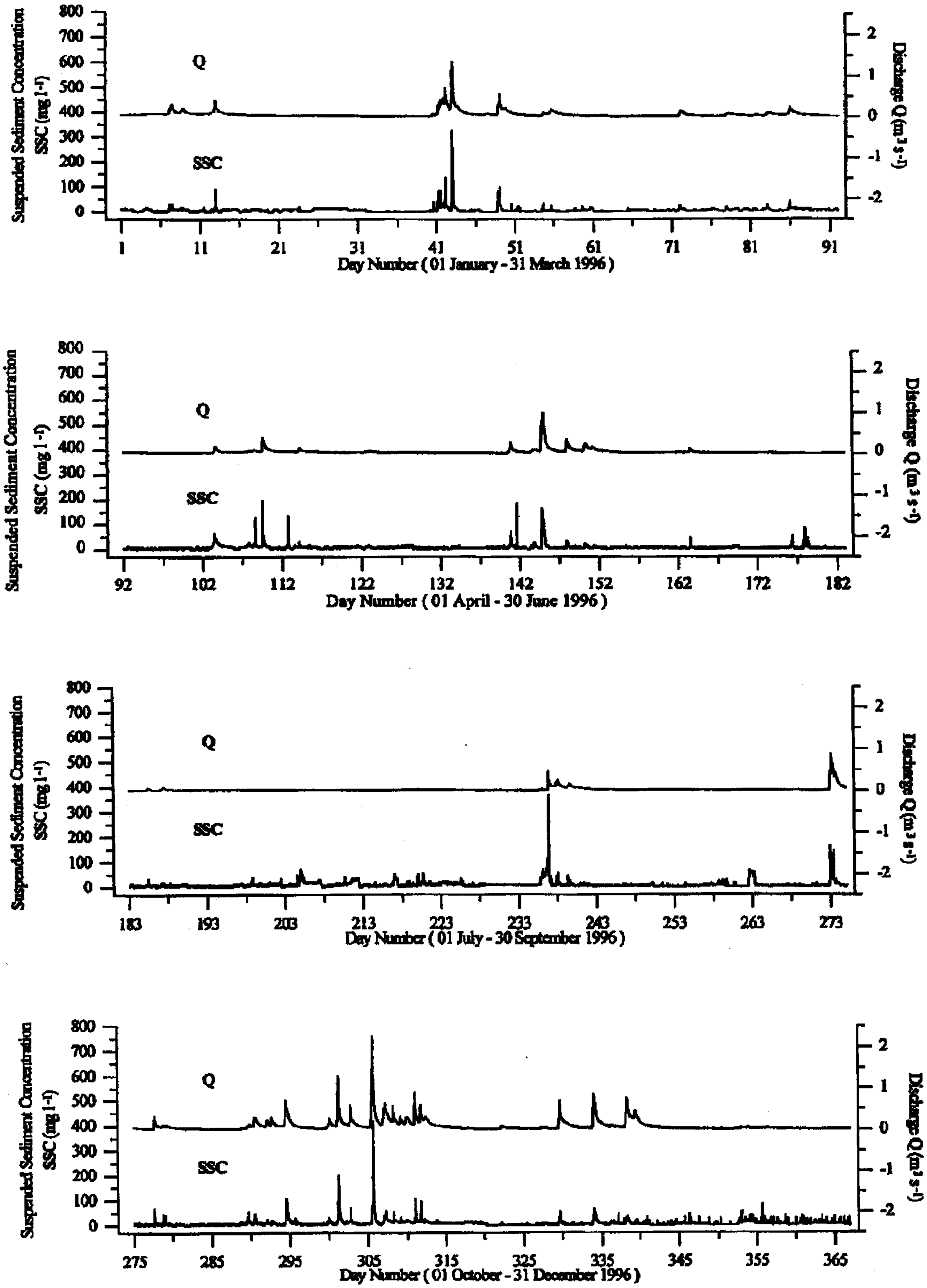
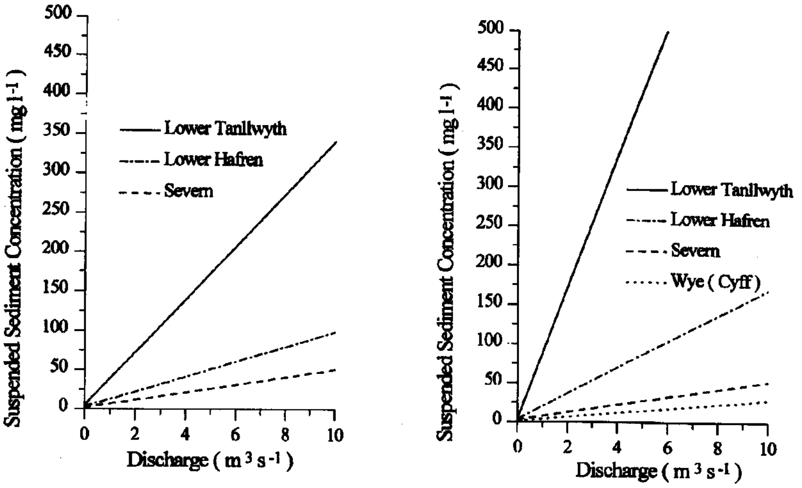
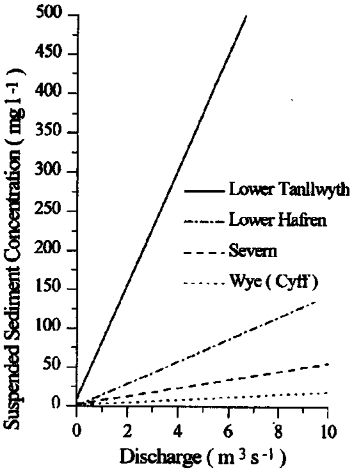


