The Impact of Particulate Outputs Associated with Timber Harvesting

Institute of Hydrology

R&D Technical Report P140

Sensitive harvesting practice: forwarder operates upon brash which protects the ground surface from erosion during extraction of Sitka spruce (*Picea sitchensis*) felled by a whole-tree harvester

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Statement of Use
This Technical Report fully describes a study, collaborative with NERC, investigating the impact on river quality of fine particulate outputs arising from forestry operations. It is for information and will be of interest mainly to Water Pollution Control staff working in afforested catchments. The results from the project will be considered in any future revisions of the Forests and Water Guidelines and other guidance documents used by the Agency and forestry interests.

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EXECUTIVE SUMMARY

Increased river sediment yields associated with forestry are likely to be particularly significant during harvesting. Extensive tree planting took place in the UK during the 20 years after the Second World War. With many forests now reaching maturity, timber harvesting in Great Britain is expected to increase by 70% above 1996 levels in the following two decades. It is therefore important to understand the dynamics of particulate outputs arising from modern timber harvesting practices in order to evaluate the potential adverse impacts and identify possible prevention and amelioration strategies.

Literature was reviewed in order to identify the forestry practices responsible for enhanced particulate outputs, and the potential impacts upon water resources and aquatic life.

The long-term record of sediment fluxes within the Institute of Hydrology Experimental catchments at Plynlimon provided the foundation for a detailed field study. The existing monitoring network was intensified to enable the investigation of particulate outputs associated with the harvesting of a 13 ha plot in the Nant Tanllwyth catchment. This represented typical Forest Enterprise (FE) practice in England and Wales, which normally involves the felling of 10-15 ha plots using a range of methods depending on specific site conditions. Detailed studies of suspended sediment concentration, bed load transport, river gravel composition and channel bank erosion were undertaken. In parallel, a detailed record was built up of the harvesting operation (January-June 1996) which involved three separate techniques.

Suspended sediment yields for 1995 and 1996 increased by 83% (from 24 to 44 t km^2 yr^{-1}) in the Tanllwyth catchment subjected to timber harvesting, but by only 44% (from 16 to 23 t km^2 yr^{-1}) in the adjacent Hafren catchment, which was only affected by a small amount of harvesting in the headwaters of its catchment. During 1996, the mean suspended sediment concentration in the Nant Tanllwyth above and below the harvesting site was 2 and 7 mg l^{-1} respectively, while at control sites on the upper and lower Hafren the mean suspended sediment concentrations were both 4 mg l^{-1}. Although these initial results indicate enhanced suspended sediment outputs associated with the harvesting operation, this increase is much lower than those recorded in previous studies of suspended sediment outputs associated with larger felling sites before publication of the First Edition of Forests and Water Guidelines. In the light of critical thresholds for fishery damage, the limited duration of exposure to potentially harmful suspended sediment concentrations is unlikely to significantly harm aquatic life.

Bed load yields for 1995 and 1996 increased by 13% (from 8.6 to 9.7 t km^2 yr^{-1}) in the Nant Tanllwyth catchment, and 15% (from 1.3 to 1.5 t km^2 yr^{-1}) in the moorland Afon Cyff catchment. Due to possible lag effects, a longer post-felling time series of bed load data will be required to assess the full impact of the harvesting operation upon bed load yields in the Nant Tanllwyth catchment.

Following timber harvesting in the Tanllwyth catchment, river gravel samples collected by freeze coring revealed an increase in fine material content in the Afon Hafren, below its confluence with the Nant Tanllwyth. However, in the light of published critical thresholds of gravel fines content, none of the samples collected from watercourses affected by the harvesting operation contained sufficient material to adversely affect salmonid spawning.

Timber harvesting in the riparian zone of the Nant Tanllwyth resulted in a statistically significant increase in the erosion rates of adjacent channel banks. This was associated with a reduction in winter temperatures due to removal of the insulating forest canopy. An increase in the period of sub-zero channel bank temperatures is likely to increase erosion through frost action.

The intensive research programme at Plynlimon is supported by studies at other harvesting sites. Higher suspended sediment concentrations were recorded in a catchment (the Afon Biga) affected by a smaller felling operation (6.5 ha) where the steeper gradient and large number of trees in the riparian zone are likely to have contributed to increased particulate outputs.

Details of previous sediment pollution incidents associated with timber harvesting investigated by the Environment Agency, and field visits to existing harvesting sites throughout England and Wales, has enabled the identification of the most significant sources of particulate outputs associated with timber harvesting.

Combination of the intensive Plynlimon research programmes, monitoring and field observations at other harvesting sites and the collation of information from the Environment Agency pollution archive has given a broad view of particulate outputs associated with timber harvesting upon which recommendations have been based for prevention, amelioration and assessment of these impacts. The most effective and practical measures which can be employed to prevent and / or ameliorate particulate outputs associated with timber harvesting are already supported by existing guidance in the Forests and Water Guidelines (Forestry Authority, 1993) and, more specifically, the FE Wales Harvesting Manual (Killer, 1994), and Forestry Commission Soft Ground harvesting Report (Forestry Commission, 1991b).

Results from the detailed monitoring programme at Plynlimon indicate that modern FE harvesting practice is likely to result in less severe particulate outputs than recorded in previous studies, which involved the felling of a larger proportion of a catchment. In the future, the combination of both afforestation and felling in strict accordance with current guidance should further reduce the impacts of particulate outputs associated with timber harvesting.

Examples of timber harvesting operations responsible for pronounced particulate outputs that were identified did not conform to current guidance (Forestry Commission, 1991b; Forestry Authority, 1993; Killer, 1994). It is therefore recommended that every effort is made to ensure that such good practice is strictly adhered to by all forest operators, including both FE and private companies / contractors.

KEY WORDS

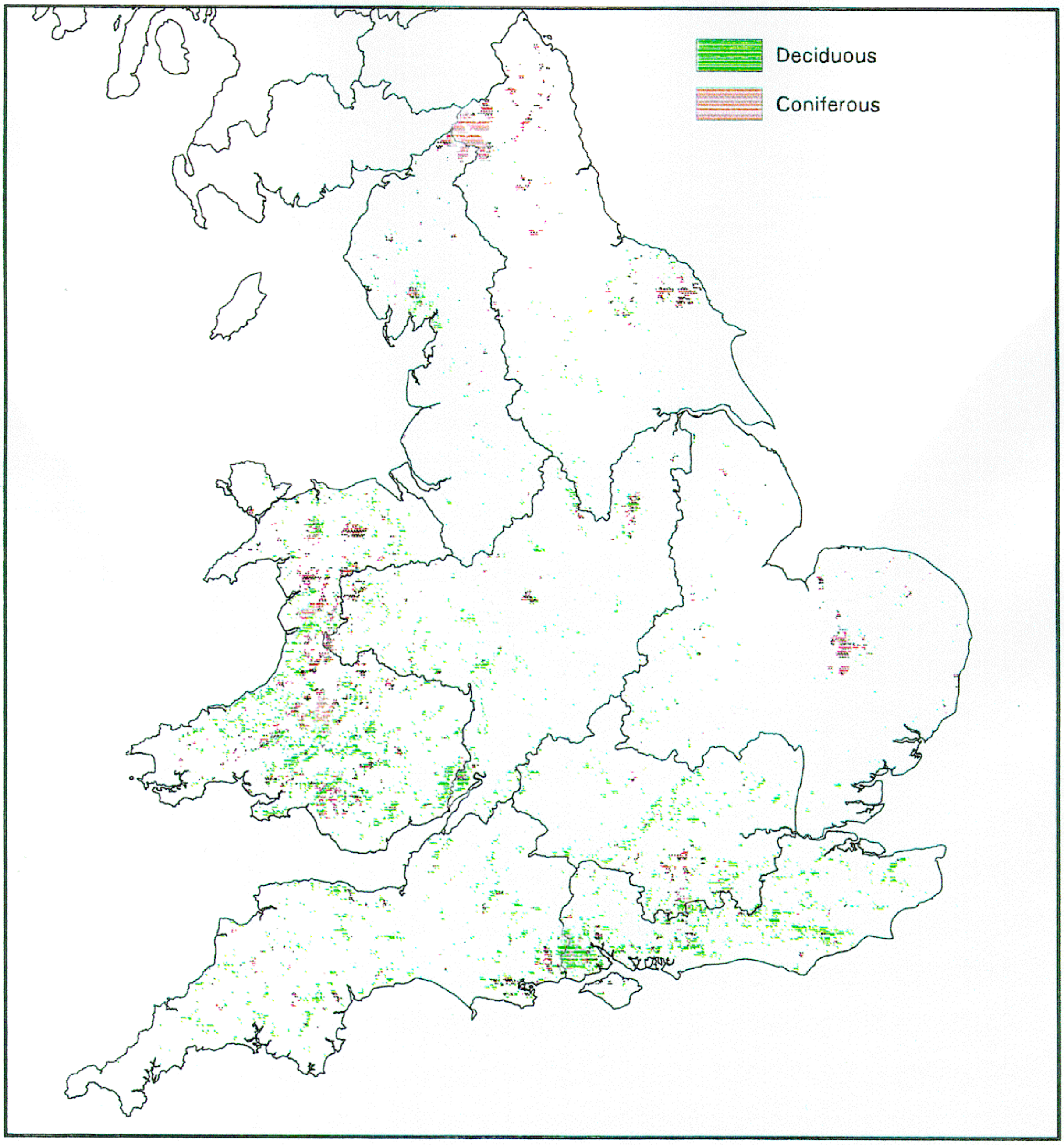
Felling, forestry, harvesting, particulates, sediment, turbidity, water quality

1 PROJECT BACKGROUND

The problem of large fluvial particulate inputs, resulting from enhanced erosion associated with timber felling operations, was highlighted in a review, commissioned by the National Rivers Authority (NRA) and carried out by the Institute of Terrestrial Ecology (ITE), (Stevens and Reynolds, 1993). Relative to other forms of upland land use, some afforested catchments have been shown to produce large yields of both coarse and fine particulate material. Previous work undertaken by the Institute of Hydrology (IH) has demonstrated that enhanced fluvial particulate inputs from forests, relative to unimproved grassland, can be a feature of the entire crop rotation, but is especially pronounced during afforestation and felling (Neal *et al.*, 1992). These enhanced yields have been observed for 4-5 years post-felling. Coarse material can destabilise channels, leading to enhanced erosion. Fine material may have a detrimental impact on water resources and aquatic life. In the past, pollution incidents resulting from particulate outputs associated with timber harvesting have therefore been reported to the Environment Agency.

Figure 1 shows the extent of deciduous and coniferous forestry in England and Wales, including the Environment Agency Regional boundaries. This data is taken from the ITE digitised 1 km Land Cover Map of Great Britain. Where indicated, deciduous or coniferous forestry is considered to be the dominant land cover. 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 to proceed at an increasing rate over the next two decades to reach 14, 660, 000 m^3 by 2016 (Forestry Commission, 1997). The requirement to assess the impact of felling operations, and to recommend soundly-based methods to ameliorate effects on watercourses, is therefore particularly urgent. Besides presenting a challenge to the pollution control authorities, this widespread harvesting offers the opportunity to redesign forests post-felling to preserve valuable top soil, and reduce both persistent enhanced fluvial particulate inputs and short-term contamination problems in subsequent rotations. Failure to identify the potential impacts and evaluate possible amelioration strategies could result in substantial deterioration in upland water quality, and failure to achieve statutory water quality objectives. This could affect economically important interests, such as salmonid fisheries and potable water resources.

Although improvements in forest management practice have been recommended in Forests and Water Guidelines (Forestry Authority, 1993), their effectiveness needs to be assessed. A review carried out by ITE (NRA, 1993) stressed the need for further research in this field, and identified gaps in knowledge. This project covers recommended areas of research, necessary for the Environment Agency to gain further understanding of the causes and mechanisms which result in the increased particulate yields associated with timber harvesting. This work will also provide a knowledge of suitable ameliorative measures which can be adopted in improved forest management policies. It will therefore be of mutual benefit to both the Agency and forestry industry.



Institute of Terrestrial Ecology / Institute of Hydrology
January 1995
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Figure 1 Location of deciduous and coniferous forestry in relation to Environment Agency Regional boundaries

2 PROJECT OBJECTIVES

2.1 Overall

To quantify the influence of timber harvesting upon fluvial particulate loads in England and Wales, and to investigate methods to ameliorate long and short term sediment pollution associated with forestry land use and practice.

2.2 Specific

a) To carry out a review of the key literature, including the impacts of fluvial particulates on aquatic fauna.

b) To carry out site specific assessments of problems of fluvial particulate inputs arising from tree felling in each Environment Agency Region, in relation to existing Agency policies and Forestry Authority guidelines.

c) To carry out a field survey of problem sites identified in Objective b, involving a range of techniques, and to produce a general description of particulate data from these felling sites.

d) To carry out a detailed monitoring programme on fine and coarse fluvial particulate inputs at the IH Experimental Catchments at Plynlimon. The programme will include studies of suspended and bed load transport, yielding results which are relevant to current forestry practices.

e) To make recommendations for rapid physical assessment of the impact of fluvial particulate pollution from forestry practices.

f) To consider the merits of, and evaluate by field studies, a variety of preventative and ameliorative measures to reduce the impact of fluvial particulate inputs arising from timber felling, including a consideration of cost / benefit for each option.

g) To produce guidelines in the form of an R&D Note for Environment Agency field staff to assess the potential impact of fluvial particulate inputs from felling, and to enable them to make recommendations to minimise adverse impacts.

This project is closely linked with the Phase II Upland Water Chemistry Study commissioned by the Environment Agency being carried out at Plynlimon (P2_i502). Both projects also have strong links with NERC strategic research. To present a broad view of the impact of timber harvesting upon both coarse and fine fluvial particulate inputs, this project will utilise the intensive long term Experimental Catchment data on sediment transport in Plynlimon watercourses, in addition to data from other afforested catchments in England and Wales.

3 LITERATURE REVIEWS

3.1 Fluvial Particulate Inputs Associated with Timber Harvesting

Fluvial sediment has been defined as either inorganic or organic particles that are, or have been, transported by water. It is useful to divide this material into suspended load and bed load depending upon the way it is transported. The latter generally involves inorganic particles greater than 0.2 mm in diameter, while finer sediment transported in suspension typically contains around 10 per cent organic matter (Walling, 1994).

International research indicates that high rates of soil erosion are not characteristic in Britain. 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 is likely to be particularly significant in upland areas where deposits of weakly-cohesive glacial and fluvio-glacial material often remain from the Pleistocene period. Past research, as reviewed by Moffat (1988) and Soutar (1989), indicates that particulate inputs to fresh waters represent an important adverse effect of British forestry. This has been widely recognised in recent years by forestry operators, conservationists and the water industry. Consequently, forestry practice has been developed over the last decade following the identification of best practices to reduce enhanced particulate outputs (Forestry Authority, 1993; Forestry Commission, 1988, 1991a, 1991b; Killer (Forest Enterprise Wales), 1994).

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, however, relevant to sediment dynamics during felling. In addition to providing the baseline data from which to judge the impacts of the final stage in the forest rotation, some practices common during felling are also undertaken during previous 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 can also take place concurrently, it may be 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 water resources and the ecology of freshwater ecosystems will be reviewed in sections 3.2 and 3.3 respectively.

3.1.1 Construction and erosion of 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. Table 1 summarises a number of catchment studies that have identified increased particulate outputs 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 enhancement in fluvial particulate outputs does decrease with time following the construction of plough furrows and drains, sediment yields stabilise at rates which are well above pre-afforestation levels. Consequently, high particulate yields are a common feature of afforested catchments in which sediment outputs have been measured (see Table 2). This is strong evidence that drain erosion can persist throughout the forest rotation.

3.1.2 Track and road construction, modification and use

To enable access for both harvesting machinery and the extraction of felled timber, new tracks may be constructed or old tracks modified during harvesting. Arnold Arnold and Associates, and Dames and Moore (1975) state that out of all the silvicultural activities, logging roads are the principal source of man-caused sediment. Similarly, Ferguson and Stott (1987) identified timber loading areas and logging roads as the main sources of enhanced suspended sediment and bed-load yields associated with forestry. An NRA R&D project to investigate the erosion of forest roads due to natural and man induced processes was undertaken by Johnson and Bronsdon (1995). This identified that most damage was associated with the freeze / thaw cycle, harvesting, traffic and blocked drains.

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 experimental catchment was 1.2 km^2 in area. A nearby control catchment, which remained as rough grassland, was also monitored. Over 4 years following track construction (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.

Although not common practice, possibly the most spectacular example of enhanced fluvial particulate levels associated with forest road construction is provided by the use of explosives in blasting the foundations for new road crossings. Leeks (1986) monitored the wave of suspended sediments which moved downstream following such an event. It is, however, unlikely that this will ever be undertaken during modern forest operations in accordance with Forests and Water Guidelines (Forestry Authority, 1993).

A further example of the potential impact of forest road construction on the acceleration of erosion, and therefore the input of particulates to watercourses, is represented by the work of Duck (1985). Following the construction of an unmetalled road at Glen Ogle in the Scottish Highlands, particulate inputs to the Ogle Burn, one of the main influents to Loch Earn, increased by an order of magnitude. Consequently, 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 than had passed a temporary gauging station, near the confluence with the loch, during an earlier 12 month monitoring period. The mean thickness of the resultant deposit should, under normal circumstances, 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 construct turning, processing and loading bays, and timber stacking areas. At the beginning of the felling operation in the Hore catchment (Plynlimon), roads were widened and turning / processing 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^{-1}, during periods of low discharge, to drain clearance in the Hore catchment prior to clearfelling.

A number of studies in the USA have also attributed high fluvial particulate levels to forest track / 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 conclusions of this study were that the immediate impact of road construction was best reflected by the suspended sediment yields which, during the first winter, were more than four times the preconstruction levels. Consequently, the United States Department of Agriculture recognises 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. A number of 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.

The following principles can be drawn from the Coweeta studies (Swift, 1984a; 1984b; 1985; 1988):

1. The most effective road system results from a transportation plan developed to serve an entire basin, rather than the sum of individual road projects constructed to serve short-term needs.

2. Soil exposed by construction should be revegetated quickly.

3. Where possible, storm waters should be removed from the road at frequent intervals and in small amounts by out-sloping and dips, rather than by consolidation into ditch-lines and culverts. The purpose is to remove storm waters from the roadbed before the flow gains enough volume and velocity to seriously erode the surface. The next step is to dispose of these waters where they will infiltrate and drop their sediment load rather than carrying it to natural watercourses.

4. Contour roads and gentle grades require less maintenance and produce less sediment.

5. The type of road surfacing is critical. The erosion control obtained by an adequate depth of gravel (15cm) contrasts dramatically with the poor control obtained with an inadequate thin (5cm) layer which was worse than bare soil. A grassed roadbed will exert a partial control at a considerably lower cost. Mean soil loss rates for five road surfaces at Coweeta were therefore, 5cm Crushed Rock > Bare Soil > Grass > 15cm Crushed Rock > 20cm Large Stone. When construction funds are limited, gravel surfacing to adequate depths should be reserved for the critical sites, such as steeper grades, erodible soils, in dips, and near stream crossings. The entire roadbed should be vegetated by grass as soon as earth moving has ceased. With heavy traffic, grass will not grow in the treads of the road but if growing conditions are suitable, it will protect the majority of the exposed soil and trap material escaping from the roadbed. An important cause of the reduction in soil loss after grassing is the trapping of sediment by grass in the dip. Several plantings of grass are cheaper and may be more effective than a limited amount of gravel stretched over the length of the road.

6. The stream crossing is the most critical part of the entire road, and every effort should be made to protect and vegetate fill slopes, and divert storm waters on the road away from the stream.

7. Filter strips and brash barriers can be used to prevent sediment from reaching streams.

8. Unnecessary maintenance must be avoided.

3.1.3 Mechanical disturbance of the catchment surface

Mechanical disturbance of the catchment surface is predominantly apparent 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 wheel tracks produced by the depression of the ground surface by the movement of felling machinery provide flow pathways which concentrate the flow of water, entrain sediment and rapidly convey it to watercourses.

A previous example of this effect came from the Hore clear-fell experiment in the IH Plynlimon experimental catchments. From 1983 the Hore sub-catchment was extensively instrumented in order to provide background sediment transport data for two years leading up to clear-felling, and to identify post-felling impacts. Considerable ground disruption by machinery used 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 first two years of harvesting. These indicated an increase in sediment concentrations by an order of magnitude for moderate to high flows. This increase in turn, was reflected in higher annual total catchment yields of suspended sediment, rising 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, recovering to a four-fold increase after log and debris jams formed across the channel (Leeks and Roberts, 1987). As this felling operation no longer represents typical Forest Enterprise (FE) practice, an investigation of the particulate outputs associated with a contemporary harvesting operation within the IH Plynlimon Experimental Catchments is therefore reported in Chapter 4.

In Great Britain, low particulate outputs have been recorded in association with harvesting methods which extract felled timber via aerial cableways to minimise the mechanical disturbance of the catchment surface (Maitland *et al.*, 1990). It should, however, be recognised that such harvesting techniques demand a higher level of road construction and improvement, the effects of which were discussed in 3.1.2. Care should also be taken to ensure that logs extracted by aerial cableways are not allowed to drag along the ground surface. This can result in serious erosion, especially if the timber is dragged through watercourses which may then be diverted along the extraction route (Forestry Commission, 1991b).

Internationally, there are many examples of surface erosion solely associated with the removal of natural tree cover. In such cases, rather than mechanical disturbance of the catchment surface, the exposure of the bare unconsolidated soil surface is the dominant factor, causing increased erosion through rain-drop impact processes resulting in increased fluvial particulate inputs by up to three orders of magnitude. Consequently, elsewhere in the world, cable logging is likely to encourage surface erosion, leading to particulate inputs to watercourses. For example, Ursic (1991) monitored the hydrological effects of harvesting mature pine by cable logging in north Mississippi, USA. The results of this study indicated that the suspended sediment concentrations in catchment watercourses were 3 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. During the Hore clear-fell experiment, when aerial cable techniques were used, the removal of tree cover was not sufficient in itself to immediately enhance sediment loads in headwater streams (Leeks and Roberts 1987). This suggests that post-felling soil exposure is not as significant in British forests, indicating that the mechanical disturbance of the catchment surface is likely to be the dominant cause of fluvial particulate inputs associated with timber harvesting. In British commercial forests, much of the forest cover dates from the 1930's onwards, before which, although vegetated, soils had been unafforested, and therefore more exposed to rainfall than the soils of natural forests which were protected by canopy interception.