Fig. 3 *1996 Water discharge (upper line) and continuous total suspended sediment concentration (lower line) data for Lower Tanllwyth (S2) site*



i 1995 Rating Curves

ii 1996 Rating Curves



iii 1997 Rating Curves

Fig. 4 *Rating curves for 1995, 1996 and 1997 at turbidity/discharge monitoring sites*

Figs 4 and 5. Data are presented for 1995, 1996 and January–June 1997. Figure 4 indicates that suspended sediment concentrations for equivalent discharge consistently followed the pattern Lower Tanllwyth > Lower Hafren > Severn > Wye. Compared to 1995 data, Fig. 5 shows that suspended sediment concentrations at both the Lower Hafren and Lower Tanllwyth sites increased during 1996. During January–June 1997, although the increase above 1995 values was maintained, both sites showed a slight decrease from the 1996 levels. Rating curves for the Severn remained comparatively stable during all three years.

Simultaneous suspended sediment concentration data during 1996 and January–June 1997 at both the Upper and Lower Tanllwyth sites is shown in Figs 6 and 7 respectively. Data for quarterly periods January–March and April–June 1996 correspond to the period when harvesting was undertaken between these sites. Subsequent data representing the post-harvesting period. Results from all suspended sediment monitoring sites are summarised in Table 1. Bed-load data from the Lower Tanllwyth and Wye (Cyff) sites are summarised in Table 2.

DISCUSSION

Comparison of results from 1995 onwards, with previous sediment research within the Plynlimon catchments (Kirby *et al.*, 1991; Leeks, 1992) has identified both some similarities and significant differences within and between the Severn and Wye catchments. Previous results from Plynlimon sediment research have revealed lower suspended sediment yields from the Nant Tanllwyth catchment, than from adjacent Afon Hafren, 12.1 t km^{-2} yr^{-1} and 35.3 t km^{-2} yr^{-1} respectively (Kirby *et al.*, 1991). This is not reflected in 1995 data which indicate that suspended sediment yields from the Tanllwyth catchment were 51 %

Table 1. Summary of recent suspended sediment monitoring results from Plynlimon Experimental Catchments

	* Upper Tanllwyth S1		Lower Tanllwyth S2			* Upper Hafren S3		Lower Hafren S4			Severn S5			Wye (Cyff) S6	
	1996	½ 1997	1995	1996	½ 1997	1996	½ 1997	1995	1996	½ 1997	1995	1996	½ 1997	1996	½ 1997
Average suspended sediment concentration (mg l^{-1})	4.3	4.3	7	8.9	13	5.2	4.9	4.9	6.7	10	4	5.1	5	1.8	1.7
Maximum suspended sediment concentration (mg l^{-1})	280.3	305	319.1	417.1	843	280.5	120.9	97.1	184	37.8	137.9	261.9	125	145.8	73.4
Total suspended sediment load (tonnes)			21.59	38.95	25.43			59.1	84.69	32.89	138.4	127	92.35	16.71	7.58
Suspended sediment yield (t km2 yr-1)			24.26	43.76				16.1	23.08		15.91	14.59		5.34	

• As flow data is not available for Upper Tanllwyth and Upper Hafren monitoring sites, suspended sediment loads and yields cannot be calculated.

½ 1997 data (6 months data only, 01.01.97–30.06.97). Therefore, 1997 annual yields cannot be calculated.

higher than from the Hafren, 24.3 t km^{-2} yr^{-1} and 16.1 t km^{-2} yr^{-1} respectively. A suspended sediment yield of 43.8 t km^{-2} yr^{-1} from the Nant Tanllwyth during 1996, when timber harvesting was undertaken within the catchment, increased this difference to 90 %. Assuming all other variables are equal and that the 1995 results represent the background difference in suspended sediment yields between the two catchments, the timber harvesting operation in the Tanllwyth has increased the annual suspended sediment yield by 39 % (corresponding to 9 t km^{-2} yr^{-1}).

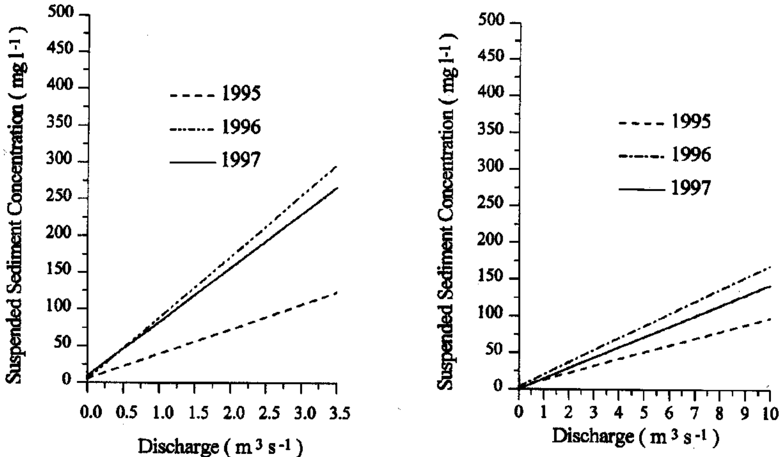
The 80 % increase in suspended sediment yield between 1995 and 1996 from the Nant Tanllwyth catchment can be compared with a 43 % increase from the Afon Hafren. Although no felling took place within the Hafren catchment during 1996, it may have been affected by the harvesting operation in the adjacent Tanllwyth through increased traffic on forest roads. This was identified by Johnson and Bronsdon (1995) as one of the major causes of forest road erosion resulting in particulate inputs to watercourses.