3.1.4 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. During such periods of low discharge, background sediment levels would have been below 1 mg/l. Similarly, Table 20 reports a suspended sediment concentration of 10 632 mg l^{-1} in a small stream when a vehicle had to operate within the channel to remove wood debris (see 6.2.4). Forests and Water Guidelines recommend that machines should not be allowed to work in streams (Forestry Authority, 1993).

Research in the USA has also identified the mechanical disruption of stream 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.

3.1.5 Management of wood debris within the river channel

In the UK, recent interest in the use of "dead" wood for environmentally sensitive engineering approaches to river management (Brookes, 1988) has led to research on the links between channel dynamics and vegetation (Gregory, 1992). The majority of research results refer to coarse woody debris (CWD). This material 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. It also plays an important role in woodland river ecology which has been reviewed by Gregory *et al.* (1994).

i. The influence of wood debris on the geomorphology of woodland river channels

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 a number of studies in the USA, reported upon by Gregory *et al.* (1994). These reveal that storage zones controlled by CWD accumulations may account for up to 40% of the channel area and contain 49% of the total particulates stored.

Mosley (1981) identified the importance of debris-dam collapse in governing the transfer of particulates downstream. Mosley emphasised the fact that such collapse is only associated with a small proportion of run-off events, and the material released only moves a short distance before being redeposited. Since woody debris provides abundant storage sites in forest streams, annual yields from small forested watersheds are frequently less than 10% of the particulates stored (Sullivan *et al.*, 1987). If debris accumulations are removed, material rapidly comes out of storage, leading to major increases in transport and yield (Gregory *et al.*, 1994). Hedin *et al.* (1988) noted a similar effect three years after deforestation, corresponding to the natural breakdown and removal of debris dams.

ii. The role of wood debris in woodland river ecology

Gregory *et al.* (1994) state that dead wood has four main functional roles in woodland river ecology. It maintains a diverse range of habitat patches, provides a complex habitat structure within CWD accumulations, represents an important food source, and acts as a fuel regulator for food webs.

Sedell *et al.* (1988) concluded that the productivity of aquatic habitats depends on the biological diversity provided by a continuous supply of CWD. Dead wood influences the functioning of aquatic ecosystems in many ways, both directly and indirectly. In any ecological classification of rivers, the presence or absence of CWD is therefore an important discriminator (Naiman *et al.*, 1992). Gregory *et al.* (1994) identified a number of studies where the abundance of CWD has been positively correlated with the diversity, density and / or biomass of invertebrates and fish.

iii. The management of woody debris in forest aquatic ecosystems

It is clear from the above that CWD has an important influence on the geomorphology and ecology of woodland river channels. However, massive accumulations of debris can restrict the upstream migration of anadromous fish (Chapman, 1962; Beschta, 1979; Bilby, 1984), and are known to result in considerable bacterial decomposition which reduces dissolved oxygen levels (Hall and Lantz, 1969). Furthermore, debris torrents which can cause serious channel scour 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 are known to play an important role in slowing the movement of particulates in drains and river channels 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 compared with 38.4 t/km^2 respectively). The initial impact of the clear-fell 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, there was a gradual rise in bed-load yield to 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 the trees were removed earlier than the rest (using skidding techniques), because of windblow problems, 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. This led to a decline in bed-load yield to 9 t/km^2 in 1985. It was therefore concluded that under some circumstances, where there is not a danger of stream diversion and additional erosion to form a new channel, 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, USA, in 1975, accelerated the scouring of previously stored sediments resulting in increased suspended sediment concentrations and therefore 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, USA. Channel cross-sections were substantially altered 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 and 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.

Effective management of the CWD associated with the management or clearance of woodland within watersheds is therefore essential to promote a healthy aquatic environment within the context of commercial forestry. In order to provide a structured approach to CWD management in association with forestry, the following suggestions were made by Gregory *et al.* (1994) These can be linked in different ways into an overall management strategy according to the nature of the channel, debris environment and adjacent land use.

1. Indiscriminate removal of CWD is undesirable and should be avoided.

2. Guidelines for selective debris removal have to take account of the amount, size and age of the debris present, and the size, gradient and energy of the stream.

3. The timing and method used for debris clearance is important. Work should avoid fish spawning and other environmentally sensitive periods, and involve the minimum of heavy equipment.

4. The stream environment can sometimes be enhanced by the addition of debris to the river (Lisle, 1981).

5. As the riparian zone provides the local source of CWD for the river, its management is very important. Murphy and Koski (1989) suggested that because nearly all CWD delivered to the river is derived from within 30m of the river bank, a 30m unlogged buffer strip should be sufficient to maintain CWD levels.

6. In addition to leaving a stream-side buffer zone, active management of that zone can yield additional benefits to the river environment.

Authors	Catchment	Afforested or Unafforested	Particulate yield as suspended sediments kg ha^{-1} yr^{-1}	Total particulate yield. Suspended sediments and bed-load kg ha^{-1} yr^{-1}	Notes
Burt *et al.* (1984)	Holmestyles	Unafforested	32	Not measured	Suspended sediments increased by 1600% a year after ploughing
		First year after ploughing	513	Not measured	
Johnson (1988)	Balquhidder Monachyle	Unafforested	Not measured	370	Total particulate yield increased by 360% following ploughing
		After Ploughing	Not measured	1332	
Francis and Taylor (1989)	Ceunant Ddu catchment (Llanbrynmair)	Unafforested	37	Not measured	Suspended sediments increased by 246% a year after ploughing
		After ploughing	90	Not measured	
Francis and Taylor (1989)	Nant Ysguthan catchment (Llanbrynmair)	Unafforested	7	Not measured	Suspended sediments increased by 479% a year after ploughing
		After ploughing	31	Not measured	

Table 1
Particulate yields associated with ploughing for forestry (Adapted from Soutar, 1989)

Authors	Catchment	Afforested or Unafforested	Particulate yield as bed-load or settled sediments kg ha^{-1} yr^{-1}	Particulate yield as suspended sediments kg ha^{-1} yr^{-1}	Total particulate yield. Suspended sediments and bed-load kg ha^{-1} yr^{-1}	Notes
Robinson (1980) Robinson and Blyth (1982)	Coalburn	Unafforested	Not measured	30	Not measured	Suspended sediments increased by 800% in first five years after ploughing. This later fell to 400% of pre-afforestation levels
		Average yield over first five years after ploughing		240		
		Longer-term yield after ploughing		120		
Stott et al. (1986) Ferguson and Stott (1987)	Balquhidder Monachyle	Unafforested Moorland	1	380	381	Total particulate yields in afforested catchment were 349% greater than those in unafforested catchment
	Balquhidder Kirkton	Afforested	21	1310	1331	
Leeks and Roberts (1987)	Plynlimon Hafren	Mature afforestation	Not measured	353	Not measured	Total particulate yields in afforested Tanllwyth catchment were 404% greater than those in unafforested Cyff catchment
	Plynlimon Tanllwyth	Mature afforestation	384	121	505	
	Plynlimon Cyff	Unafforested pasture	64	61	125	

Table 2
Long term particulate yields associated with afforestation (Adapted from Soutar, 1989)

3.2 Reported Impacts of Particulate Outputs From Forestry Upon Water Resources

The impacts of sediment outputs from forests on water supply functions can include accelerated deposition within reservoirs (Duck, 1985) and increased treatment costs or damage to distribution systems (Marks, 1994). 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 cost of £143 000 and at an additional running cost of £20 000 per annum (Edwards, 1986).

During the afforestation of the Cray Reservoir catchment in the Brecon Beacons, work involving road construction, land drainage and ploughing led to a deterioration in the quality of the water supply. Because of the high quality of this resource, sophisticated treatment was previously unnecessary, with disinfection and simple screening producing water quality standards exceeding EC Drinking Water Directives. Following afforestation, which commenced in March 1981, a number of rainfall-related discolouration events were reported by the reservoir keeper. This culminated during 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 and 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, with 300-400 complaints being received between 21st September and 7th October (Stretton, 1984). Consequently, alternative supplies had to be obtained at a cost of £28.90 per 1000 m^3 instead of the normal cost of £0.94 per 1000 m^3. In 18 months this cost the Welsh Water Authority 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 (Forestry Commission, 1991).

In September 1989, culvert construction under a forest road in the River Ogmore catchment, South Wales, resulted in the disturbance of the River Lynfi above a potable water intake. Consequently, water grossly polluted with suspended solids was abstracted, resulting in the contamination of the service reservoir and distribution network. Abstraction was stopped and the remaining supply subjected to a chlorination order with secondary treatment with sodium thiosulphate. A boiling recommendation was issued to the homes affected. Abstraction had to be closed for a considerable time while the distribution system was flushed. Considerable costs, running to tens of thousands of pounds, were incurred on the Welsh Water Authority. Although this incident is not specific to timber harvesting, it is relevant to this project as road building and / or modifications, involving the placing of culverts, is usually associated with any felling activity.

Other impacts of particulate outputs in general upon water resources can include the effect of increased turbidity in reducing the aesthetic quality and therefore recreational value of watercourses. Furthermore, as sediment can carry chemical pollutants such as nutrients, heavy metals and agrochemicals, and biological contaminants such as bacteria and viruses, it can also be indirectly responsible for both chemical and biological pollution (Robinson, 1973).

3.3 Reported Impacts of Particulate Outputs From Forestry Upon Aquatic Life

Impacts of fluvial particulate inputs upon aquatic life are reported in general. Although some research does not specifically relate to particulate outputs specifically associated with harvesting, since enhanced sediment delivery to fluvial systems has been associated with all stages of the forest rotation (Newson and Leeks, 1987; Soutar, 1989; Leeks, 1992), it is likely to result in similar impacts.

Particulate outputs can include both fine and coarse material. The majority of research on physical sediment pollution has, however, been undertaken on the impacts of fine material outputs which therefore forms the bulk of this review. It should be added that changes in coarse sediment inputs can cause channel instability, resulting in geomorphological change which may affect the community within this habitat.

Although both are related to fluvial particulate inputs, different ecological impacts are associated with suspended sediment and sediment deposition. The impacts of each are therefore described for fish, invertebrates and plants.

3.3.1 Impacts of fluvial sediment inputs upon salmonid fish

Most research on fluvial sediment impacts upon freshwater biota has been directed towards salmonid fish species, which are common within European and North American upland watercourses. These include salmon and trout which are of economic importance through both commercial and sport fishing. Although salmonids are known to be particularly susceptible to sediment pollution, similar impacts may affect species belonging to other families, but these have not been extensively recorded in the literature.

Many of the reported impacts of fluvial sediment inputs on salmonids are specifically associated with forestry. For example, in an investigation of forestry impacts upon water quality in Idaho USA, over a quarter of the operations studied by Bauer (1985) were found to represent a major hazard to salmonid habitats.

For the purposes of this review, the impacts of fluvial sediment inputs on salmonid fish have been separated into the affects upon reproductive success and upon post-emergence survival. These impacts approximately correspond to the effects of sediment deposition and suspended sediment respectively.

i. Reproductive success: sediment deposition

The most significant impact of fluvial sediment inputs on salmonid populations is reduced reproductive success due to fine sediment deposition within spawning gravel. This can result in severely depleted salmonid populations in reaches where overall habitat characteristics and general water quality are capable of supporting juvenile fish (Wightman, 1987; Naismith *et al.*, 1996).

Bed material within British upland gravel-bed watercourses commonly contains a disproportionately low 2-4 mm particle size fraction and is therefore often bi-modal. As scouring during flood periods removes fine sediments, the gravel mode coarser than 4 mm makes up the dominant fraction with a subordinate sand mode of matrix material finer than 2 mm (Carling and Reader, 1982; Petts *et al.*, 1989). Carling and Reader (1981) state that the matrix mass in natural gravel-bed rivers is typically between 10 and 28 %. Particle size analysis of gravel samples (<63 mm) collected from Plynlimon streams during 1996 and 1997, by both freeze coring (n = 132) and conventional grab sampling (n = 25), revealed an average matrix mass of 11.4 and 8.1 % respectively. The lower proportion of matrix material in conventional grab samples is likely to be related to the inefficiency of fine particle collection by this method (see 4.5.3).

Survival rates of salmonid eggs and newly hatched alevins within spawning bed gravel are reduced as the proportion of fine matrix material increases in relation to the gravel fraction (Platts et al., 1989; Scrivener and Brownlee, 1989; Forestry Authority, 1993). Primarily, this can be related to the reduction in intragravel permeability and dissolved oxygen supply. Further reductions in salmonid spawning success associated with sediment deposition can be caused by reduced spawning gravel porosity, area and stability, and impacts 'post emergence' upon alevin health and susceptibility to predation.

Fluvial particulate inputs during natural flood events and high erosion potential may not result in significant gravel sedimentation, as under such conditions input material is entrained and transported away from upland spawning areas. As salmonid spawning gravels tend to be located in upland reaches, subsequent deposition in lowland areas may not necessarily affect reproductive success. Impacts of sediment deposition are most significant when fluvial particulate inputs correspond to periods of low discharge and therefore limited transport potential, when fine material can more easily infiltrate the gravel.

As commercial forestry operations, such as drain clearance, can result in fluvial particulate inputs during low flow conditions, sediment deposition and bed material fining has been associated with forestry land use within upland gravel bed rivers (Leeks, 1992; Stott, 1997a). The Forests and Water Guidelines (Forestry Authority, 1993) detail methods by which forestry operators can reduce such impacts.

i.a Intragravel permeability and dissolved oxygen supply

The survival of salmonid eggs and alevins depends upon the relative values of oxygen consumption and delivery. Delivery of intragravel dissolved oxygen (DO) is controlled by its concentration in the river-water and the intragravel flow rate. The latter depends on gravel permeability, which decreases as the proportion of fine matrix increases. Reduced permeability, and therefore intragravel flow, associated with sediment deposition can lower DO availability below the critical thresholds of around 3-5 mg l^{-1} (at field temperatures of about 5 ^{0} C) which are required for salmonid egg and alevin survival (Johnson, 1980, Wightman, 1987; Stott, 1989; Naismith *et al.,* 1996). Low and high gravel permeability has therefore been related to low (Lacroix, 1985) and high (McNeil and Ahnell, 1964) salmonid spawning success respectively.

To ensure sufficient intragravel DO for successful salmonid reproduction, MAFF (1991) reported that spawning gravel permeability should exceed 1 m hr^{-1}, corresponding to a maximum fines content between 12 and 15 %. Calculations of permeability have therefore been used to assess gravel suitability for salmonid spawning. This was undertaken by Moring (1982), who reported that due to fluvial sediment inputs associated with forest harvesting in Oregon USA, the average gravel permeabilities in three tributaries of the Alsea River significantly decreased.

In addition to impacts associated with DO supply, reduced gravel permeability may also inhibit the removal of metabolic waste products (Moring, 1982; Scrivener and Brownlee, 1989).

i.b Gravel porosity

Gravel porosity is a measure of intragravel pore spaces and their connection with the main river environment: it also decreases as the proportion of fine matrix material increases. Reduced porosity has therefore been attributed to the entrapment of newly hatched alevins and the prevention of successful emergence (Megahan *et al.*, 1980; Olsson and Persson, 1986; Petts, 1988; Ringler and Hall, 1988; Scrivener and Brownlee, 1989). Although Crisp (1993) reported that alevin emergence through several centimetres of sand above the spawning gravel had little effect on survival, this was under experimental conditions with clean sand. It is likely that material deposited under natural conditions would include finer particles and organics which may increase mortality due to entrapment and oxygen depletion respectively (Beaumont, 1997).

i.c Spawning gravel area and stability

Spawning fish will avoid turbid water and gravels affected by sedimentation. Consequent limitation of the potential spawning area may result in inefficient spawning at suitable sites due to excessive redd construction. Increased density of spawning fish may also increase their vulnerability to predation and overfishing (Olsson and Persson, 1986; Maitland *et al.*, 1990).

Reduced channel depth associated with sediment deposition can create a physical barrier to migration, and can even result in sub-surface summer flows (Forestry Authority, 1993). However, as salmonids migrate during the autumn / winter seasons, corresponding to periods of high flow, such an impact on migration is unlikely. Sub-surface summer flows will, however, affect the standing crop of juveniles (Wightman, 1997).

Research at Plynlimon has identified significantly higher bed load yields from forested than grassland catchments (Leeks, 1992; Leeks and Marks, 1997). Inputs of coarse sediment can encourage gravel erosion (Forestry Authority, 1993). This may result in egg mortality by either the direct removal of salmonid redds, or increased susceptibility to wash out if redd depths are decreased due to erosion of overlying material. Tripp and Poulin (1986) investigated the impacts of gravel scouring, associated with fluvial sediment inputs from forest harvesting, on salmonid spawning habitats within streams on the Queen Charlotte Islands, Canada. Within logged reaches, estimated egg losses were 66-86% for chum salmon (*Oncorhynchus keta*) and 45-70% for coho salmon (*Oncorhynchus kisutch*). Losses of only 2-14% and 0-4%, for chum and coho salmon respectively, were recorded in stable reaches.

A potential advantage of gravel deposition associated with inputs of coarse sediment may be an increase in the potential spawning area. Recently deposited gravel will, however, tend to have a lower critical erosion threshold, thereby reducing its resistance to mobilisation during flood periods. This can result in spawning bed instability, and consequent increased mortality of salmonid eggs and alevins (McNeil, 1966).

i.d Post emergence alevin health and predation susceptibility

As the homogenous particle size in simulated redds decreased from 32 to 1.5 mm, premature emergence and an extension of the total emergence period of brown trout (*Salmo trutta*) alevins was reported by Olsson and Persson (1986). It was suggested that this response may be triggered by gravel fining associated with sediment deposition, and represent an adjustment of trout to increase survival in streams with unstable spawning gravels. However, premature alevins are poor swimmers due to their small size and large yolk reserve, and the predator satiation possibly associated with synchronous emergence may not be apparent if the emergence period is extended. Predation susceptibility could therefore be increased with a consequent reduction in post emergence survival. It should, however, be recognised that given the wide range of particle sizes in natural river gravels, as indicated by studies at Plynlimon, it is unclear how fine material deposition within a typical gravel of mixed size composition would affect alevin emergence patterns.

ii. Factors affecting the impacts of sediment deposition upon salmonid reproduction

Spawning gravel fining is the main cause of reduced salmonid reproduction success associated with fluvial particulate inputs and sediment deposition. The most appropriate gravel characteristic which can be used to measure this is particle size. However, particle chemistry and shape, and variation in response and behaviour between fish species are also important.

ii.a Particle size

Optimum survival of salmonid eggs and alevins will occur within a specific size range of bed material. Megahan *et al.* (1980) reported 6.7 - 101.6 mm as the ideal spawning gravel particle size range for North American salmonids, outside which reproduction success is significantly reduced. Similar relationships exist for British species. Crisp and Carling (1989) demonstrated that despite the availability of a wide variety of gravel sizes, chosen salmonid redds in north east England and south west Wales usually had a median grain size of 20 - 30 mm (coarse gravel), indicating selection by the fish.

Authors agree that a high percentage of fines in spawning gravels will be detrimental to fish populations (Fraser, 1972; Platts and Megahan, 1975; Tappel and Bjornn, 1983). As sediment deposition commonly results in gravel fining, variation in the proportion of material below a specific size threshold can be appropriate for impact assessment associated with fluvial particulate inputs.

Petts (1988) stated that the most significant grain-size measurement relating to reductions in salmonid egg and fry survival is variably defined as the proportion of inorganic sediment finer than a critical size of between 9.5 mm and 0.84 mm. North American authorities have used the proportion finer than 1 mm to assess spawning gravel quality (Cordone and Kelley, 1961; Adams and Beschta, 1980). Similarly, the Forests and Water Guidelines (Forestry Authority, 1993) state that ideal substrates contain less than 15 % by weight of material finer than 1 mm. A number of studies have attributed reduced reproduction success of specific salmonid species to the proportion of spawning bed material finer than a critical size threshold. This has been defined as 6.35 mm for chinook salmon (*Oncorhynchus tshawytscha*) (Bjornn, 1973), 0.83 mm (Hall and Lantz, 1969) and 3.33 mm (Ringler and Hall, 1988) for coho salmon, 0.83 mm for pink salmon (*Oncorhynchus gorbuscha*) (McNeil and Ahnell, 1964) and 0.84 mm for all Pacific salmon species (Bradley and Reiser, 1991). Again, similar relationships have been reported for British species. Olsson and Persson (1986) correlated reduced reproduction success of brown trout with the proportion of spawning bed material finer than 18 mm.

The proportion of fine material (< 2 mm) is most commonly used as the particle size threshold for measuring spawning gravel suitability for salmonid reproduction. The upper threshold for which has been reported as 20 % (Petersen, 1978; Wightman, 1987; Naismith *et al.*, 1996).

ii.b Particle organic content

Although the dissolved oxygen content is likely to be high in cool fast flowing upland watercourses, oxygen is utilised during the decomposition of fine organic debris which may exacerbate any impacts of dissolved oxygen deficiency associated with reduced spawning gravel permeability. This may be particularly significant in forested catchments, within which fluvial particulate loads may consist of up to 20% organic material (Maitland *et al.*, 1990), particularly during harvesting (Ringler and Hall, 1988).

ii.c Particle shape

Particle shape can influence sedimentation rates and gravel permeability and winnowing. Scrivener and Brownlee (1989) reported that round gravels accumulate more fine sediment than angular material during periods of low flow, but this relationship is reversed as flow rates increase. Once fines have intruded into the stream-bed, permeability and cleaning potential is thought to increase with gravel roundness (McNeil and Ahnell, 1964).

ii.d Variation in fish response and behaviour associated with species and size

The effect of gravel sedimentation on salmonid reproduction can be influenced by a number of biological factors. The significance of fining impacts within specific horizons will depend on redd depth. Susceptibility to short-term sedimentation impacts will also depend on the timing of spawning, and therefore the development of eggs and newly hatched alevins.

To accurately assess the potential impacts of sediment deposition, it is important to identify the habitat importance of the affected horizons. Studies of the most common salmonid species found in British gravel bed rivers, brown trout, sea trout (*Salmo trutta*) and Atlantic salmon (*Salmo salar*), report increasing redd depth with fish size (Ottaway *et al.*, 1981; Elliott, 1984). For these species, the regression lines of Crisp and Carling (1989) indicate egg burial depths ranging from 8 to 24 cm as female fish length increases from 20 to 80 cm.