Table 2. Recent bed-load data from Nant Tanllwyth and River Wye (Cyff) catchments

	Nant Tanllwyth		Afon Cyff	
	1995	1996	1995	1996
Total bed load tonnes)	7.66	8.65	4.18	4.63
Bed load yield (t km^2 yr^{-1})	8.61	9.72	1.33	1.48

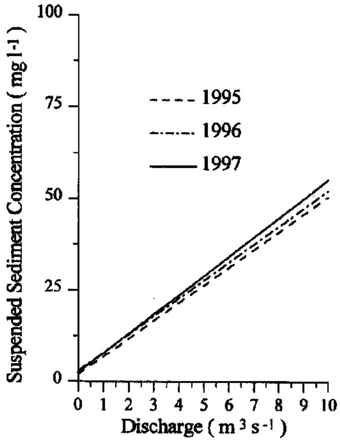
The average suspended sediment concentrations at the Upper and Lower Tanllwyth sites for the complete 1996 and 1997 data sets (see Table 1) and the continuous data series shown in Figs 6 and 7 reveal an increase in suspended sediment concentrations between the sites during the post-harvesting period. Average suspended sediment concentrations remain stable at the Upper Tanllwyth between 1996 and 1997. The increase at the lower site is not caused by different weather conditions between the two periods, as this would affect both sites.

The temporal response of the Tanllwyth river suspended sediment to timber harvesting in 1996 is very different from the immediate enhancement of suspended sediment concentrations, (by an order of magnitude), observed during the Hore felling experiment. Consequently, in this current example, post-harvesting soil erosion appears to be more significant than the immediate disruption of the catchment surface during the felling operation. However, a similar lagged effect upon peak bed-load yields was observed at downstream monitoring stations following clear-felling in the Hore catchment. This was found to be due to the build-up of sediment behind timber debris within the channel and drains (Leeks, 1992). Suspended sediment yields may reveal a similar lag as the timber debris or brash, which protected the catchment



i Lower Tanllwyth (S2) rating curves (1995, 1996, 1997)

ii Lower Hafren (S4) rating curves (1995, 1996, 1997)



iii Severn (S5) rating curves (1995, 1996, 1997)

Fig. 5 *Rating curves for 1995, 1996 and 1997 at Tanllwyth (S2), Hafren (S4) and Severn (S5) monitoring sites*

surface during and immediately after the harvesting operation, broke down and exposed more soil to erosion processes during the post-harvesting period. Alternatively, the lag may be due to the spatial patterns and scale of the felled plots, which is much smaller and more remote from streams than was the case in the Hore catchment felling experiment.

Although there has been a slight increase in bed-load yields from the Nant Tanllwyth catchment relative to the Afon Cyff between 1995 and 1996 (see Table 2), a longer post-felling time series of bed-load data will be required to assess the impact of the harvesting operation upon bed-load yields.

In comparing bedload sediment yields from the grassland Afon Cyff and the forested Tanllwyth, previous results from the Cyff and Lower Tanllwyth bed-load monitoring sites reported yields of 6.4 and 38.4 t km^{-2} yr^{-1} respectively, representing a ratio of 1:6.0 between grassland and forested catchments (Kirby *et al.*, 1991). The 1995 and 1996 data in Table 2 indicates much lower yields than the longer term values quoted in earlier papers, probably due to the relatively low rainfalls in these years (6th and 3rd lowest in the Plynlimon total annual rainfall records). However, the Cyff:Tanllwyth annual sediment yield ratios of 1:6.5 in 1995 and 1:6.6 in 1996 are very similar to previous results.