Due to size variation, a very rough approximation is that brown trout, sea trout and Atlantic salmon construct their redds within 0-10, 10-20 and 20-30 cm depth zones respectively within the spawning gravel (Beaumont, 1996). Consequently, the eggs of migratory fish may be better protected from wash-out, but more vulnerable to sedimentation which is often more significant within deeper horizons (Crisp and Carling, 1989).

Void spaces in surface gravel layers must be sufficient to allow hatched alevins to escape (Scrivener and Brownlee, 1989). As salmon fry are generally larger than those of trout, limited porosity reduction may only restrict the movement of salmon alevins. Thus sedimentation impacts in upper gravel horizons, where only brown trout redds exist, may indirectly affect the reproductive success of fish that bury their eggs deeper.

The timing of sediment deposition and spawning gravel fining may affect the impacts on salmonid reproduction success. In British rivers, the critical period when eggs and alevins are living in the spawning gravels, and are therefore vulnerable to the effects of siltation, is normally from October to March (Turnpenny and Williams, 1980; Milner *et al.*, 1985). As intragravel development rate depends mainly on temperature, this can extend to May or even June in some northern and / or upland streams (Wightman, 1997).

Salmonid eggs and alevins are vulnerable to the impacts of reduced dissolved oxygen supply associated with sediment deposition and spawning gravel fining during their entire period within the spawning gravel. Although oxygen demand is highest around hatching time (Hayes *et al.*, 1951), the relationship between salmonid egg and embryo development and their susceptibility to sedimentation impacts is unclear. Both reduced (Stuart, 1953; Cordone and Kelley, 1961; Bradley and Reiser, 1991) and increased (Naismith *et al.*, 1996) susceptibility with stage of development have been reported.

iii. Post emergence survival: suspended sediment

After emergence from the spawning gravel, the most significant impact of fluvial sediment inputs on salmonid fish is the influence of suspended particulates. This can be divided into the effect of suspended material on gill functions, and the lesser effect of reduced visibility associated with turbidity on feeding and social organisation.

iii.a Gill functions

Suspended sediment may cause gill irritation and damage by congestion and mechanical abrasion (Cordone and Kelley, 1961; Alabaster, 1972). Berg and Northcote (1985) observed gill irritation in juvenile coho salmon subjected to sediment associated turbidity of just 20 nephelometric turbidity units (NTU). In the headwaters of the River Severn at Plynlimon, an approximate 1:1 relationship exists between sediment concentration in mg l^{-1} and turbidity in NTU. Such conditions are therefore likely to occur in similar upland forested catchments, where suspended sediment concentrations exceeding 20 mg l^{-1} commonly occur during hydrological events (Leeks and Marks, 1997). However, in addition to concentration, other suspended sediment parameters such as particle size distributions and length of exposure will affect the impacts upon salmonid fish. As these are rarely considered in the biological literature, reported impacts associated with specific concentrations are likely to vary. Due to the very peaked sediment response of upland catchments to hydrological events, impacts may not be sustained for long enough to cause damage.

Suspended sediment can also increase the susceptibility of fish to disease. Mucus secretion from irritated gill tissues provides a focus for the growth of bacteria and fungus (Berg and Northcote, 1985) and abrasive damage can provide a route of entry for pathogens (Kelly, 1994).

iii.b Reduced visibility associated with turbidity - Feeding

Increased turbidity associated with suspended sediment can result in sight impairment, reducing the success of sight feeding by predatory fish such as salmonids (Hynes, 1973; Wilzbach *et al.*, 1986). As food is often scarce in the headwater streams which drain upland forested catchments, an increase in either the magnitude, frequency or duration of turbidity events could affect fish health.

Although salmon have been observed to cease feeding during spate conditions and associated high turbidity (Kelly, 1994), it cannot be established whether this is due to an inability to feed by visual stimuli, or an attempt to seek shelter during the flood period. Detailed investigations have, however, been undertaken to quantify the reduction in feeding efficiency specifically associated with turbidity. Berg and Northcote (1985) reported that coho salmon subjected to a suspended sediment pulse, and associated turbidity increase from 0 to 30 NTU, showed significant reductions in reactive distance, prey capture success and the percentage of prey ingested. Similarly, Barrett *et al.* (1992) identified that the average reactive distances of rainbow trout (*Oncorhynchus mykiss*) in 15 and 30 NTU treatments were only 80% and 45% respectively, of those observed at ambient turbidities (4-6 NTU).

Significant reductions in feeding efficiency have been associated with specific concentrations of suspended sediment. Although it may also reflect additional stress imposed by the unfamiliar environment, a suspended sediment concentration of just 3-4 mg l^{-1} has been observed to stop salmonids feeding in an artificial site (Kelly, 1994). Bachmann (1958), in Cordone and Kelley

(1961), investigated the effect of suspended sediment on rainbow trout feeding within a natural river. While fish within a control section fed actively, those subjected to an artificially created silt turbidity of 35 mg l^{-1} for two hours, although showing no distress or mortality, ceased feeding and moved to cover.

iii.c Reduced visibility associated with turbidity - Organisation

As the social organisation of many fish populations, especially salmonids, is strongly influenced by visual contact, territoriality is affected by the reduced visibility associated with turbidity. Berg and Northcote (1985) reported that when a coho salmon population was visually isolated at 30 NTU, dominance hierarchy and territoriality was disrupted, and reformed when turbidity decreased to 20 NTU. As territoriality provides greater feeding opportunity and reduces energy expenditure, predation and the risk of movement to less favourable habitats, its disruption could have adverse impacts upon fish populations.

Fish use visual contact with the bed to maintain position in flowing water. Consequently, movement to less favourable holding positions may also reduce feeding success during periods of high turbidity, when fish have been observed to move to the bottom in order to make visual or even tactile contact (Berg and Northcote, 1985).

iii.d Reduced visibility associated with turbidity - Migration

During migration, in addition to increased discharge and changes in water chemistry, high turbidity in estuarine waters has been linked to the successful entry of salmonids to a river system (Wightman, 1997). Within the river, however, further migration may be barred by excessive turbidity (Forestry Authority, 1993).

iv. Threshold concentrations of suspended sediment

It is evident that suspended particulates can have a number of adverse affects on fish. However, physical variation between sediment properties and transport dynamics, intra- and inter-species biological differences, and combined impacts with chemical pollutants prevents accurate assessment of the potential impacts associated with specific concentrations.

Impacts upon gill functions may depend more on the physical properties of suspended particles than concentration. Consequently, threshold levels, above which gill functions will be affected, cannot be defined. For a specific suspended sediment concentration, gill damage is likely to be more significant for finer particle sizes which can cause significant gill abrasion by passing or lodging between lamellae (Kelly, 1994). Furthermore, particles which can pass through the primary lamellae of the gill, which is resistant to such damage, can then affect the more delicate secondary lamellae. Particle shape, texture and mineralogy will also govern the effect on gill function. Hard angular solids cause more surface abrasion than soft, rounded or organic particles. The latter, however, are more likely to adhere to fish gills and cause damage by clogging (Kelly, 1994).

As particle heterogeneity introduces considerable scatter in the positive relationship between suspended sediment concentration and turbidity, turbidity impacts cannot be related to specific suspended sediment concentrations. Similar to impacts upon gill function, turbidity increases will generally be more significant for finer particle sizes, but other properties such as mineralogy and shape introduce further variation (Gippel, 1989).

The dynamics of suspended sediment transport will also affect its impact on fish. For an equivalent concentration or turbidity, the gradual increase and decrease common during natural high flow events may result in less severe impacts than sudden pulses unrelated to flow. Sudden suspended sediment pulses may be caused by the direct supply of material to the river channel, which can occur during commercial forestry operations such as drain clearance. Berg and Northcote (1985) identified that the alarm reaction exhibited by salmonids, subjected to a sudden increase of suspended sediment was not apparent when an equivalent concentration was attained gradually over several hours. It was reported that sudden increases may cause downstream displacement away from the sediment source, potentially into less favourable habitats. Physical impacts upon gill structures can also vary with the transport pattern of suspended sediment. While acute exposure can lead to immediate mechanical damage, chronic exposure can eventually result in the fusion of gill lamellae (Wightman, 1997).

Impacts of suspended sediment which would not pose a serious risk to fish health in isolation may result in fish mortality where water quality is affected by chemical pollutants (Herbert and Merkens 1961; Alabaster, 1972; Maitland *et al.*, 1990). For example, gill damage by toxic chemicals may affect the mucus secretion which enables healthy fish to survive the impacts of gill clogging, thereby resulting in fish mortality during conditions of suspended sediment transport which normally pose no serious health risk (Cordone and Kelley, 1961; Berg and Northcote, 1985).

Effects of physical sediment pollution may be exacerbated by impacts associated with the hydrochemistry of upland forested watercourses (Neal *et al.*, 1997). For example, both dissolved inorganic aluminium (Dobbs *et al.*, 1989; Reader and Dempsey, 1989; Wood, 1989) and suspended particulates can affect the respiration of salmonids. Within natural systems affected by fluvial particulate inputs, it may therefore be difficult to isolate the specific impact of suspended particulates from the synergistic stresses induced by other pollutants.

Despite the confounding physical, chemical and biological parameters which affect the relationship between suspended sediment concentration and impacts upon fish health, attempts have been made to define a suspended sediment concentration above which damage can occur and below which there is no adverse affect. For example, Alabaster and Lloyd (1980) stated that while suspended solids concentrations below 25 mg l^{-1} would probably have no harmful effect, waters normally containing concentrations of over 80 mg l^{-1} were unlikely to support good freshwater fisheries. Similarly, Hynes (1973) quoted 80 mg l^{-1} as the upper level of suspended sediment tolerable by biota in running water, and that serious fishery damage may be associated with chronic exposure to concentrations exceeding this threshold. Alabaster and Lloyd (1980), however, reported that these thresholds relate to normal levels and that concentrations of several thousand mg l^{-1} may not kill fish during several hours or days exposure. Such temporary high concentrations should, however, be prevented in rivers where good fisheries are to be maintained, particularly in salmonid spawning areas where its subsequent deposition may result in far more significant impacts associated with reduced reproduction success.

3.3.2 Impacts of fluvial sediment inputs upon invertebrates

Whereas impacts upon fish can be indirect and complex, aquatic invertebrate populations are known to respond more directly to the influence of fluvial particulate inputs. In an investigation into the value of biomonitors of stream quality in agricultural areas, especially as to the relative merits of using fish or invertebrates, Berkman *et al.* (1986) found that invertebrates were more sensitive than fish to habitat quality in sediment-impacted streams.

i. Sediment deposition

Similar to its suitability for salmonid spawning, particle size will affect habitat quality of bed material for benthic invertebrates. Although the optimum particle size will vary for different species, coarse gravels are likely to be the most productive. These provide a stable habitat with high permeability to ensure the supply and removal of metabolites, and high porosity to provide suitable spaces and connectivity.

Detrimental impacts upon benthic invertebrates have therefore been associated with the fining of bed material (Herbert and Merkens, 1961; Petts, 1987). Even a relatively thin sediment deposit can have a marked effect on stream invertebrates, eliminating certain species such as mayflies and stoneflies and encouraging burrowing worms and midge larvae (Nuttall, 1972). As the latter are less available to predators than the original organisms, this may have significant knock on effects to animals higher in the food chain (Maitland *et al.*, 1990). A number of investigations have attributed reductions in invertebrate populations to fluvial sediment inputs specifically associated with commercial forestry practice, particularly harvesting operations (Wustenberg, 1954; Tebo, 1955; 1957; 1967; Bachman, 1958).

ii. Suspended sediment

Adverse impacts of suspended sediment on invertebrates are similar to those reported for fish. This includes impacts upon gill functions by mechanical abrasion, congestion and mucus secretion (Haile, 1983), and reduced sight feeding success associated with turbidity.

3.3.3 Impacts of fluvial sediment inputs upon plants

Algae and higher plants cycle inorganic nutrients, and through photosynthesis play an essential role in stream aeration and natural purification (Cordone and Kelley, 1961). As they represent an important primary production component of ecological food chains, impacts upon these organisms can significantly affect the entire community within aquatic ecosystems.

i. Sediment deposition

Fining of gravel bed material will reduce the surface area of the stream bed and may reduce the habitats available for colonisation by aquatic flora (Cordone and Kelley, 1961). Although not identified by recent studies at Plynlimon (see 4.5), bed material fining within upland gravel bed rivers has been associated with forestry land use (Leeks, 1992; Stott, 1997a). In extreme cases, sediment deposition may result in the smothering of benthic plants and algae (Cordone and Kelley, 1961), and deposited fine material may be easily erodible and therefore unsuitable for subsequent colonisation (Maitland *et al.*, 1990). Such impacts are, however, unlikely to be of high significance within upland gravel bed watercourses where low rates of primary production are likely to be characteristic due to the constraints on plant colonisation and growth, imposed by limited bed stability.

ii. Suspended sediment

Increased turbidity will reduce light penetration through the water column, and can therefore be responsible for limiting the growth of chlorophyllous organisms. Suspended sediment can also destroy algae and plants by abrasive action (Cordone and Kelley, 1961).

3.3.4 Conclusions

Both sediment deposition and suspended sediment transport can affect fish, invertebrates and plants within upland gravel bed rivers. Many studies have identified increased bed load and suspended sediment fluxes associated with forestry land use and practice. The most significant impact of fluvial sediment inputs is likely to be reduced salmonid reproductive success due to spawning gravel fining. Studies of bed composition must therefore be incorporated into any investigation to identify the ecological impacts of fluvial sediment inputs to upland gravel bed rivers.

It is important to recognise that the relationship between the ecological impacts associated with specific sediment thresholds is likely to be affected by the temporal and spatial variation of many additional parameters. These include particle composition, transport and deposition patterns, chemical stress and susceptibility of biota. Extrapolations of individual studies to wider relevance should therefore be treated with caution and appear to have resulted in a lack of consistency in the literature. In conclusion, while geomorphological research may not be targeted to identify the potential ecological impacts of fluvial particulate inputs, biological investigations may not take into account the variations in sediment properties or transport dynamics. Consequently, definition of the potential impacts of fluvial sediment inputs on the ecology of upland gravel bed rivers demands the integration of specific geomorphological and biological research.

4 DETAILED MONITORING PROGRAMME WITHIN THE INSTITUTE OF HYDROLOGY EXPERIMENTAL CATCHMENTS AT PLYNLIMON

In addition to the literature reviews in Chapter 3, this study also included substantial field science building upon past studies and newly instrumented river reaches. A map of the sediment monitoring sites employed to investigate the impacts of particulate outputs associated with a typical plot-scale harvesting operation within the Plynlimon Experimental Catchments is shown as Figure 2. Previous harvesting studies at Plynlimon no longer represent typical FE practice and are therefore unsuitable for impact assessment associated with contemporary operations. For example, the Afon Hore clear-fell experiment (Leeks, 1992) involved the felling of 91 ha, comprising 29 % of the total catchment area (Roberts and Crane, 1997). Current FE harvesting policy favours the phased felling of smaller plots, normally in the region of 10 - 20 ha.

4.1 Site Details

The harvesting plot selected for this study represented typical Forest FE felling practice, consisting of 13 hectares of dominantly Sitka spruce (*Picea sitchensis*) bordering the southern bank of the Nant Tanllwyth and comprising 15 % of the total catchment area. Timber density was 300 tonnes per hectare, producing a total of 4000 tonnes of timber. The harvesting site was divided into three areas (shown as 1-3 on Figure 3), each felled using a specific technique appropriate to the site conditions (see below and Tables 3 - 5 for further details).

4.1.1 Harvesting area 1

Dry ground conditions and a shallow gradient enabled an upper area of the site to be harvested by the whole tree method. A clambunk machine felled the trees using a harvester head attached to a crane arm which loads them onto its trailer using large hydratongs. The whole trees were then transported to the roadside stacking area where the brash was removed and the timber cut into required lengths for stacking. Brash was therefore concentrated at roadside stacking points, leaving the felled area free of debris. This reduces both the post-harvesting waiting period and site preparation necessary before re-afforestation.

Some brash thatching was undertaken along the edge of the site, where vehicle operation was concentrated adjacent to the stacking areas and access roads. This complied with the recommendation in Forests and Water Guidelines (Forestry Authority, 1993) to maintain an adequate supporting brash mat for the principal vehicle routes. Since brash removal takes place at stacking areas rather than within the felling site during whole tree harvesting, it would be impractical to carry brash from the stacking areas back to the felling site. Consequently, this technique is only suited to sites with dry ground conditions and shallow gradients where brash thatching along all vehicle access routes within the felling site is unnecessary.

4.1.2 Harvesting area 2

The majority of the remaining area of the site is nearer the valley bottom and has a steeper gradient with wetter ground conditions. It was therefore necessary to protect the soil along all vehicle access routes with brash matting. This site was therefore harvested using the shortwood (Harvester) system which involves the removal of brash where the tree is felled, and therefore allows brash thatching along all vehicle access routes within the felling site. A tracked vehicle was used with a harvester head attached to a crane arm which fells the tree, immediately removes the brash and cuts the timber into the required lengths on-site. A forwarder was then used to transport the cut timber to roadside stacking areas. All vehicles operated on thick brash mats.

4.1.3 Harvesting area 3 - Tanllwyth riparian zone

Large harvesting machinery cannot operate along river banks. Trees in the riparian zone, directly bordering the south bank of the Nant Tanllwyth, were therefore removed by skidding. This method involved manual felling by chainsaw operators who undertook brash removal where the trees fell. The "lopped and topped" poles were then dragged (skidded) to processing sites using a tractor. Cutting into the required lengths was undertaken manually at the processing sites. The cut timber was then transported by forwarder to roadside stacking areas.

On 3 June 1996, to allow felled timber to be skidded to a processing area on the northern side of the river, a temporary log bridge was built at the north-eastern end of the Tanllwyth harvesting site. This was removed on 21 June 1996, when all harvesting operations were completed.

Although the FE Wales Harvesting manual (Killer, 1994) gives guidance on the construction of temporary log bridges, this type of crossing was not recommended, for safety reasons, due to the difficulty in checking its structural integrity, and obscuration of the bridge line by the brash covering needed to distribute wheel loads and collect wheel mud. This bridge was constructed in accordance to guidance in the FE Wales Harvesting manual (Killer, 1994) and Forestry Commission (FC) Soft Ground Harvesting Report (Forestry Commission, 1991b). The latter states that such crossings should not produce any silt providing that the recommended measures have been taken.

Harvesting method	Whole tree (Clambunk)
Main tree species	Sitka spruce (*Picea sitchensis*)
Start date	29 January 1996
Finish date	25 March 1996
Area	3.5 Ha
Timber removed	620 m^3 (calculated by field survey)

Table 3 Harvesting site summary, Tanllwyth Area 1

Harvesting method	Shortwood (Harvester)
Main tree species	Sitka spruce (*P. sitchensis*)
Start date	12 February 1996
Finish date	19 April 1996
Area	8 Ha
Timber removed	1425 m^3 (calculated by field survey)

Table 4 Harvesting site summary, Tanllwyth Area 2

Harvesting method	Skidding
Main tree species	Norwegian spruce (*P. abies*)
Start date	29 April 1996
Finish date	21 June 1996
Area	1.5 Ha
Timber removed	311 m^3 (calculated by field survey)

Table 5 Harvesting site summary, Tanllwyth Area 3

4.2 Monitoring of Suspended Sediment Outputs Associated with Harvesting Operation

A continuous record of suspended sediment concentration (15 minute interval data) was obtained for river monitoring sites S1 - S6 (see Figure 2) by using the Wallingford Integrated System for Environmental monitoring in Rivers (WISER) instrumentation (see Wass *et al.*, 1997). Grid references of these sites and dates of monitoring for this project are shown in Table 6.

Site	Grid Reference	Start of monitoring	End of monitoring
Upper Tanllwyth (S1)	SN 837878	01.01.96	30.06.97
Lower Tanllwyth (S2)	SN 842877	01.01.95	30.06.97
Upper Hafren (S3)	SN 837883	01.01.96	30.06.97
Lower Hafren (S4)	SN 843877	01.01.95	30.06.97
Severn (S5)	SN 853872	01.01.95	30.06.97
Wye (Cyff) (S6)	SN 824842	01.01.96	30.06.97

Table 6
Grid references and periods of data collection at WISER river monitoring sites within the Institute of Hydrology Experimental Catchments

WISER employs the dual application of optical turbidity instruments which operate on both nephelometric and absorptiometric principles. While the nephelometric sensor is very accurate at measuring lower turbidity levels, it has a limited operating range. Although the absorptiometric instrument is less accurate at measuring low turbidity levels, it has a wider operating range and can therefore accurately operate to higher levels. This ensures accurate monitoring of the full range of turbidity levels, and provides backup protection in the event of instrument failure. Turbidity data was initially calibrated into Formazin Turbidity Units (FTU). A relationship was then established between turbidity (FTU) and suspended sediment concentration (mg l^{-1}) by laboratory determination of the suspended sediment concentration in water samples, collected both automatically and manually. At the Lower Tanllwyth (S2), Lower Hafren (S4), Severn (S5) and Wye (S6) sites, suspended sediment concentration and water discharge records have been combined to enable total flux calculations. No water discharge gauging was undertaken at the Upper Tanllwyth (S1) and Upper Hafren (S3) sites.

All quarterly continuous suspended sediment concentration and water discharge data is shown in Chapter 1 of R&D Project Record P2/i465/19 (Figures 1 - 15). For the Upper Tanllwyth (S1) and Upper Hafren (S3) sites, the suspended sediment concentration record has been combined with the downstream water discharge records at Lower Tanllwyth (S2) and Lower Hafren (S4) sites respectively. All plots show the importance of discharge in controlling suspended sediment concentration and transport. This relationship is shown in the rating curves in Figures 4 - 5.

Comparisons of continuous suspended sediment concentration between different sites are shown by Figures 16 - 26 in Chapter 2 of R&D Project Record P2/i465/19. For statistical analyses, suspended sediment concentration data was normalised by the removal of zero values and application of a logarithmic function. Figures 27 - 41 in Chapter 3 of R&D Project Record P2/i465/19 show the data distributions before (a) and after (b) application of a $\log_{10}$ function. Results are summarised in Table 7.

4.2.1 Interpretation of results from Nant Tanllwyth in comparison with other Plynlimon sub-catchments

As the felling operation took place from 29 January 1996 to 21 June 1996, annual data can be regarded as corresponding to three phases in relation to the harvesting operation: pre-felling control data (1995), during and immediately after felling (1996) and post felling (1997). Catchment suspended sediment outputs can be compared in Table 7 using both annual yields and mean suspended sediment concentration for the complete data sets. Suspended sediment yields are calculated by dividing the total annual suspended sediment load by the catchment area to give values in t km^2 yr^1. Mean suspended sediment concentrations represent the average of the complete normalised ($\log_{10}$) 15 minute data sets. As the suspended sediment yields are calculated from the real data whereas mean suspended sediment concentrations are statistically derived, they do not always reveal the same patterns. Although the yields represent the true catchment suspended sediment outputs, they represent single values and therefore cannot be used for inter-catchment statistical comparisons. In this study, suspended sediment concentrations are therefore used for statistical comparisons between catchment suspended sediment outputs. Results for both suspended sediment yields and concentrations are therefore reported separately.

i. Suspended sediment yields

Previous research at Plynlimon (Leeks, 1992), and the results presented in Table 7, show that for all years when data is available, catchment suspended sediment yields follow the pattern:

Lower Tanllwyth (S2) > Lower Hafren (S4) > Severn (S5) > Wye (S6)

Table 7 shows that before harvesting (1995), suspended sediment yields from the Tanllwyth (24.3 t km^{-2} yr^{-1}) catchment were 51 % higher than from the Hafren (16.1 t km^2 yr^1). During 1996, when timber harvesting was undertaken within the catchment, this difference increased to 90 %, corresponding to sediment yields of 43.8 and 23.1 t km^{-2} yr^{-1} . If 1995 results are used to represent the background difference in suspended sediment yields between the two catchments, and assuming all other variables are equal, the timber harvesting operation could have led to a 39 % increase in yields from the Tanllwyth, 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. As Figure 3 shows that felled timber from the Tanllwyth site was removed to the south along the main forest road, away from the Hafren catchment, this increase is unlikely to have been caused by increased traffic on forest roads associated with the Tanllwyth harvesting operation. As 1995 and 1996 annual rainfall totals at the Moel Cynedd Meteorological Station (see Figure 3) were 2047 and 1963 mm respectively, this increase was also not associated with a rise in precipitation inputs between the two years. As modern FE practice involves the felling of small 10-20 ha plots which are often dispersed throughout the forest, it is very difficult to isolate a major watercourse from any felling activity within its catchment. Consequently, the most likely explanation for this increase in suspended sediment yield from the Afon Hafren catchment between 1995 and 1996 is that some small areas of timber harvesting took place in the headwaters of the catchment during 1996 - 1997. Consequently, suspended sediment outputs from the Nant Tanllwyth may be more significant than indicated in this investigation when compared with the Afon Hafren as a control catchment unaffected by this activity. More of the 90 % (19.5 t km^{-2} yr^{-1}) increase in suspended sediment yields from the Nant Tanllwyth catchment between 1995 and 1996 could therefore have been attributed to the harvesting operation.

Suspended sediment yield for the entire Severn catchment (Site S5) slightly decreases between 1995 and 1996. This is supported by the 1995 and 1996 annual rainfall totals from the Moel Cynedd Meteorological Station, which suggests that the increase in the Tanllwyth and Hafren is unlikely to have been related to different weather / hydrological conditions between the two years, which would also have been likely to affect the results from the Severn (S5) site. It should, however, be recognised that annual rainfall totals may not correspond to rainfall erosivity which relates to many additional factors such as rainfall intensity and drop size. Furthermore, the effect of variations in weather conditions may be influenced by the erodibility of the land surface which is likely to increase in association with timber harvesting operations. Consequently, increases in rainfall erosivity may increase erosion in catchments affected by timber harvesting operations while having little influence within stable areas. It is, however, surprising that suspended sediment yields at the Severn (S5) site did not reflect the upstream increases at the Lower Tanllwyth (S2) and Lower Hafren (S4) sites. This could be due to dilution from the Afon Hore and other tributaries which were less affected by recent harvesting operations.

ii. Suspended sediment concentrations

Mean suspended sediment concentrations for the normalised data sets (see 4.2) are shown in Table 7. Box plots showing the mean and 0^{th} (minimum value), 1^{st}, 5^{th}, 25^{th}, 50^{th} (median), 75^{th}, 95^{th}, 99^{th} and 100^{th} (maximum value) percentiles for the normalised suspended sediment concentration data sets at the Upper Tanllwyth (S1), Lower Tanllwyth (S2), Upper Hafren (S3), Lower Hafren (S4), Severn (S5) and Wye, Cyff, (S6) sites are shown in Figures 6 - 11 respectively. Figures 12 - 14 show the suspended sediment concentration data for all sites during each monitoring period, 1995, 1996 and 1997 respectively. Table 8 summarises how these plots can be interpreted..

Similar to the results for suspended sediment yields, Figures 4 and 12 - 14 show that for all years when data is available, suspended sediment concentrations also follow the pattern:

Lower Tanllwyth (S2) > Lower Hafren (S4) > Severn (S5) > Wye (S6)

To test if the differences between average suspended sediment concentrations were statistically significant, both analysis of variance (*f*) and *t*-tests were undertaken on the normalised data sets.

As higher values indicate a larger difference, the values for *f* and *t* can be used as an indicator of the difference between the means of like sized data sets. Table 9 shows a summary of the statistics between the 1995 and 1996 annual data sets. Table 10 shows a summary of the statistics between 1997 six monthly data sets. Both tests for each of the comparisons shown in these tables indicate that the means are significantly different at the 0.001 level. High significance levels are, however, likely when dealing with such large data sets. As expected, the same rank in order of difference is shown by both *f* and *t* values.

In contrast to the results for suspended sediment yields, Table 9 shows that the difference in mean suspended sediment concentration at the Lower Tanllwyth (S2) site above that for the Lower Hafren (S4) site is highest during 1995. Consequently, any particulate outputs associated with felling in the Nant Tanllwyth catchment during 1996 do not appear to have been sufficient to increase the difference in mean suspended sediment concentrations between the two rivers.

For all sites where data is available, annual mean suspended sediment concentrations increase between 1995 and 1996 (see Table 9, and also Figures 7, 9 and 10 for Lower Tanllwyth (S2), Lower Hafren (S4) and Severn (S5) sites respectively). Table 9 shows that the magnitude of this increase follows the order:

Lower Hafren (S4) > Lower Tanllwyth (S2) > Severn (S5)

This indicates that the increase in mean suspended sediment concentrations between the before harvesting, control, (1995) and during harvesting (1996) period is slightly higher in the unfelled (Hafren) control catchment. The increases in concentration in the Tanllwyth are, however, higher than for the entire Upper Severn catchment at site S5. As data is only available for the first 6 months of 1997, mean suspended sediment concentrations for 1997 cannot be compared statistically with those for the complete 1996 data set.

Tables 9 and 10 and Figures 13 and 14 show that during and after harvesting (1996 and 1997 respectively) the difference in mean suspended sediment concentrations is higher between the Upper (S1) and Lower (S2) Tanllwyth sites than between the control Upper (S3) and Lower (S4) Hafren sites. This indicates that the input of particulates between the Upper and Lower Tanllwyth sites, corresponding to the harvesting area, is more pronounced than any particulate inputs between the Upper and Lower Hafren sites, which corresponds to an unfelled area of forestry. However, as no control data is available for the Upper Tanllwyth (S1) site from before the harvesting period, it is difficult to determine if the higher particulate inputs to the Nant Tanllwyth are specifically associated with felling or simply due to the known higher erosion levels within this catchment.

Table 7 and Figures 7 and 9 reveal a further increase in mean suspended sediment concentrations between 1996 and 1997 by 78 % at the Lower Tanllwyth (S2) and 91 % at the Lower Hafren (S4) sites respectively. Table 7 and Figures 6 and 8 indicate that concentrations remain comparatively stable between 1996 and 1997 at the Upper Tanllwyth (S1) and Upper Hafren (S3) sites respectively. This indicates increases in particulate outputs between Upper and Lower Tanllwyth and Hafren sites between 1996 and 1997, which are unlikely to have been caused by different hydrometeorological conditions between the two periods which would also have been likely to affect upper control sites. As discussed in i., it should, however, be recognised that the effect of variations in hydrometeorological conditions may be influenced by the erodibility of the land surface which is likely to increase in association with timber harvesting operations. Consequently, increases in rainfall erosivity may increase erosion in catchments affected by timber harvesting operations while having little influence within stable areas.

Similar to the results of suspended sediment yields between 1995 and 1996 (see i.), the most likely explanation for this increase in mean suspended sediment concentrations from the Afon Hafren catchment during 1996 and 1997 is that some small areas of timber harvesting took place in the headwaters of the catchment during these periods. Again, it is surprising that mean suspended sediment concentrations at the Severn (S5) site did not reflect the upstream increases at the Lower Tanllwyth (S2) and Lower Hafren (S4) sites. This could be due to dilution from the Afon Hore and other tributaries which were less affected by recent harvesting operations.

No increase in suspended sediment concentrations were recorded in association with use of the temporary log bridge at the north-eastern end of the Tanllwyth harvesting site between 03.06.96 and 21.06.96. This bridge was constructed in accordance with guidance in the FE Wales Harvesting manual (Killer, 1994) and Forestry Commission (FC) Soft Ground Harvesting Report (Forestry Commission, 1991b). The latter states that such crossings should not produce any silt providing that the recommended measures have been taken.

4.3 Detailed Field Investigation of Surface Drainage Within Tanllwyth Harvesting Site During Flood Event

A detailed investigation of the suspended sediment concentration in all surface drainage identified within the Tanllwyth harvesting site, and other control sites, was undertaken during a flood event on 12.02.97. Samples were collected at the sites indicated on Figure 15 and analysed for total suspended solids concentration by vacuum filtration (for details of harvesting areas etc. see Figure 3). Results and exact time of sampling are shown in Table 11 and summarised in Table 12. Discharge at the Lower Tanllwyth (S2) monitoring site can be used as an indicator of flow conditions within the catchment at the time of sampling. Full details of the flood hydrograph are shown on Figure 16 which shows the discharge at the Lower Tanllwyth site during 12.02.97. Discharge for this period can also be seen on Figures 2 and 5 in R&D Project Record P2/i465/19, corresponding to day number 43 on the x axis.

Average flow at the Lower Tanllwyth site is 0.063 $m^3 s^{-1}$ (based on a ten year 1988 - 1997 period). On 12.02.97 flow at the Lower Tanllwyth monitoring site reached 1.4 $m^3 s^{-1}$ at 0930, representing the third largest peak discharge during the 1997 monitoring period (see Figures 2 and 5 in R&D Project Record P2/i465/19). Sampling was undertaken during the receding limb of the hydrograph between 11.00 and 14.40 GMT, when discharge fell from 1.2 $m^3 s^{-1}$ to 0.6 $m^3 s^{-1}$ respectively. Figure 16 shows that suspended sediment concentrations (calculated by continuous turbidity monitoring) at the Lower Tanllwyth (S2) site decrease rapidly after reaching maximum levels at the peak of the flood hydrograph. Due to the apparent exhaustion of available erodible material, the results of this study are therefore likely to represent lower suspended sediment concentrations than would have occurred during the rising limb or peak of the flood hydrograph.

The majority of Harvesting Area 1 lies in the Tanllwyth catchment, with drainage flowing north into Harvesting Area 2. However, as this drainage was dispersed and poorly defined, it could not be sampled as easily as that which flowed to the Afon Hafren below the confluence with the Nant Tanllwyth and therefore below the Lower Hafren (S4) monitoring site (see Figure 2). Consequently, in this study the drainage sampled within Harvesting Area 1 (sample nos. 28 - 31) lies outside of the Nant Tanllwyth catchment and drains to the Afon Hafren. It was however included to serve as an indicator of the particulate outputs from the area.

As suspended sediment concentrations in surface drainage within Harvesting Areas 1 and 2/3 do not appear significantly higher than those within control (unfelled) sites, no increase in particulate outputs appears to be associated with any of the felling methods. Higher concentrations were found in the upper reaches of drainage within Area 2, although upon reaching the main Tanllwyth watercourse, concentrations were similar to control levels. This could be attributable to dilution from further drainage within lower reaches. The mean suspended sediment concentration within all areas affected by timber harvesting is only slightly higher than that for drainage within mature (unfelled, control) forest areas. These results therefore indicate low particulate outputs associated with ground disruption by harvesting activity. These low suspended sediment concentrations may, however, be due to the exhaustion of available erodible material due to the timing of sampling during the receding limb of the flood hydrograph. Furthermore, the combined suspended sediment concentration and discharge record for 01 January - 31 March 1997 in Figure 5 in R&D Project Record P2/i465/19 also indicates that much of the available material appears to have been eroded by a previous flood event on 04 February 1997 (day number 35). This flood incorporated the largest peak discharge attained during the Jan. - June 1997 monitoring period and represented the first pronounced high flow event since 05 December 1996 (day number 340) (see Figure 4 in R&D Project Record P2/i465/19), corresponding to a low flow period of over 60 days.

During the same flood event on 12.02.97, further field investigation was undertaken at other harvesting sites within the IH Experimental Catchments at Plynlimon. The most pronounced source of particulate outputs was identified at a small harvesting site within the Afon Hafren Catchment, where drainage along an access track, which had been used by a forwarder to remove felled timber to a roadside stacking area, contained a suspended sediment concentration of 697 mg l^{-1}. This supports the findings in 6.1 which identify access tracks, used for the extraction of timber from harvesting sites to the main forest roads, as the major source of particulate outputs associated with timber harvesting. Consequently, higher suspended sediment concentrations were measured at the Lower Hafren (S4) monitoring site (21.5 mg l^{-1}) than at the Lower Tanllwyth (S2) monitoring site (14.1 mg l^{-1}). This could help to explain the increase in mean suspended sediment concentrations at the Lower Hafren (S4) monitoring site between 1996 and 1997, discussed in 4.2.1.

4.4 Measurement of Bed-Load Sediment Outputs Associated With Harvesting Operation

Table 13 shows that before harvesting (1995), bed load yields from the Nant Tanllwyth catchment were 647 % higher than from the Afon Cyff moorland catchment (8.61 t km^{-2} yr^{-1} and 1.33 t km^{-2} yr^{-1} respectively). During 1996, when timber harvesting was undertaken within the

Nant Tanllwyth catchment, this difference only increased to 657 %, corresponding to bed load yields of 9.72 and 1.48 t km^{-2} yr^{-1} for the Nant Tanllwyth and Afon Cyff catchments respectively. If 1995 results are used to represent the background difference in suspended sediment yields between the two catchments, and assuming all other variables are equal, the timber harvesting operation only appears to have led to a 1.5 % increase in bed load yields from the Tanllwyth, corresponding to approximately 0.1 t km^{-2} yr^{-1}. Annual bed load yields for 1997 could not be calculated within the timescale for this project. In the future, subsequent monitoring may reveal increased bed load yields from the Nant Tanllwyth catchment associated with the harvesting operation due to the known lag affect of peak bed load outputs following timber harvesting operations (see 8.1.2).

4.5 Measurement of the Impacts of Particulate Outputs Associated with Timber Harvesting on the River Gravel Habitat

4.5.1 Importance of investigating impacts on the river gravel habitat

The substrate of gravel bed rivers can be classified into the active layer, armour layer and substrate. The active layer consists of relatively fine well mixed temporary surface deposits, relating to the last flood event. Selective erosion of finer sediments during moderate flood events (Petts *et al.*, 1989), and / or upward dispersive forces between larger particles on the channel bed (Andrews and Parker, 1987) creates an armour layer. The armour layer is usually incomplete and consists of individual coarse particles on the surface of the substrate, but below the active layer. As the armour layer is only moved during high magnitude floods, it is effective in protecting the underlying substrate from erosion. The substrate represents the bulk of channel bed material and remains undisturbed until the overlying armour layer is removed.

As fluvial sediments are commonly deficient in the size range between 2 and 4 mm, the substrate of gravel bed rivers is often bi-modal, with a dominant gravel and subordinate sand mode of matrix material, coarser than 4 mm and finer than 2 mm respectively (Carling and Reader, 1982). The substrate of natural gravel-bed rivers, in both upland and lowland areas, typically contains between 10 and 28 % of matrix material finer than 2 mm (Carling and Reader, 1981). The natural substrate in the rivers studied by Petts *et al.*, (1989) always contained less than 20 % of sub 2 mm particle sizes.

As the proportion of fine matrix increases in relation to the gravel framework, substrate permeability and porosity is reduced, the affects of which are discussed in 3.3.1. Consequently, the ratio between the coarse framework and fine matrix components is the most significant factor controlling the habitat quality of river gravels. On this basis, as the relative proportion of fine material in river gravels increases, and habitat quality is therefore reduced, Carling and Glaister (1987) classified substrate composition into three types: open framework, matrix filled contact framework and dilated framework gravels respectively. Partial framework dilation occurs when the matrix component exceeds 32 % (Petts *et al.*, 1989).

Fines can be deposited within river gravels to the depth of surface water penetration, and can sift lower if open pore spaces are available. Consequently, within an open framework gravel, incorporation of fines can occur to depths of 30 cm or more after deposition. Vertical substrate profiles commonly reveal a gradient of increased fining with depth. This can be explained by the reduced velocity and turbulence of intra-gravel water percolating through the lower substrate horizons, resulting in reduced flow energy with gravel depth. Consequently, within deeper horizons, the energy of intra-gravel flow may fall below transport thresholds, resulting in the deposition of material which would remain in transport higher in the profile (Scrivener and Brownlee, 1989). Similarly, critical erosion velocities for fine material occur more frequently in the upper horizons than deeper within the substrate, resulting in fines removal by hydraulic winnowing (Scrivener and Brownlee, 1982; Carling, 1984; Crisp and Carling, 1989). Alternatively, Petts (1988) states that fines ingress occurs under the influence of two separate mechanisms, the initial deposition of fines into the surface voids, and subsequent movement into deeper voids by gravitational settling, assisted by turbulent pulses and intra-gravel flow. The common pattern of fining within river gravel profiles is therefore from the base upwards (Beschta and Jackson, 1979; Carling, 1984; Scrivener and Brownlee, 1989).

The rate of fines infilling depends upon a complex interaction of factors, including void dimensions, the size and density of suspended sediment particles, and the suspended sediment transport rate and concentration. Petts (1988) states that the suspended sediment concentration close to the bed surface represents the dominant control. River gravel fining may therefore represent an important impact of fluvial particulate inputs. For a true evaluation of this impact on river gravel habitat, samples must be collected from the upper 30 cm of the substrate. This represents the critical zone for both invertebrates and the initial stages of many vertebrate life cycles, all of which can be adversely affected by sediment deposition.

4.5.2 Site selection for river bed gravel survey

The locations of the six substrate sampling sites employed for this study are shown on Figure 2 and described in Table 14. G1 represents the control site on the Nant Tanllwyth, above the harvesting area. In case the bed load trap affected gravel sedimentation rates, two samples were collected downstream of the harvesting area from both G2 and G3, above and below the bed load trap respectively. Sites G4 and G5 were included to identify the affect of any particulate outputs from the Nant Tanllwyth on gravel sedimentation within the Afon Hafren. Site G6 was included as a control in an unafforested moorland catchment.

To investigate the ecological impacts of river gravel fining, it is necessary to study the areas of substrate that represent the most important habitat. All sites were therefore located at the ideal salmonid spawning area, where the tail end of a pool merges into a riffle (Ottaway et al., 1981).

4.5.3 Choice of method for investigating impacts on the river gravel habitat

Due to the inefficiency of fine particle collection, conventional shovel methods of sampling river gravels under flowing water fail to accurately represent composite substrate material. This has been attributed to elutriation during sampling (Petts, 1988; Petts *et al.*, 1989), and selective bias toward the collection of large particles (Thoms, 1992), both of which are exacerbated by problems of shovel penetration resulting in the over-collection of surface material. Historically, investigations of channel substrate pollution have therefore been constrained by both biased unrepresentative sampling, and focusing on the surface layer where depositional processes are less significant.

The freeze coring method can collect representative samples of the upper 30 cm of gravel substrates (Petts *et al.*, 1989), under flowing water and even through ice (Ringler and Hall, 1988). Marks (1995) identified freeze coring as the optimum method of substrate sampling to investigate the impacts of particulate outputs associated with timber harvesting. This is supported by Petts *et al.*, (1989) who state that in general, the freeze coring technique is the most successful for assessment of the impacts of elevated suspended sediment loads on spawning grounds for fish, especially salmonids.

Numerous comparative studies indicate the advantages of freeze coring over conventional shovel sampling methods for the collection of fine material within river gravel samples. In comparison to shovel samples, the increased proportion of fine material (< 2 mm) in freeze core samples has been quantified as up to five, three to six and four times by Petts (1988), Petts *et al.* (1989) and Thoms (1992) respectively. This disparity becomes even more significant for smaller particle sizes. For example, Petts (1988) reported that the proportion of material finer than 250 μm in freeze core samples was 40 times higher than in an equivalent shovel sample.

Due to the accuracy of the freeze core method, fewer samples are required to obtain a representative fraction of the substrate. For example, when compared with conventional shovel samples, Thoms (1992) states that one third of the number of freeze core samples are required for accurate representation of the physical characteristics of river gravel. This technique is therefore commonly applied whenever the collection of a representative undisturbed substrate sample is required. It has therefore been employed to study the stratigraphy of river gravels (Stocker and Williams, 1972; Carling and Reader, 1981; Carling, 1984; Ringler and Hall, 1988), the vertical distribution of benthic invertebrates (Milan, 1994; Bretschko and Klemens, 1986), the structure and quality of salmonid redds (Ottaway *et al.*, 1981; Crisp and Carling, 1989), reservoir impacts on downstream substrate composition (Petts and Thoms, 1986; Petts, 1988; Petts *et al.*, 1989; Milan, 1996) and heavy metal contamination of channel substrates (Petts *et al.*, 1989).

For this project, substrate sampling by both conventional shovel sampling and freeze coring was undertaken to investigate impacts on the river gravel habitat by particulate outputs associated with timber harvesting. Although freeze core samples are expected to give the most representative results, the method is very labourious and expensive. Conventional shovel sampling was therefore undertaken adjacent to all freeze coring sites. Comparison of results will enable the appraisal of each method.

4.5.4 Sample collection and preparation - Freeze coring

i. Collection

Five freeze core samples, yielding a composite weight of over 20 kg, were collected from each site in early January 1996, before the start of harvesting in the Tanllwyth catchment on 29

January 1996. This was repeated in April 1997, 10 months after completion of the Tanllwyth harvesting operation. From the analysis of 32 randomly distributed freeze core samples within one riffle, Thoms (1987), in Petts *et al.* (1989), identified this as the minimum sampling requirement for representative determinations of fine sediment concentration within river gravel substrates. This sampling strategy is therefore commonly applied for this application (Petts, 1988; Milan, 1996).