Concluding remarks

In the UK, concerns with regard to sediment pollution in upland rivers and reservoirs have been reflected in the adoption of forest and water guidelines during the last decade. Research at Plynlimon has contributed to the development of this guidance. In conducting the research, consideration has always been given to the possible operational value of the results and providing additional

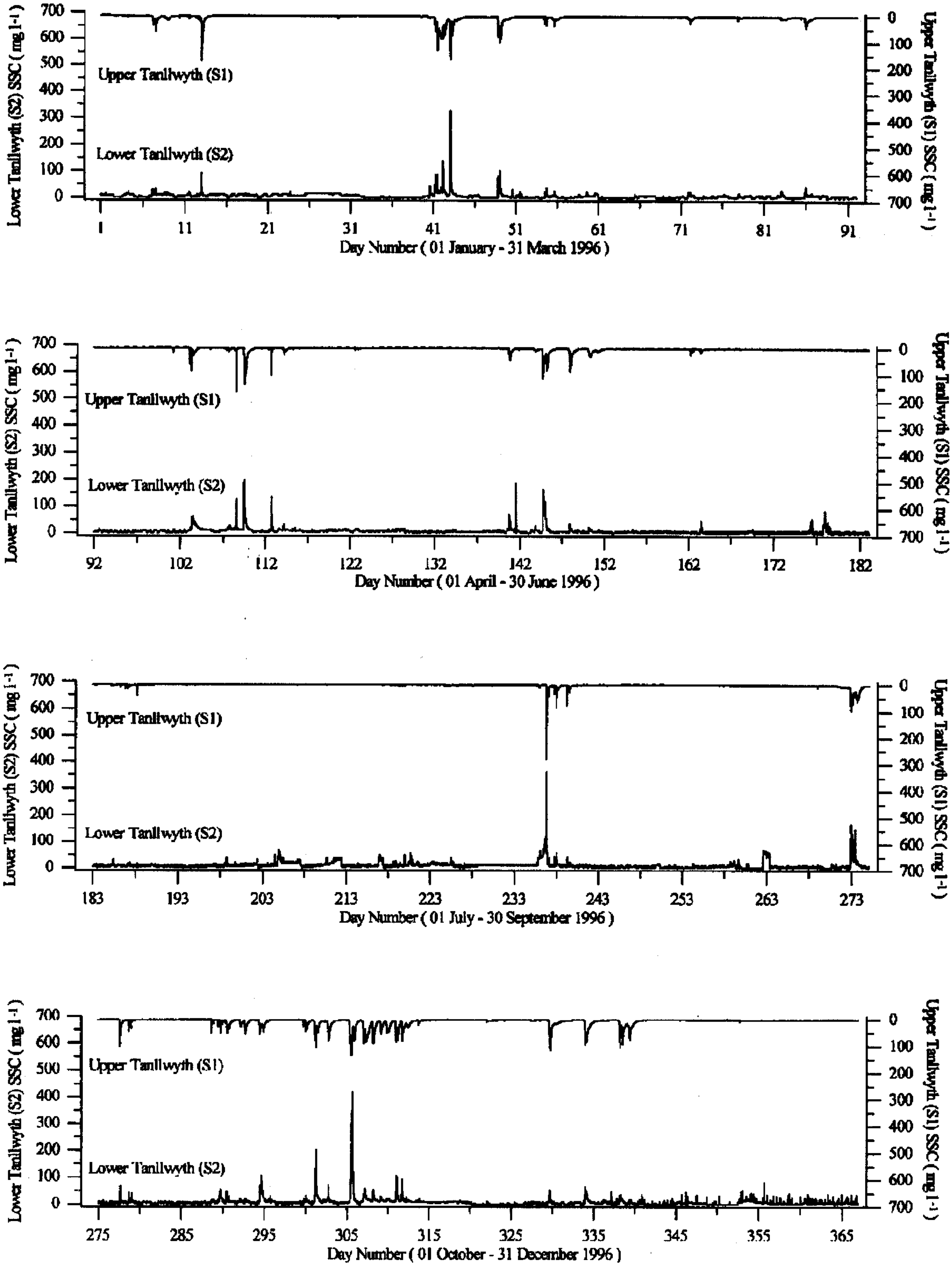


Fig. 6 *1996 continuous total suspended sediment concentration (SSC) data at Upper (S1) and Lower (S2) Tanllwyth sites*