A number of cryogenic media can be employed for freeze coring. These include liquid nitrogen (Stocker & Williams, 1972; Milan, 1994, 1996), liquid oxygen (Efford, 1960), solid carbon dioxide and acetone or alcohol mixture (Sharpio, 1958; Ringler and Hall, 1988; Scrivener and Brownlee, 1989) and freezing with liquid carbon dioxide (Walkotten, 1976). As the latter is safest and most reliable, it was considered the most suitable for this project.

The method of freeze core sample collection is described in Petts *et al.* (1989) and Thoms (1992). A standpipe was driven into the gravel bed to a depth of over 30 cm, around which any substrate disturbance is confined to a narrow 5 mm zone. An inner tube is inserted into this standpipe and used to inject the liquid carbon dioxide (CO_2) through fine nozzles onto the inner surface of the standpipe. Vaporization of the CO_2 causes rapid cooling, freezing intra-gravel water and gravel particles to form a columnar frozen core of substrate around the outside of the standpipe. Large ice crystals do not form during the freezing process, so the sediments are undisturbed.

Initial testing was undertaken to develop an optimum technique. Mosley and Tindale (1985) state that due to textural differences, surface and sub-surface sediments should be sampled and analysed separately. Petts *et al.*, (1989) therefore recommend the removal of the surface armour layer prior to freeze core sampling. As the armour layer protects the underlying sediment from entrainment, elutriation of underlying fine material was observed during its removal. Consequently, for this study, the armour layer was not removed prior to sampling. Instead, the large particles at the top of frozen cores were identified as components of the armour layer and marked using a scribe. These were later discarded during analysis.

The success of substrate freezing is reduced by heat transfer from the river water. Similar to the bottomless bucket used by Thoms (1992), sample size was considerably increased by using a length of 50 cm x 50 cm plastic pipe, with a rubber seal on the bottom, to divert flow around the standpipe during freezing. In the majority of cases, each sample required a full cylinder of CO_2 (British Oxygen Company, size LB, min CO_2 content = 6.35 kg). To standardise, it was therefore decided to use a full CO_2 cylinder for each sample. After freezing, the standpipe was winched from the gravel to remove the surrounding core of frozen substrate.

ii. Preparation

In British watercourses, the major ecological impact of substrate fining is its effect on salmonid spawning success (see 3.3.1). To assess the impact of substrate fining, it is important to identify both the depositional pattern within the substrate profile, and the habitat significance of the horizons affected.

Due to vertical gradients in substrate composition, to enable representative determinations of fine sediment concentration and accurate comparative analyses, freeze core samples have to be separated into depth zones. In an investigation of the vertical distribution of sediment and organic debris in coho salmon (*Oncorhynchus kisutch*) redds, Ringler and Hall (1988) divided the upper 25 cm of freeze core samples into three equal strata (0-8.3, 8.3-16.6 and 16.6-25 cm). Freeze core samples have been separated into 0-15 and 15-30 cm horizons for investigations of the impacts of river regulation on substrate composition (Petts, 1988; Milan, 1996), geochemical pollution associated with fine material (Petts *et al.*, 1989) and forest harvesting impacts on salmonid spawning gravel composition (Scrivener and Brownlee, 1989).

Investigations of salmonid spawning depths for North American species report an increase in spawning depth with fish size (Van den Berghe and Gross, 1984). Studies of the most common salmonid species endemic to British gravel bed rivers, brown trout (*Salmo trutta*), sea trout (migratory form of *S. trutta*) and Atlantic salmon (*S. salar*) identify the same relationship (Ottaway *et al.*, 1981; Elliott, 1984). For these species combined, this is illustrated by the regression lines of Crisp and Carling (1989) which indicate egg burial depths ranging from 8 to 24 cm as female fish length increases from 20 to 80 cm. Due to the variation between the average size of spawning females, a rough approximation is that brown trout, sea trout and Atlantic salmon bury their eggs within 0-10, 10-20 and 20-30 cm zones respectively (Beaumont, 1996).

To enable the investigation of fining impacts on the individual substrate horizons where spawning of British salmonid species occurs, freeze core samples were separated into the 0-10, 10-20 and 20-30 cm depth fractions. Ideally, this should be undertaken by allowing the core to melt overnight above a sample splitter. This, however, limits the daily total of samples to the available standpipes. Since only three were available for this study, an alternative separation method was employed. As the frozen substrate is very brittle, tapping the standpipe with a hammer causes the surrounding material to fall away. For each sample, this was undertaken on a plastic sheet on a level surface. The frozen substrate was then divided into the three depth fractions, each of which was placed in a clean plastic tray. Trays were taken back to the laboratory for air drying prior to analysis.

4.5.5 Sample collection and preparation - Conventional shovel sampling

The simplest method to obtain a sample of bed material is to use a shovel. Due to the difficulty in collecting armour layer particles by this technique, and the fact that fine material elutriation was inevitable, the armour layer was removed prior to sampling. During sampling, it was evident that material could only be successfully collected from approximately the upper 15 cm of the substrate. Due to the collapse and infilling of surrounding substrate into the sampling excavation, it was decided that the collection of deeper material would be unrepresentative. At each site, to match the amount of material collected by the freeze core method, two samples were collected with a composite weight of over 20 kg. This material was placed in a clean plastic tray and taken back to the laboratory for air drying prior to analysis.

4.5.6 Sample analysis

Carling and Reader (1981) state that volumetric freeze core samples require no correction for sampling bias, and statistical analysis of grain size data may proceed directly. This is contradicted by Petts (1988) who reports that, similar to samples collected by conventional shovel methods, the freeze core technique is also biased towards the collection of coarse material. As only a small area of a particle needs to be frozen to enable its collection, large particles may be inadvertently incorporated from a larger area around the core than adjacent infilling material. To reduce the within riffle variability of percentage fine material calculations, this bias is commonly corrected by disregarding material coarser than a particular size. For example, Adams and Beschta (1980) and Ringler and Hall (1988) discarded particles coarser than 50 mm. Similarly, Petts (1988) excluded all particles coarser than 32 mm.

For the freeze core samples collected for this study, it was decided to discard the material coarser than 63 mm. This enables the analysis of all particle sizes up to and including the gravel fraction. This is considered representative as Thoms (1992) concluded that, although freeze coring does not sample cobble- and boulder-size particles effectively, it accurately collects particles up to 64 mm. Furthermore, removal of the coarse fraction complies with the recommendation of Mosley and Tindale (1985) who state that, in a representative sample, the largest particle must not exceed 5 % of the total sample weight. To enable accurate comparative investigation of the two sampling techniques, this size fraction was also discarded from the shovel samples collected for this project.

All samples were sieved for 20 minutes through a nest of British Standard test sieves consisting of 63, 45, 22.4, 11.2, 5.6, 2.8, 1.4, 0.71, 0.355, 0.180, 0.09 and 0.045 mm aperture sizes. Following sieving, the sediment in each sieve was accurately weighed and the particle size distributions plotted.

4.5.7 Interpretation

i. Particle size thresholds

The literature review discussed in 3.3.1 iia identified the proportion of matrix material finer than 2 mm as the most appropriate substrate composition criterion for assessment of river gravel habitat quality. The sub 2mm fraction has therefore been calculated for each of the samples collected for this study. The upper threshold for the proportion of fine material in river gravels suitable for salmonid spawning has been reported as 20 % (Platts and Megahan, 1975; Petersen, 1978; Tappel and Bjornn, 1983; Wightman, 1987; Naismith *et al.,* 1996).

ii. Horizon thresholds

Careful interpretation of particle size distributions within the three substrate horizons of freeze core samples is necessary for the accurate investigation of potential ecological impacts. As the redds of migratory salmonids are constructed deeper within the substrate than those of non-migratory fish, their eggs are better protected from wash-out, but are more vulnerable to possible sedimentation, which is known to be more significant within deeper horizons (Crisp and Carling, 1989). This may be exacerbated by any additional impacts on the overlying horizons which can prevent the migration of hatched alevins to the main river, resulting in their entrapment within the substrate.

Scrivener and Brownlee (1989) report that the best index of spawning success within all horizons may be the composition of the surface layer of freeze core substrate samples. This was attributed to the fact that although migratory salmonids bury their eggs deeper within the substrate, the void spaces in the surface layers must be sufficient to allow them to escape. Consequently, a reduction in porosity in the surface layer, where only brown trout eggs are buried, may also affect sea trout and salmon fry. Furthermore, eggs may be deposited deeper (below the top layer) but subsequent scour leaves them at shallower depths during the incubation period.

4.5.8 Results

Table 15 shows the results of this investigation. As samples were collected in January 1996 and April 1997, 1996 and 1997 samples are representative of periods before and after harvesting in the Nant Tanllwyth catchment respectively. The results of changes in river gravel fines content following timber harvesting in the Nant Tanllwyth catchment are discussed separately for freeze core and conventional shovel samples.

i. Freeze core samples

Nant Tanllwyth (G1 - G3)

Following timber harvesting, in relation to the unaffected Upper Tanllwyth (G1) control site, increases in river gravel fines content below the harvesting site were only apparent for the 0-10 cm and 20-30 cm depth horizons, and therefore 0-30 cm aggregate, at the Lower Tanllwyth a (G2) site (above the bed load trap).

Gravel fines content in 1996 before harvesting (baseline) samples were, however, lowest at the Lower Tanllwyth a (G2) site for all depth horizons, making any subsequent increases more marked. The 123.95 % increase in river gravel fines content, from 3.51 % to 7.86 %, in the 0-10 cm depth horizon at site G2, is particularly pronounced. For all 6 sites, this represents the largest increase within this horizon, and second largest increase for all depths. The proportion of fine material in the 1997 0-10 cm depth horizon at site G2 (7.86 %) is, however, the sixth lowest out of the total of 36 samples, corresponding to both years at 6 sites and 3 depths. The large increase is therefore due to the exceptionally low proportion of fine material in the 1996 0-10 cm depth horizon at site G2 (3.51 %) and represents the lowest proportion in all 36 samples.

No increase in gravel fines content above that recorded at the Upper (G1) control site was apparent at the Lower Tanllwyth b (G3) site below the bed load trap. The largest increases of gravel fines content in 10-20 cm, 20-30 cm and 0-30 cm aggregate samples were found at the Wye (G6) control site. This was unexpected within such a stable moorland catchment which was not subjected to any management practices between the two sampling periods.

Afon Hafren (G4-G5)

An increase in gravel fines content at the Lower (G5) site, below the confluence with the Tanllwyth, above that recorded at the Upper (G4) control site was apparent for all horizons.

ii. Conventional shovel samples

Apart from the Upper Tanllwyth control site (G1), all conventional shovel samples reveal a decrease in gravel fines content between 1996 and 1997 (before and after timber harvesting in the Nant Tanllwyth catchment respectively).

Nant Tanllwyth (G1 - G3)

Neither of the Lower G3 and G4 sites, above and below the bed load trap respectively showed an increase in the proportion of fine particulate material in comparison to the Upper G1 site.

Afon Hafren (G4-G5)

The Lower G5 site, below the confluence with the Tanllwyth, showed no increase in the proportion of fine particulate material in comparison to the Upper G4 site.

iii. Conclusions

Between 1996 and 1997 (before and after felling respectively), an increase in the proportion of fine material at experimental sites (downstream of the Nant Tanllwyth harvesting site) above that at control sites (unaffected by the Nant Tanllwyth harvesting operation) was evident in the freeze core samples collected from the Lower Tanllwyth a (G2), and Lower Hafren (G5) sites. The apparent increase at the Lower Tanllwyth a (G2) site is, however, likely to have been exacerbated by the low background level of river gravel fines in baseline samples collected before timber harvesting in 1996.

An increase in river gravel fines following timber harvesting appears apparent at the Lower Hafren (G5) site. River gravel fines are most likely to have originated as suspended sediment, the concentrations of which are known to have increased in the Nant Tanllwyth during timber harvesting within the catchment (see 4.2). This material is unlikely to have deposited in the Nant Tanllwyth until water velocities were reduced further downstream. Consequently, increased sedimentation may not have occurred until after its confluence with the Afon Hafren. This could explain why a larger increase in gravel fines following timber harvesting was found between the Upper (G4) and Lower (G5) Hafren sites than the Upper (G1) and Lower (G2 and G3) Tanllwyth sites. These results are however inconclusive as the largest increases of gravel fines content between before felling (1996) and post-felling (1997) periods in 10-20 cm, 20-30 cm and therefore 0-30 cm aggregate samples was found at the Wye (G6) control site. This was unexpected within such a stable moorland catchment which was not subjected to any pronounced land management practices between the two sampling periods.

In this study the impacts of particulate outputs associated with timber harvesting on the river gravel habitat appear to be minimal. Only the 1997 10-20 cm freeze core sample from the River Wye (G6) control site, and therefore the 0-30 cm aggregate, contained more fine particulate material than the 20 % threshold discussed in 4.5.7 as being sufficient to affect salmonid spawning. In light of this, none of the river gravels sampled within the Nant Tanllwyth and Afon Hafren afforested catchments contained sufficient fine material to adversely affect salmonid spawning.

4.6 Measurement of Bank Erosion in the Main Tanllwyth Channel Associated with Harvesting Operation

The impact of timber harvesting in the riparian zone (Harvesting Area 3, see Figures 3 and 17) upon bank erosion in the main Nant Tanllwyth channel, in comparison with the control upland grassland Afon Cyff control channel, was investigated by Dr Tim Stott of Liverpool John Moores University (Stott, 1997b; Stott and Marks, 1998). This work is described.

Bank erosion rates were monitored using erosion pins (300 mm x 3 mm welding rod) pushed into the bank in vertical lines (100 mm spacing) at sites on either the right or left bank, at a point on the channel where the cohesive bank sediment was exposed and not vegetated. Repeat measurements, to 0.1 mm accuracy, were undertaken using calipers.

A total of 16 sites were installed on the Nant Tanllwyth, corresponding to a total of 105 pins (see Figure 17). Repeat survey was undertaken on 14 occasions between 22.10.94 and 20.05.97. A further 5 sites, corresponding to a total of 30 pins, were installed on the Afon Cyff and resurveyed on 4 occasions between 24.04.95 and 15.02.97. In order to assess the possibility of pins being heaved out of the banks by frost, a further 32 pins were installed at 11 of the Nant Tanllwyth sites on 13.01.97 where the pins were pushed into the bank until they hit a wooden stake installed vertically some 250 mm from the bank face. Resurveys of these pins after 36, 86 and 127 days showed that none had been heaved by frost.

Felling of the riparian zone, Harvesting Area 3 (see Figure 3) was undertaken between 29.04.96 - 21.06.96 (see 4.1.3 and Table 5). To ensure the same measurement periods for the Nant Tanllwyth and Afon Cyff channel bank erosion rates, pre- and post-harvesting measurements for both sites corresponded to 27.04.95 - 02.04.96 and 02.04.96 - 15.02.97 respectively. Table 16 shows mean bank erosion rates for the Nant Tanllwyth and Afon Cyff sites and the statistical analyses undertaken at 0.05 level to test the significance of any changes associated with timber harvesting. This shows that mean bank erosion rates for the Nant Tanllwyth and Afon Cyff, 34.6 and 31.2 mm yr^{-1} respectively, are not significantly different in the pre-harvesting period. After harvesting, mean bank erosion rates in the Nant Tanllwyth at sites E1 - E12, adjacent to the felled area, were significantly higher than in the Afon Cyff, 95.8 and 65.5 mm yr^{-1} respectively. No significant difference in mean bank erosion rates existed between Tanllwyth sites E13-E16, adjacent to an unfelled area, and the Afon Cyff, 70.5 and 65.5 mm yr^{-1} respectively. It can therefore be concluded that timber harvesting in the riparian zone of the Nant Tanllwyth resulted in increased erosion of adjacent channel banks.

Out of the total erosion measured during this study, 89 % occurred during the winter periods (December - March inclusive). The large increase in erosion rates between the pre- and post-harvesting periods at the Cyff and Tanllwyth (E13-E16) control sites (unaffected by the felling operation) from 31.2 to 65.5 mm yr^{-1} and 34.6 to 70.5 mm yr^{-1} respectively, may be attributable to the greater proportion of winter periods during the post harvesting measurement period. Furthermore, average flow for the pre- and post-harvesting measurement periods, was 0.03 and 0.05 m^3s^{-1} respectively at the Lower Tanllwyth monitoring site (S2), and 0.11 and 0.17 $m^3 s^{-1}$ respectively at the Cyff (S6) monitoring site. Consequently, the increase in bank erosion measured at control sites, unaffected by felling, during the post harvesting measurement period can therefore be explained by the longer winter duration and higher flow conditions associated with increased frost action and fluvial erosion respectively.

To increase the temporal resolution of bank erosion data for detailed process investigation, a photo-electronic erosion pin (PEEP) (Lawler, 1991; Lawler and Leeks, 1992) was installed at site P1 in a drainage ditch within a mature forest area unaffected by timber harvesting for a 12 month period, July 1995 - July 1996, and then moved to site P2 on the main Tanllwyth channel following timber harvesting (see Figure 17). In addition to temperature on the bank surface, measured by a thermistor, this data was stored in a datalogger at 15 minute intervals. Hourly air temperature and rainfall data were available from the nearby Moel Cynedd automatic weather station (AWS) and 15 minute flow data for the Nant Tanllwyth from the Lower (S2) monitoring site (see Figure 17).

Stott (1997b) undertook a study of 24 variables, known to affect bank erosion, based upon precipitation at the Moel Cynedd AWS, flow at the Lower Tanllwyth (S2) monitoring site and temperature indices based upon air and bank temperatures at the Moel Cynedd AWS and P1 / P2 PEEP bank erosion monitoring sites respectively (see Figure 17). Using stepwise multiple regression, temperature indices were identified as the most significant influence on mean channel bank erosion rates in the Nant Tanllwyth. This was attributed to the well established link between frost action and stream bank erosion (Lawler, 1986; 1987; 1993).

Stott (1997b) compared the relationship between air temperatures at the Moel Cynedd AWS, located in an exposed area unaffected by forestry, and channel bank temperatures at sites within both mature and recently felled forest, P1 and P2 respectively (see Figure 17). Winter temperatures within a mature (08.12.95 - 05.01.96) and felled (08.12.96 - 05.01.97) forest showed a 29 % higher bank:AWS ratio of sub-zero periods at the felled site. Summer temperatures for the mature (20.07.95 - 08.09.95) and felled (20.07.96 - 08.09.96) forest areas showed a higher bank:AWS temperature ratio within the felled area. Consequently, during both winter and summer seasons exposed banks within the felled area were more sensitive to changes in air temperature as measured by the AWS, resulting in lower and higher extreme temperatures respectively. This can be explained by the effect of forestry on insulation during the winter and shading during the summer, resulting in higher winter temperatures and lower summer temperatures under forest cover, and a reduced annual temperature range.

Felling is therefore likely to result in an increased annual temperature range due to a rise and fall of summer and winter temperatures respectively. This is likely to increase channel bank erosion in upland forest plantations due to reduced winter temperatures and therefore an increase in the period with sub-zero temperatures when banks can be affected by frost action. Increased response to air temperature may also result in a greater diurnal temperature range and more freeze thaw cycles during the winter. An increase in higher maximum temperatures may increase evaporative losses and result in more extreme wetting and drying cycles resulting in increased erosion associated with the formation of desiccation cracks. Although outside the scope of this study another important affect of felling can be increased soil moisture due to reduced evapotranspiration. Research at Plynlimon has shown that up to 30 % of precipitation may be lost by evapotranspiration from forest vegetation. By increasing positive pore water pressure, this can weaken the soil and increase its susceptibility to erosion. Finally, the removal of riparian vegetation can result in channel bank instability due to the decay of root systems which may have bound the soil.

Although the results of this investigation show that felling riparian forestry is likely to increase channel bank erosion, it should not be interpreted that riparian forestry may therefore reduce channel bank erosion and consequently particulate outputs. It is most likely that natural uncultivated riparian vegetation would be associated with the least bank erosion, and the benefits of establishing buffer areas adjacent to watercourses are well proven at removing particulate material from upland forestry drainage (Swift and Norton, 1993). Although outside the remit of this project, similar to its affect on channel banks, riparian forestry can also affect stream temperatures and therefore aquatic ecology. In a review of some of the literature on trout growth, Smith (1980) suggests that shading by the forest canopy, resulting in lower summer stream temperatures, can reduce the period of optimum growth conditions compared with short vegetation canopies. The results of this investigation therefore support the following recommendations in Forests and Water Guidelines (Forestry Authority, 1993).

BUFFER AREAS (Pages 13 & 14)

MANAGING RIPARIAN VEGETATION (Page 14)

HARVESTING (Page 17)

- ***Felling in the riparian zone*** *will be an infrequent event once the recommended vegetation has become established....*

	★ 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
Mean suspended sediment concentration $(mg\ l^{-1})$ #	1.7	1.6	5.3	6.5	11.6	3.7	3.5	3.4	4.4	8.4	2.9	3.5	3.6	1.2	1.3
Maximum suspended sediment concentration $(mg\ l^{-1})$	280	305	319	417	843	281	121	97	184	38	138	262	125	146	73
Total suspended sediment load (tonnes)			21.6	39.0	25.4			59.1	84.7	32.9	138.4	127.0	92.4	16.7	7.6
Suspended sediment yield $(t\ km^2 yr^{-1})$			24.3	43.8				16.1	23.1		15.9	14.6		5.3	

★ 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.