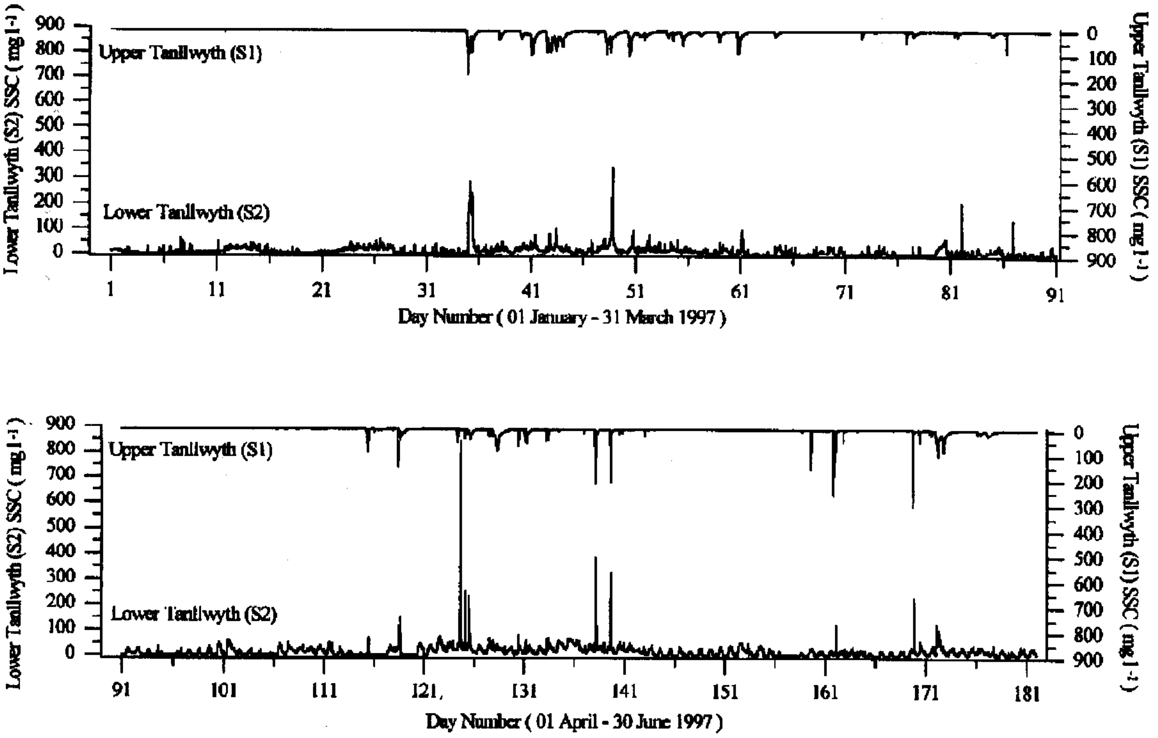


Fig. 7 *1997 continuous total suspended sediment concentration (SSC) data at Upper (S1) and Lower (S2) Tanllwyth sites*

guidance and support for catchment and forest management.

In addition to the detailed monitoring of suspended sediment and bedload transport using the Plynlimon monitoring networks, numerous other studies have been focused upon particle properties (eg. Sawyer *et al.* 1997, Brewer *et al.* 1992), reach dynamics (Arkell *et al.* 1983), bank erosion (Lawler and Leeks 1992, Lawler *et al.* 1997) and sediment sources (Bonnett *et al.* 1989, Collins *et al.* 1997). These studies have made full use of the opportunities to use relevant parallel data from the Plynlimon hydrological and sediment monitoring networks. The Plynlimon research by both IH and many university research teams provides a detailed view of combined suspended and bedload sediment dynamics in British upland catchments. However, there remain many areas worthy of future scientific study. These include further work on movement of sediment across catchment surfaces, the mechanisms controlling delivery of material from catchment surfaces and the interactions between bedload and suspended load, in addition to the relationships between the physical flux of sediment and water chemistry.

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