Means based on log 10 data (see Figures A29 - A43(b))

Table 7
Summary of suspended sediment monitoring results

Parameter	Symbol
Minimum value (0th percentile)	Bottom upward-pointing triangle symbol
1st percentile	Second downward-pointing triangle symbol
5th percentile	Bottom of the vertical line
25th percentile	Bottom of the box
Median (50th percentile)	Middle line
75th percentile	Top of the box
95th percentile	Top of the vertical line
99th percentile	Diamond symbol above the vertical line
Maximum value (100th percentile)	Top round symbol
Mean	Square symbol in box

Table 8
Summary of box plot interpretation (Figures 6 - 14, 19)

Data for comparison	Mean (Log 10)	Analysis of variance F ratio	Rank in order of difference	t-Test t value	Rank in order of difference
Upper Tanllwyth (S1) 1996	0.21814	31942	3	179	3
Lower Tanllwyth (S2) 1996	0.8148				
Upper Hafren (S3) 1996	0.56438	706	9	27	9
Lower Hafren (S4) 1996	0.64319				
Lower Hafren (S4) 1995	0.5346	4779	4	69	4
Lower Tanllwyth (S2) 1995	0.72372				
Lower Hafren (S4) 1996	0.64319	3038	5	55	5
Lower Tanllwyth (S2) 1996	0.8148				
Lower Tanllwyth (S2) 1995	0.72372	1112	7	33	7
Lower Tanllwyth (S2) 1996	0.8148				
Lower Hafren (S4) 1995	0.5346	1223	6	35	6
Lower Hafren (S4) 1996	0.64319				
Severn (S5) 1995	0.45968	953	8	31	8
Severn (S5) 1996	0.53913				
Wye (S6) 1996	0.07721	61495	1	248	1
Lower Tanllwyth (S2) 1996	0.8148				
Wye (S6) 1996	0.07721	33597	2	183	2
Lower Hafren (S4) 1996	0.64319				

Table 9
Summary of statistics undertaken to test the significance of the difference between mean suspended sediment concentrations for 1995 and 1996 annual data sets.

Data for comparison	Mean (Log 10)	Analysis of variance F ratio	Rank in order of difference	t-Test t value	Rank in order of difference
Upper Tanllwyth (S1) 1997	0.20236	23903	3	155	3
Lower Tanllwyth (S2) 1997	1.06341				
Upper Hafren (S3) 1997	0.54141	12122	4	110	4
Lower Hafren (S4) 1997	0.92355				
Lower Hafren (S4) 1997	0.92355	1026	5	32	5
Lower Tanllwyth (S2) 1997	1.06341				
Wye (S6) 1997	0.10523	44847	2	212	2
Lower Tanllwyth (S2) 1997	1.06341				
Wye (S6) 1997	0.10523	60564	1	246	1
Lower Hafren (S4) 1997	0.92355				

Table 10

Summary of statistics undertaken to test the significance of the difference between mean suspended sediment concentrations for 1997 six monthly data sets.

No.	Sampling time GMT	Sampling location	TSS Conc. (mg l^{-1})
x	11.00	Drainage on access track at small harvesting site within Afon Hafren catchment	697.3
1	11.15	Tributary of Afon Hafren (mature forest not affected by harvesting)	2.8
2	11.20	Lower Hafren monitoring site (S4)	21.5
3	11.25	Lower Tanllwyth monitoring site (S2)	14.1
4	11.30	Tributary of Tanllwyth (sampled within Harvesting Area 3)	2.8
5	11.35	Drain (sampled within Harvesting Area 3)	2.7
6	11.40	Upper reach of drain (sampled within Harvesting Area 2)	23.3
7	11.45	Tributary of drain (sampled within Harvesting Area 2)	1.3
8	11.50	Tributary of drain (sampled within Harvesting Area 3)	5.6
9	11.55	Lower reach of drain (sampled within Harvesting Area 3)	5.6
10	12.00	Small ephemeral drain (sampled within Harvesting Area 3)	5.5
11	12.05	Small ephemeral drain (sampled within Harvesting Area 3)	1.3
12	12.10	Small ephemeral drain (sampled within Harvesting Area 3)	1.3
13	12.15	Small ephemeral drain (sampled within Harvesting Area 3)	4.9
14	12.25	Upper reach of drain (sampled within Harvesting Area 2)	9.6
15	12.35	Lower reach of drain (sampled within Harvesting Area 3)	6.4
16	12.45	Upper reach of drain (after road culvert, within Harvesting Area 2)	6.0
17	12.55	Lower reach of drain (within Harvesting Area 3)	6.3
18	13.00	Drain (sampled adjacent to Harvesting Area 3) receives drainage from harvesting site and area of mature forest not affected by harvesting	5.6
19	13.05	Drain (mature forest not affected by harvesting)	13.4
20	13.15	Drain (mature forest not affected by harvesting)	0
21	13.25	Upper Tanllwyth monitoring site (S1)	9.0
22	13.35	Drain (mature forest not affected by harvesting)	6.6
23	13.45	Drain (mature forest not affected by harvesting)	0
24	13.50	Small ephemeral drain (mature forest not affected by harvesting)	5.5
25	13.55	Small ephemeral drain (mature forest not affected by harvesting)	2.6
26	14.00	Drain (mature forest not affected by harvesting)	1.3
27	14.15	Drain (sampled at limit of Harvesting Area 2)	1.3
28	14.25	Drain (sampled at limit of Harvesting Area 1)	1.3
29	14.30	Drain (sampled at limit of Harvesting Area 1)	1.2
30	14.35	Drain (sampled at limit of Harvesting Area 1)	1.3
31	14.40	Road drain (sampled at limit of Harvesting Area 1)	5.7

Table 11 Results of detailed investigation of particulate outputs during flood event (12.02.97)

Drainage within Harvesting Area 1		Drainage within Harvesting Area 2		Drainage within Harvesting Areas 2 and 3		Drainage within mature (unfelled, control) forest areas	
Sample No.	**TSS Conc. (mg l^{-1})**	**Sample No.**	**TSS Conc. (mg l^{-1})**	**Sample No.**	**TSS Conc. (mg l^{-1})**	**Sample No.**	**TSS Conc. (mg l^{-1})**
28	1.3	6	23.3	4	2.8	1	2.8
29	1.2	7	1.3	5	2.7	19	13.4
30	1.3	14	9.6	8	5.6	20	0
31	5.7	16	6	9	5.6	22	6.6
		27	1.3	10	5.5	23	0
				11	1.3	24	5.5
				12	1.3	25	2.6
				13	4.9	26	1.3
				15	6.4		
				17	6.3		
				18	5.6		
Mean	**2.4**	**Mean**	**8.3**	**Mean**	**4.4**	**Mean**	**4.0**
Mean (all areas affected by timber harvesting)			**4.95**				

Other		
Sample No.	**Description**	**TSS Conc. (mg l^{-1})**
x	Drainage on access track at small harvesting site within Afon Hafren catchment	697.3
2	Lower Hafren monitoring site (S4)	21.5
3	Lower Tanllwyth monitoring site (S2)	14.1
21	Upper Tanllwyth monitoring site (S1)	9.0

Table 12 Summary of results of detailed investigation of particulate outputs during flood event (12.02.97)

Sites		Mean erosion rate mm yr^{-1}	n	d.f	*t*-statistic	*t* critical two-tail (p=0.05)	Significant at 0.05 level
Before harvesting 27.04.95 - 02.04.96	Tanllwyth	34.6	376	181	0.52	1.96	No
	Cyff	31.2	70				
After harvesting 02.04.96 - 15.02.97	Tanllwyth sites E1-E12 (adjacent to felled area)	95.8	348	230	1.96	1.96	Yes
	Tanllwyth sites E13-E16 (adjacent to unfelled area)	70.5	139	208	0.27	1.96	No
	Cyff	65.5	72				

Table 16 Mean bank erosion rates for the Nant Tanllwyth and Afon Cyff sites and the statistical analyses undertaken at 0.05 level to test the significance of any changes associated with timber harvesting

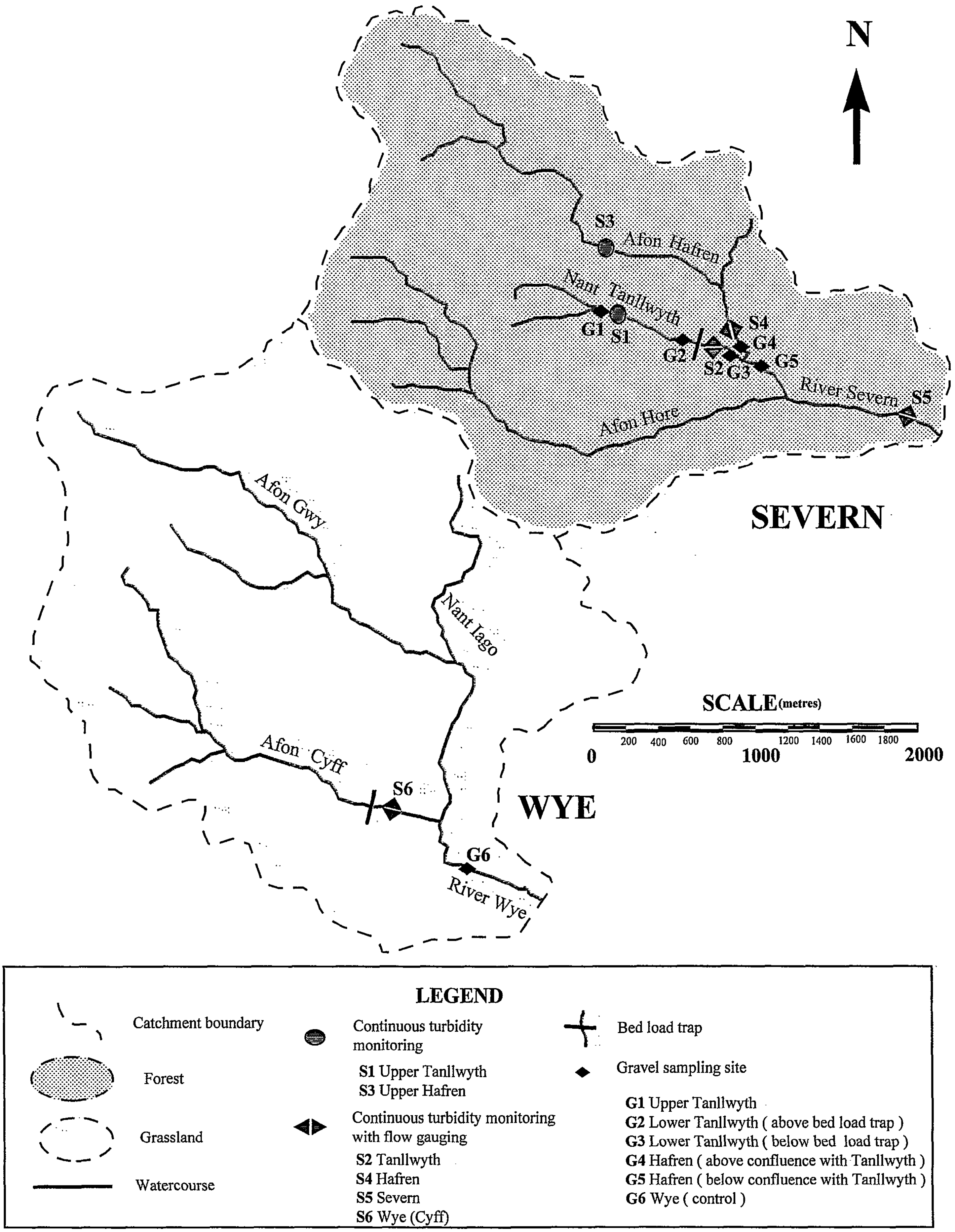


Figure 2 Sediment monitoring network within Plynlimon Experimental Catchments

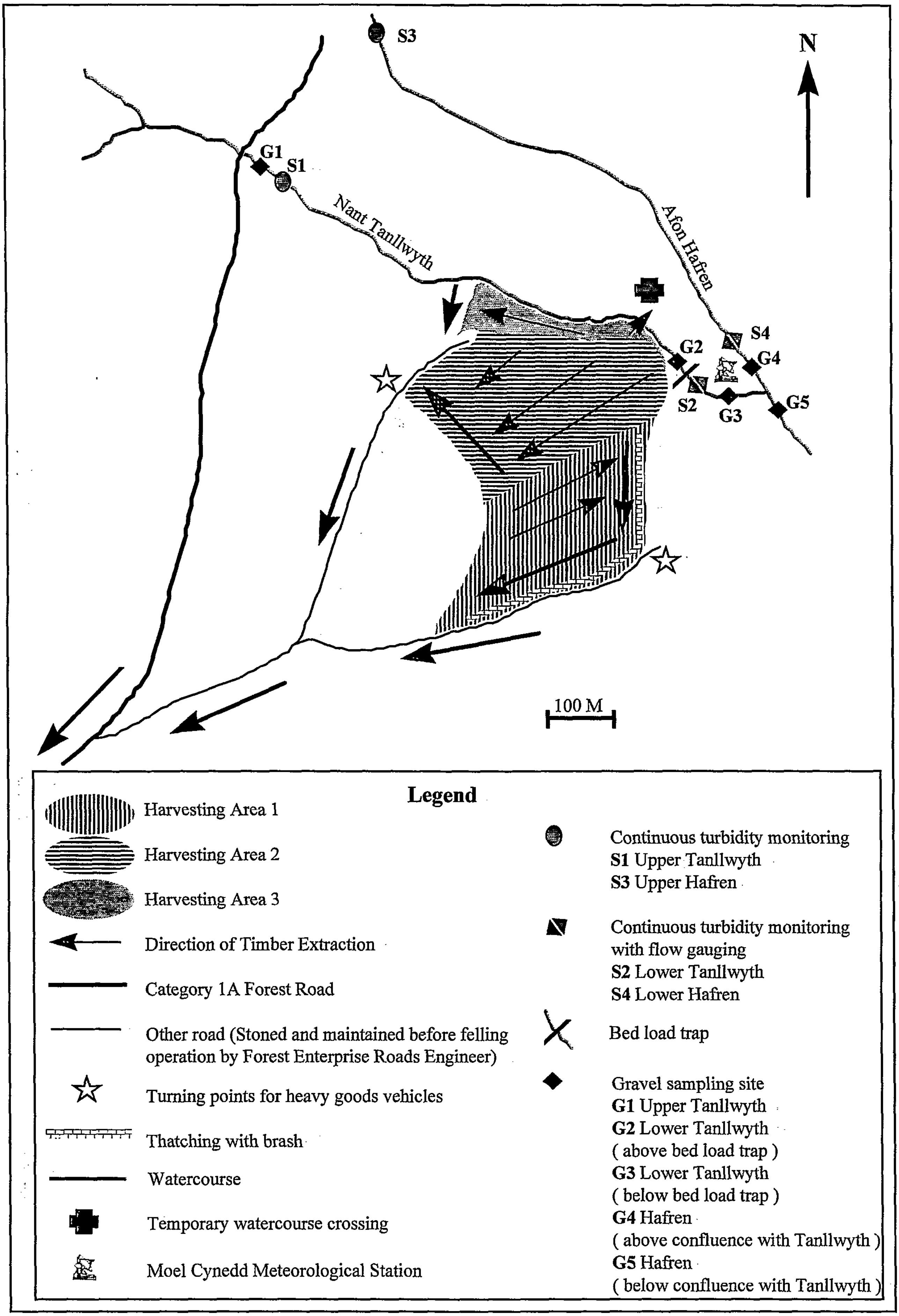
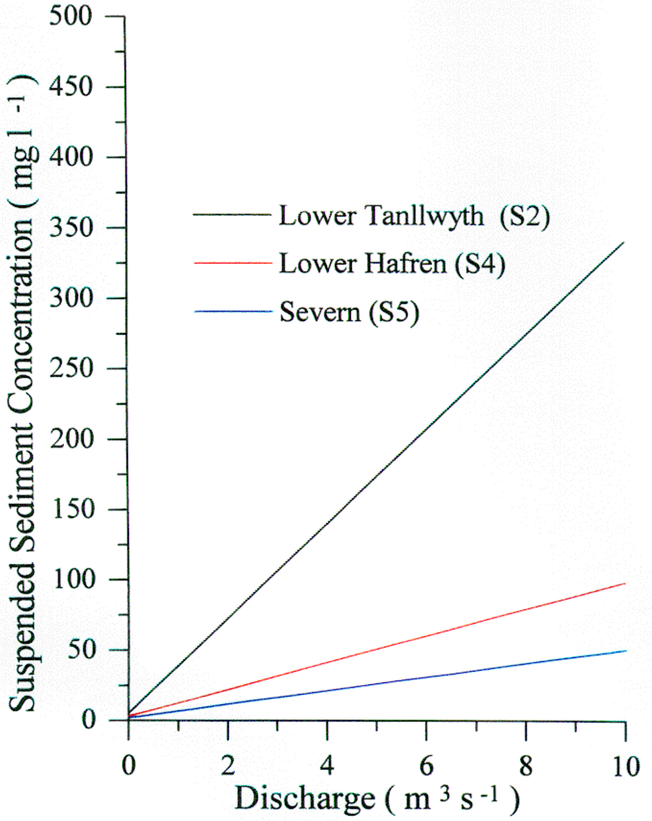
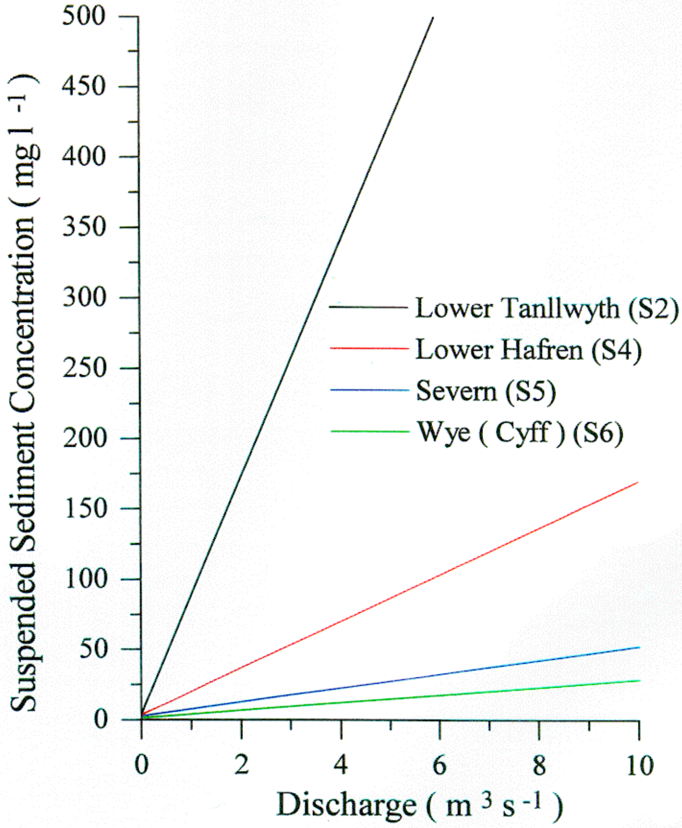


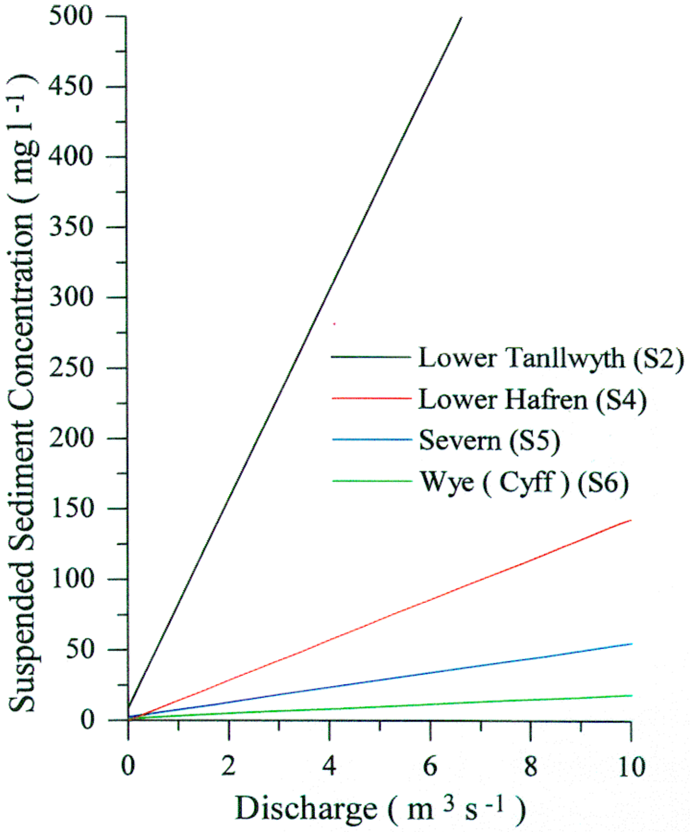
Figure 3 Details of harvesting operation in Nant Tanllwyth catchment



i 1995 Rating Curves

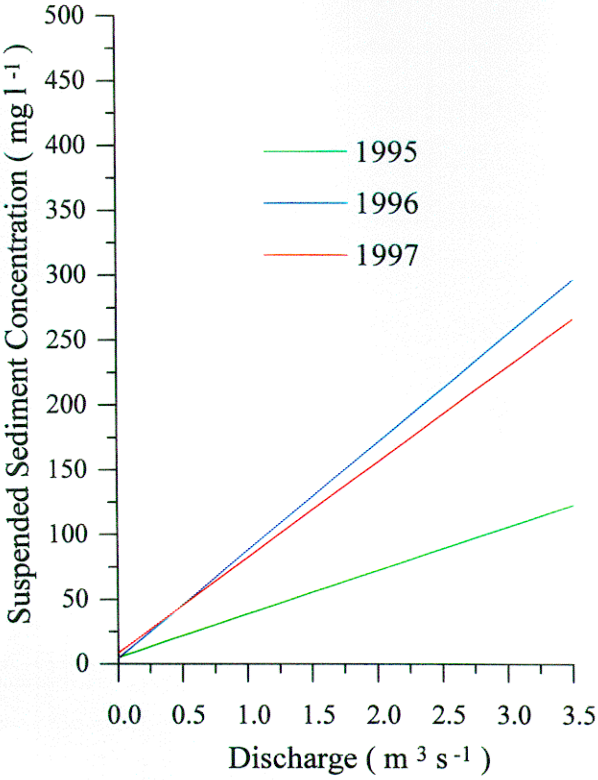


ii 1996 Rating Curves

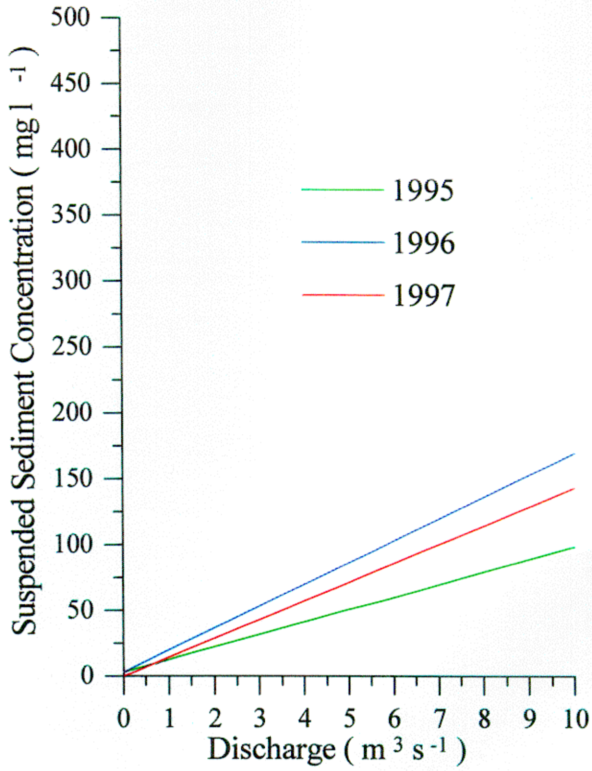


iii 1997 Rating Curves

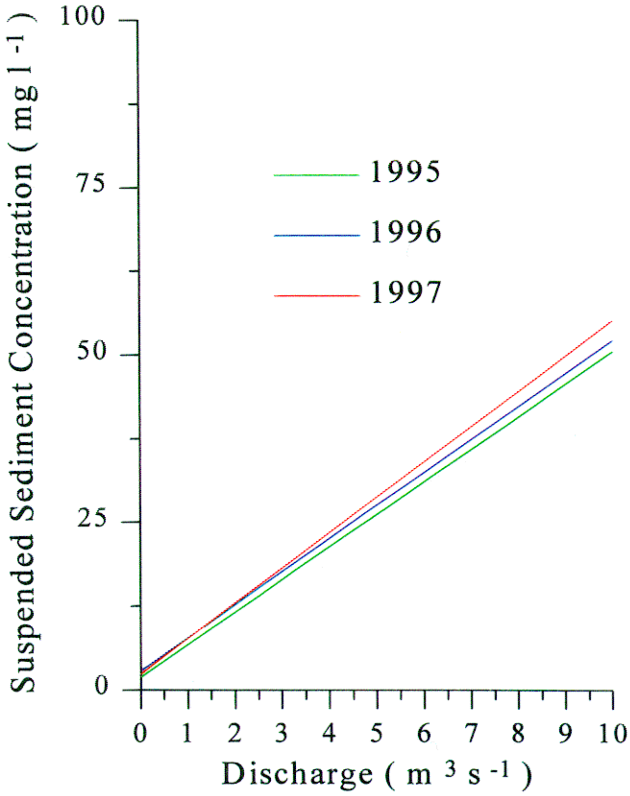
Figure 4
Rating curves for 1995, 1996 and 1997 at turbidity / discharge monitoring sites



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)

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

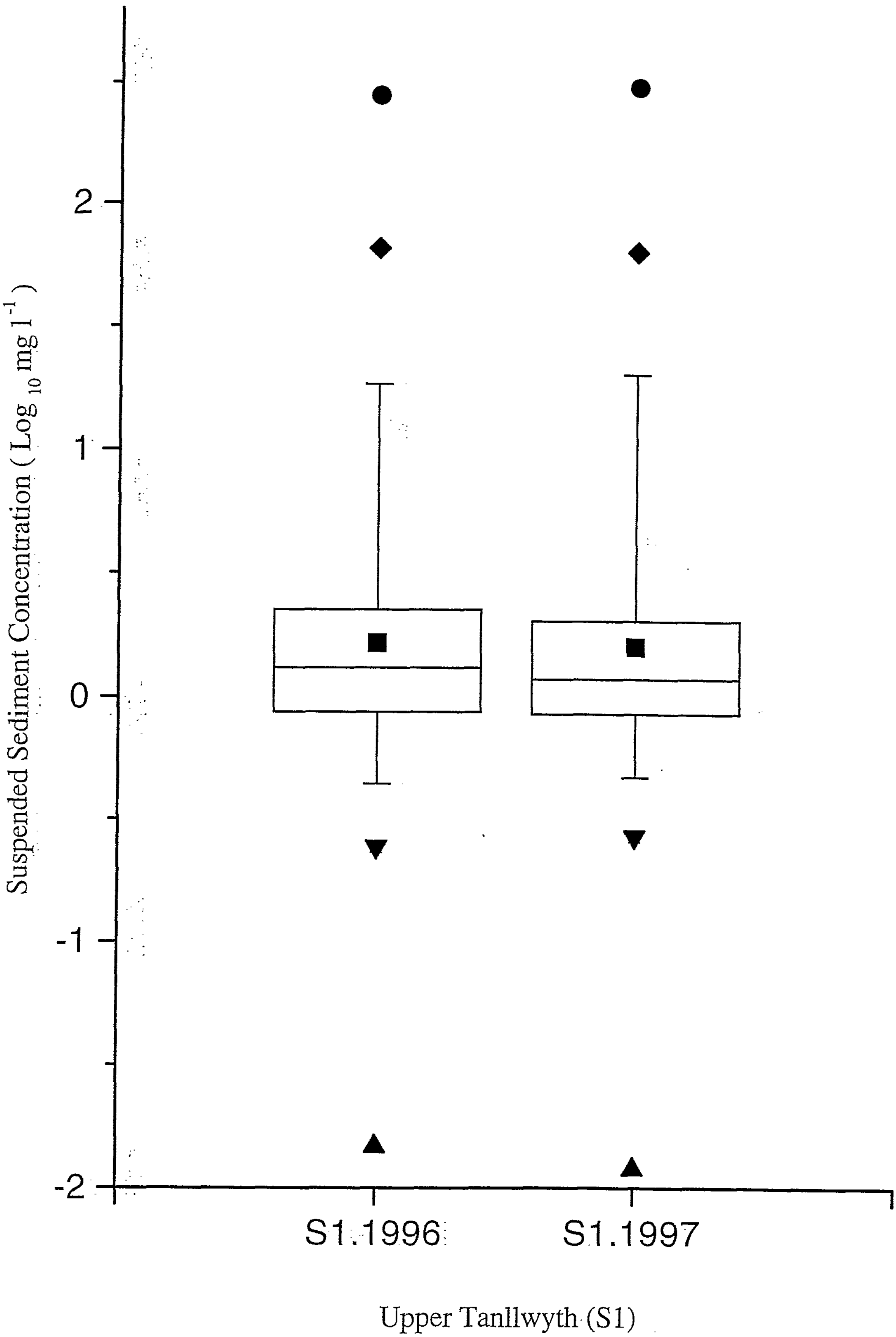


Figure 6
Box charts of continuous suspended sediment concentration data ($\log_{10}$) at the Upper Tanllwyth (S1) site during 1996 and Jan. - June 1997

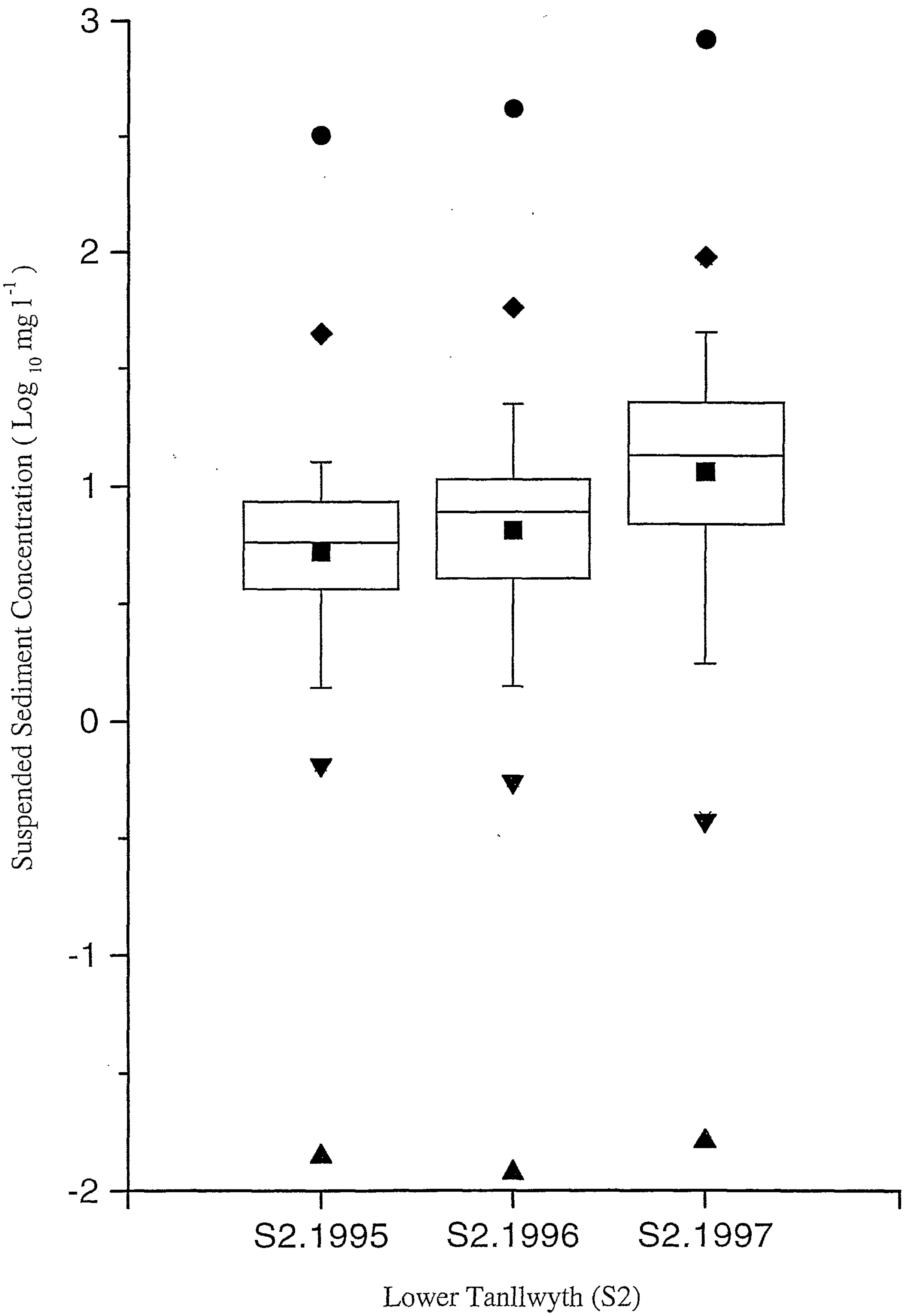


Figure 7
Box charts of continuous suspended sediment concentration data ($\log_{10}$) at the Lower Tanllwyth (S2) site during 1995, 1996 and Jan. - June 1997

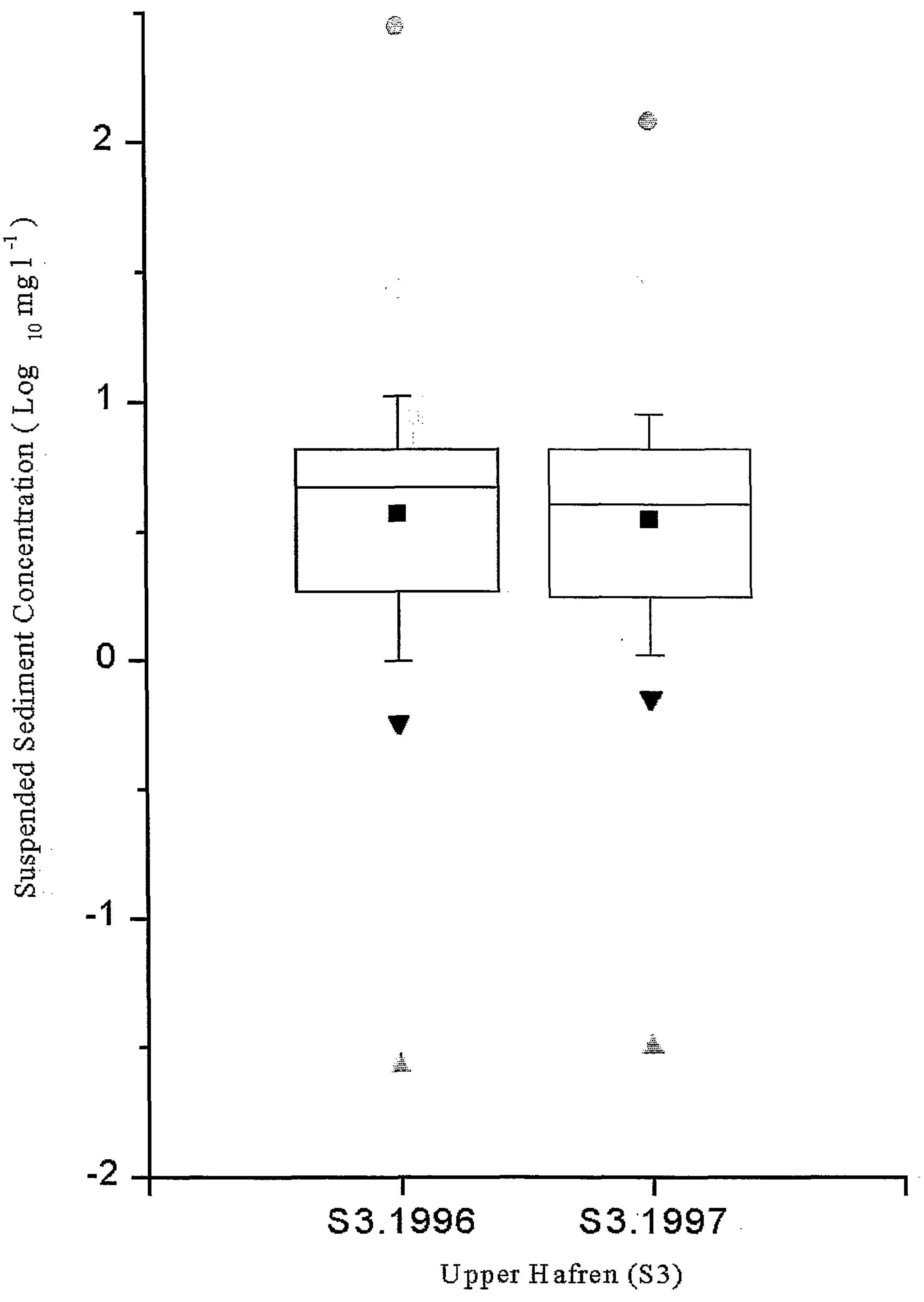


Figure 8

Box charts of continuous suspended sediment concentration data ($\log_{10}$) at the Upper Hafren (S3) site during 1996 and Jan. - June 1997

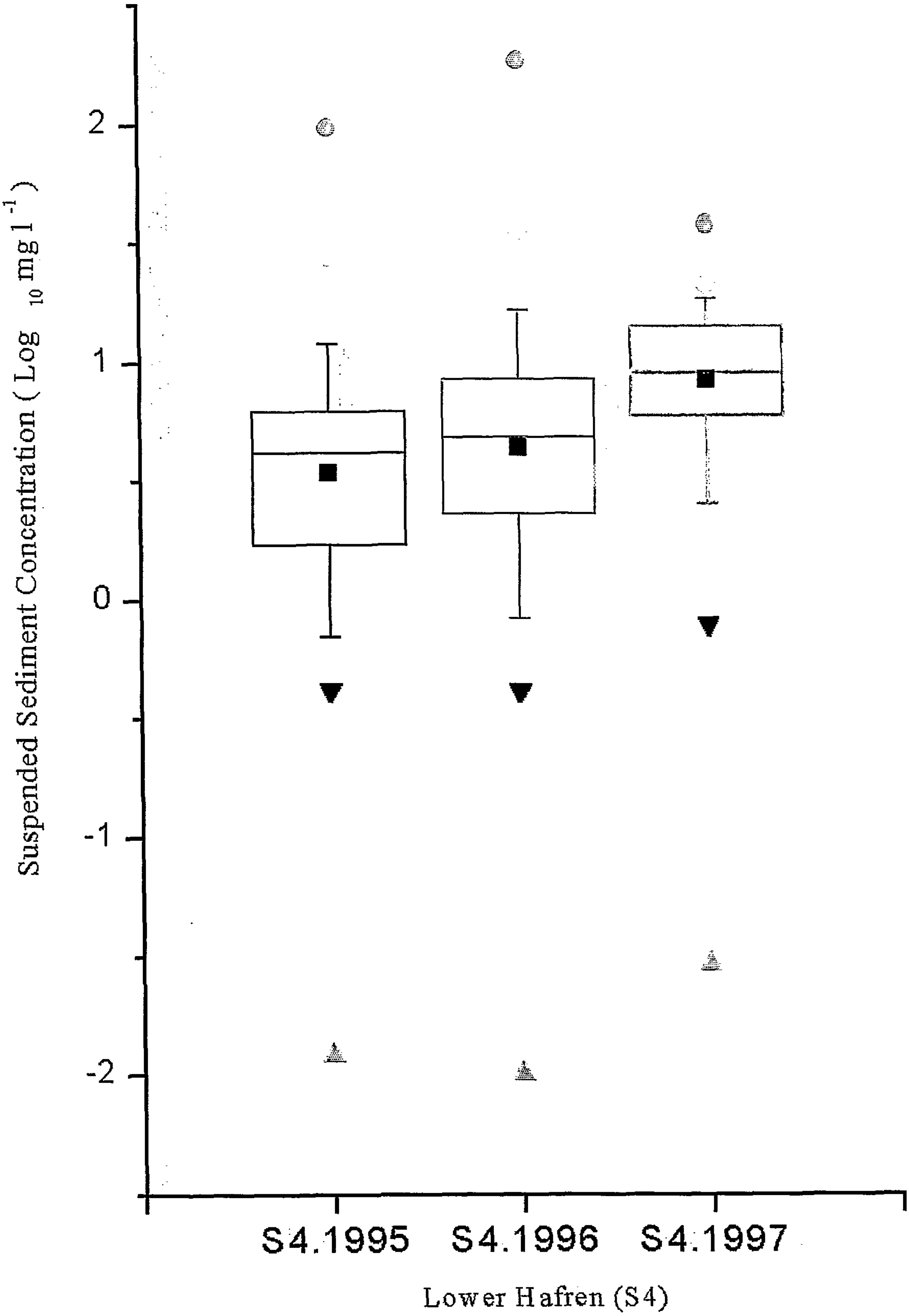


Figure 9

Box charts of continuous suspended sediment concentration data ($\log_{10}$) at the Lower Hafren (S4) site during 1995, 1996 and Jan. - June 1997

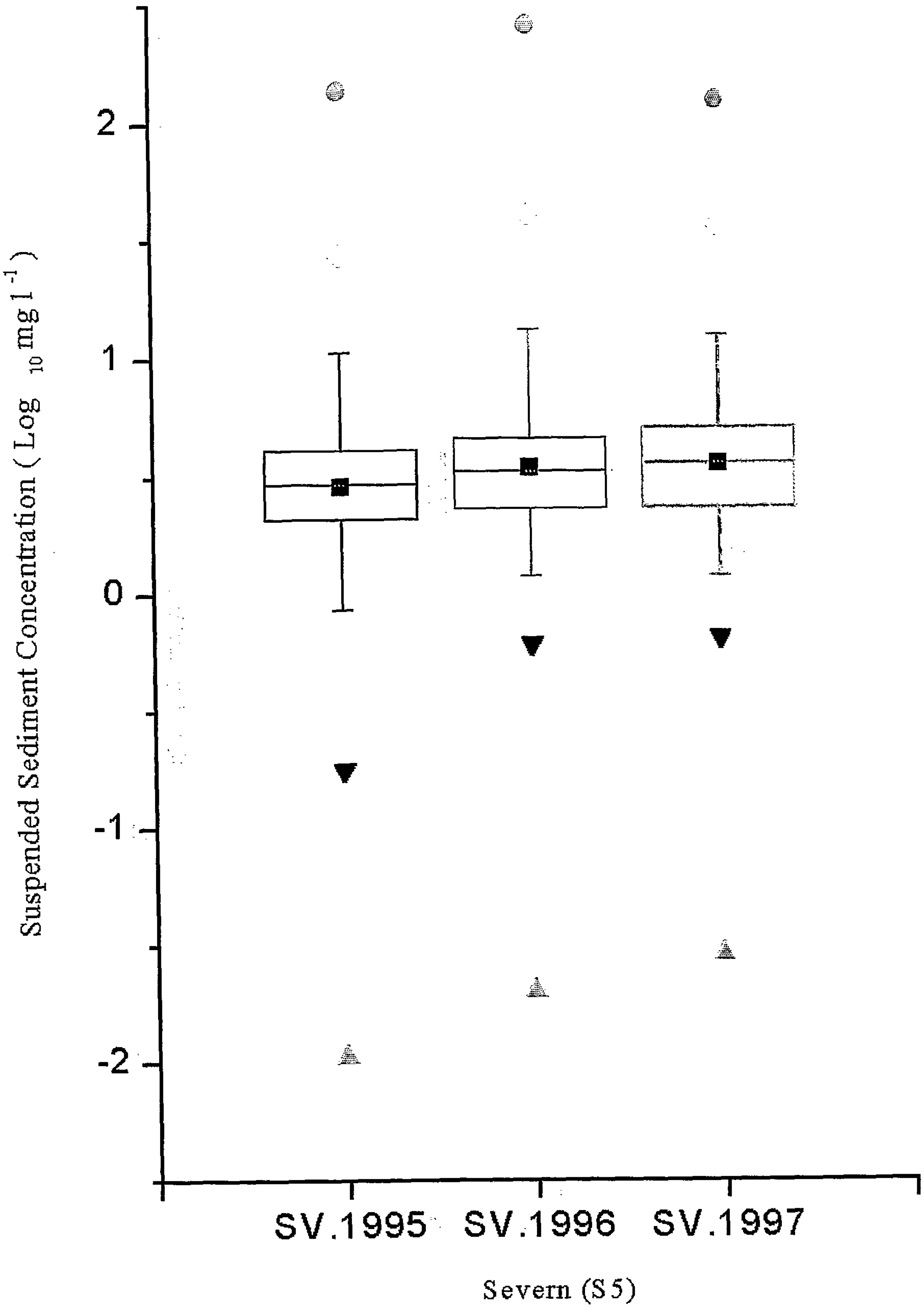


Figure 10

Box charts of continuous suspended sediment concentration data ($\log_{10}$) at the Severn (S5) site during 1995, 1996 and Jan. - June 1997

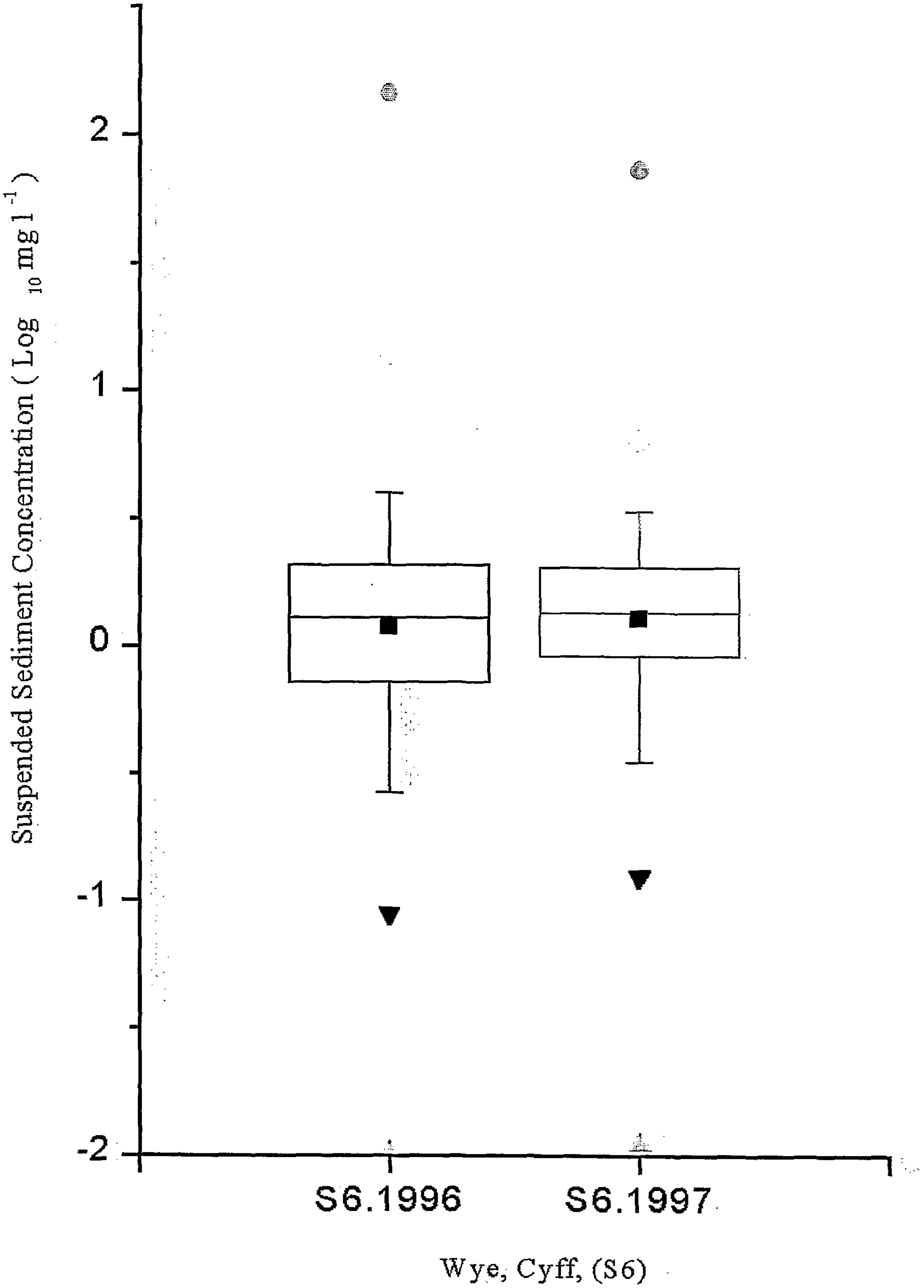


Figure 11

Box charts of continuous suspended sediment concentration data ($\log_{10}$) at the Wye, Cyff, (S6) site during 1996 and Jan. - June 1997

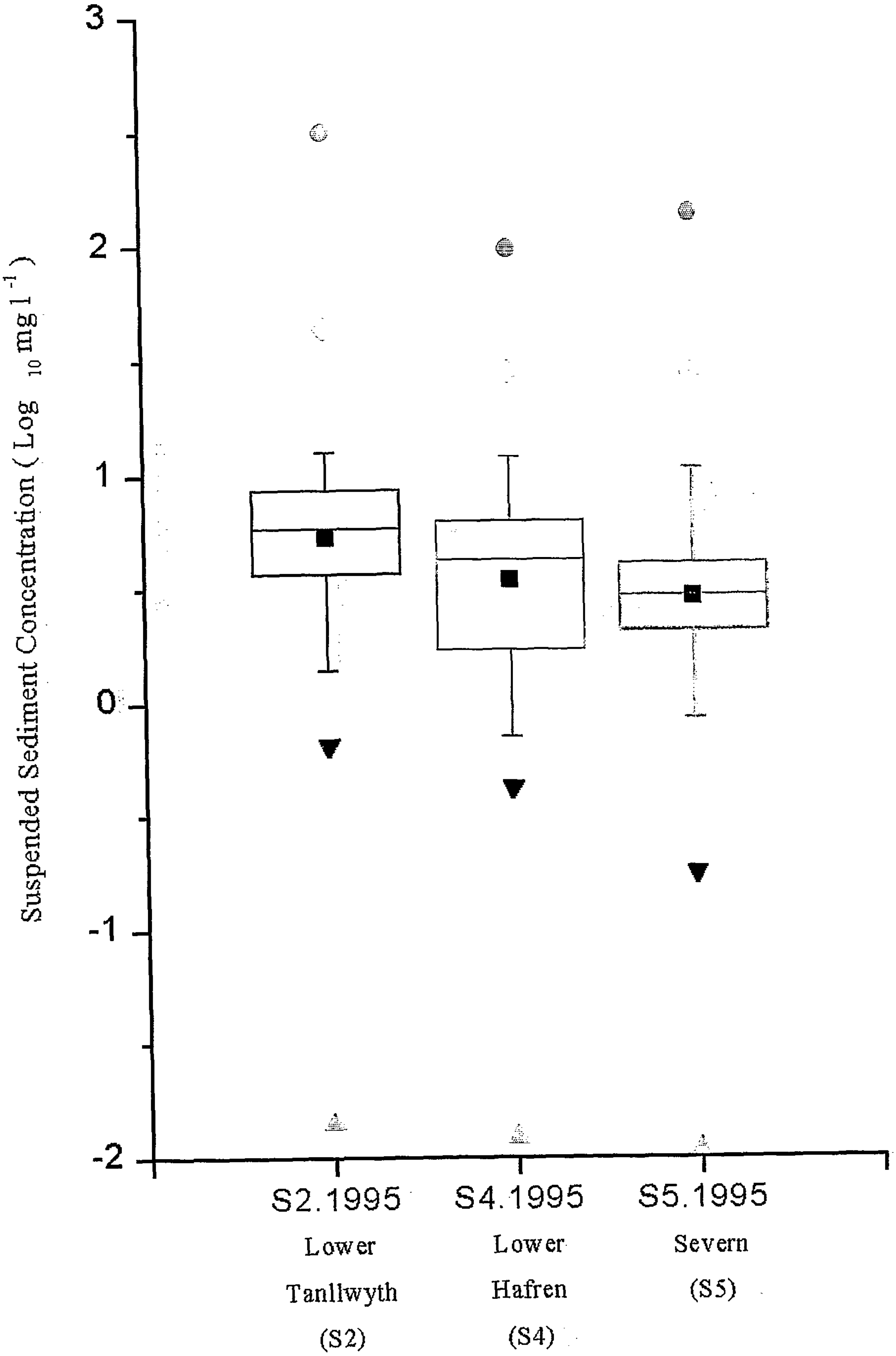


Figure 12

Box charts of continuous suspended sediment concentration data ($\log_{10}$)
during 1995 at the Lower Tanllwyth (S2), Lower Hafren (S4) and Severn (S5) sites

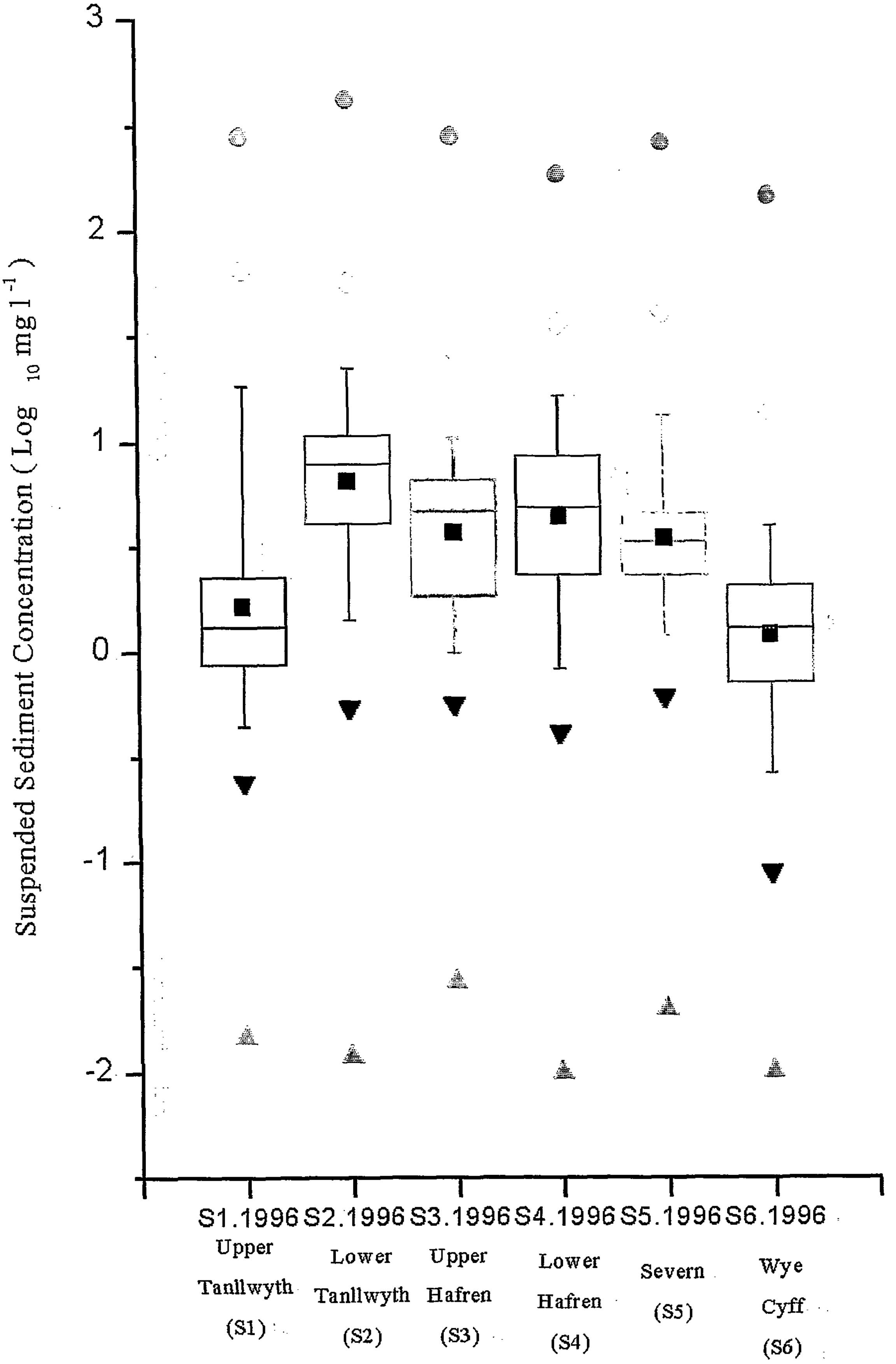


Figure 13

Box charts of continuous suspended sediment concentration data ($\log_{10}$) during 1996 at the Upper Tanllwyth (S1), Lower Tanllwyth (S2), Upper Hafren (S3), Lower Hafren (S4), Severn (S5) and Wye, Cyff, (S6) sites

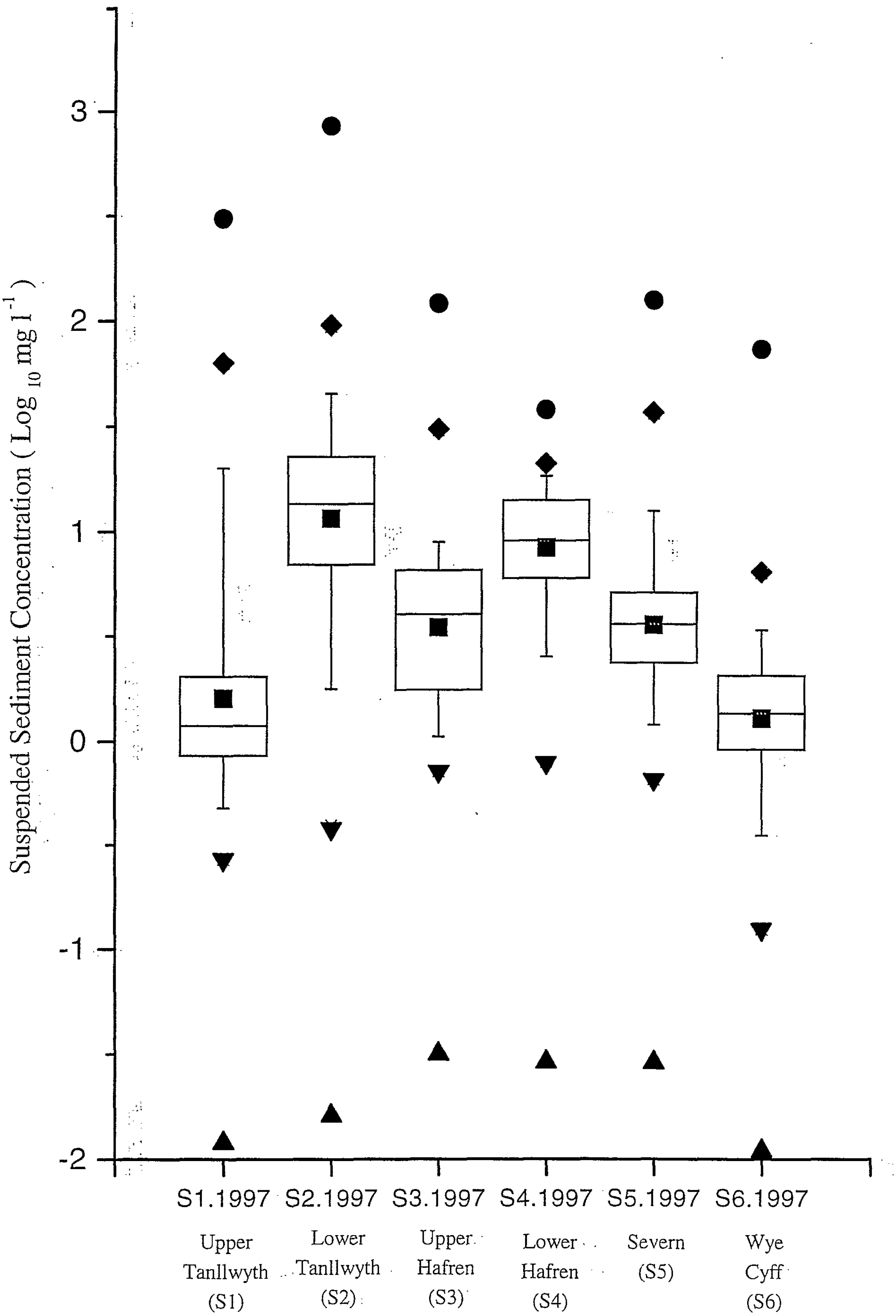


Figure 14

Box charts of continuous suspended sediment concentration data ($\log_{10}$) during Jan. - June 1997 at the Upper Tanllwyth (S1), Lower Tanllwyth (S2), Upper Hafren (S3), Lower Hafren (S4), Severn (S5) and Wye, Cyff, (S6) sites

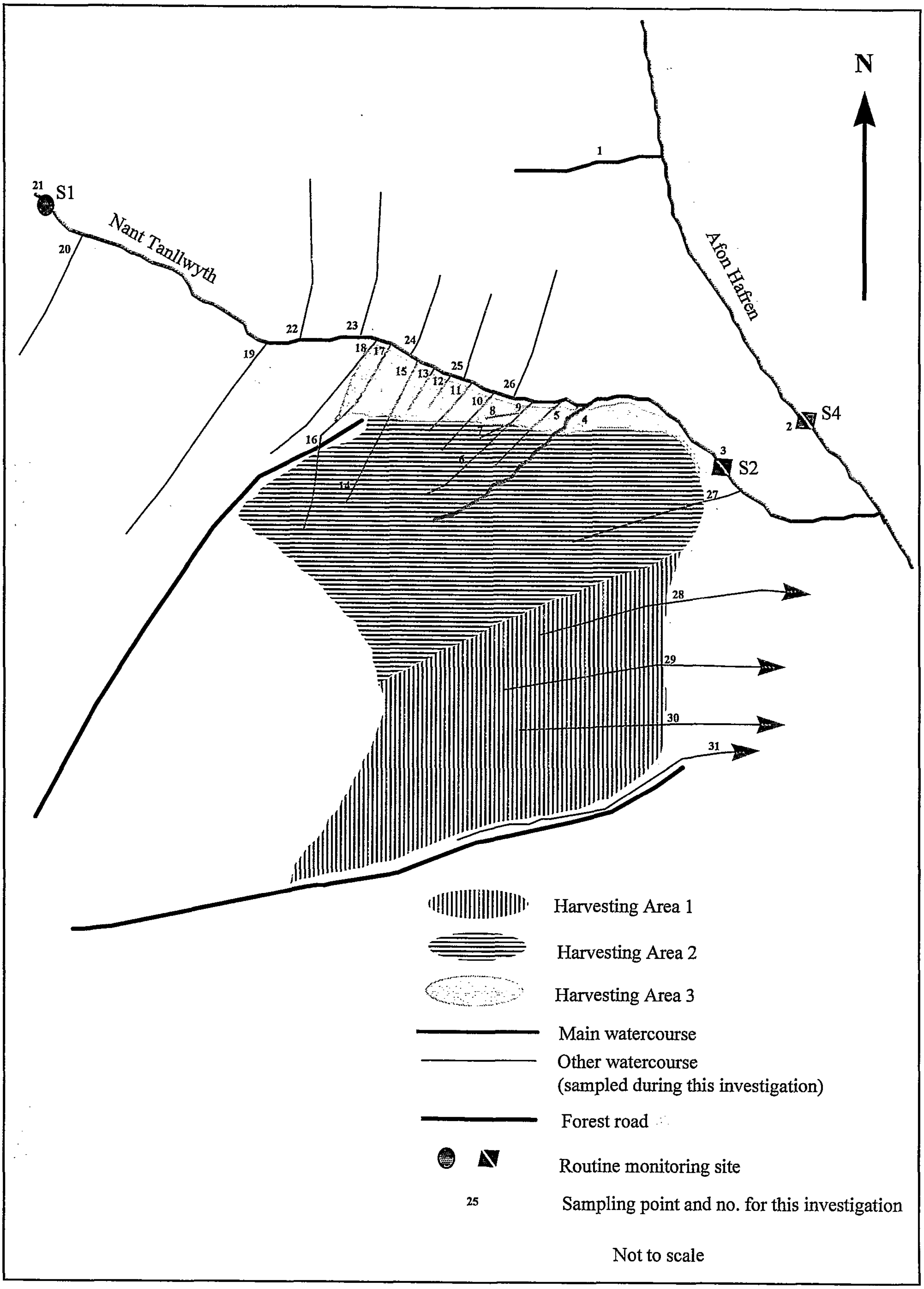


Figure 15 Sampling sites for detailed investigation of particulate outputs from Tanllwyth harvesting site during flood event (12.02.97)

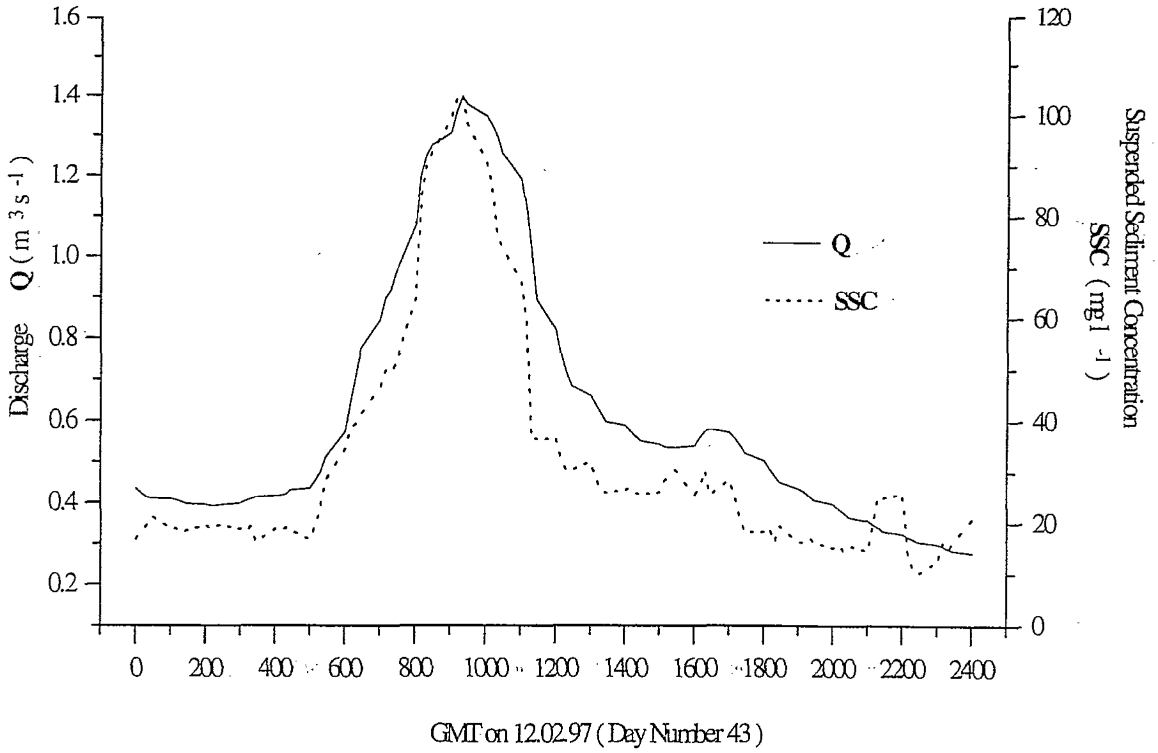


Figure 16 Discharge (Q) and suspended sediment concentration (SSC) at the Lower Tanllwyth (S2) monitoring site during 12.02.97

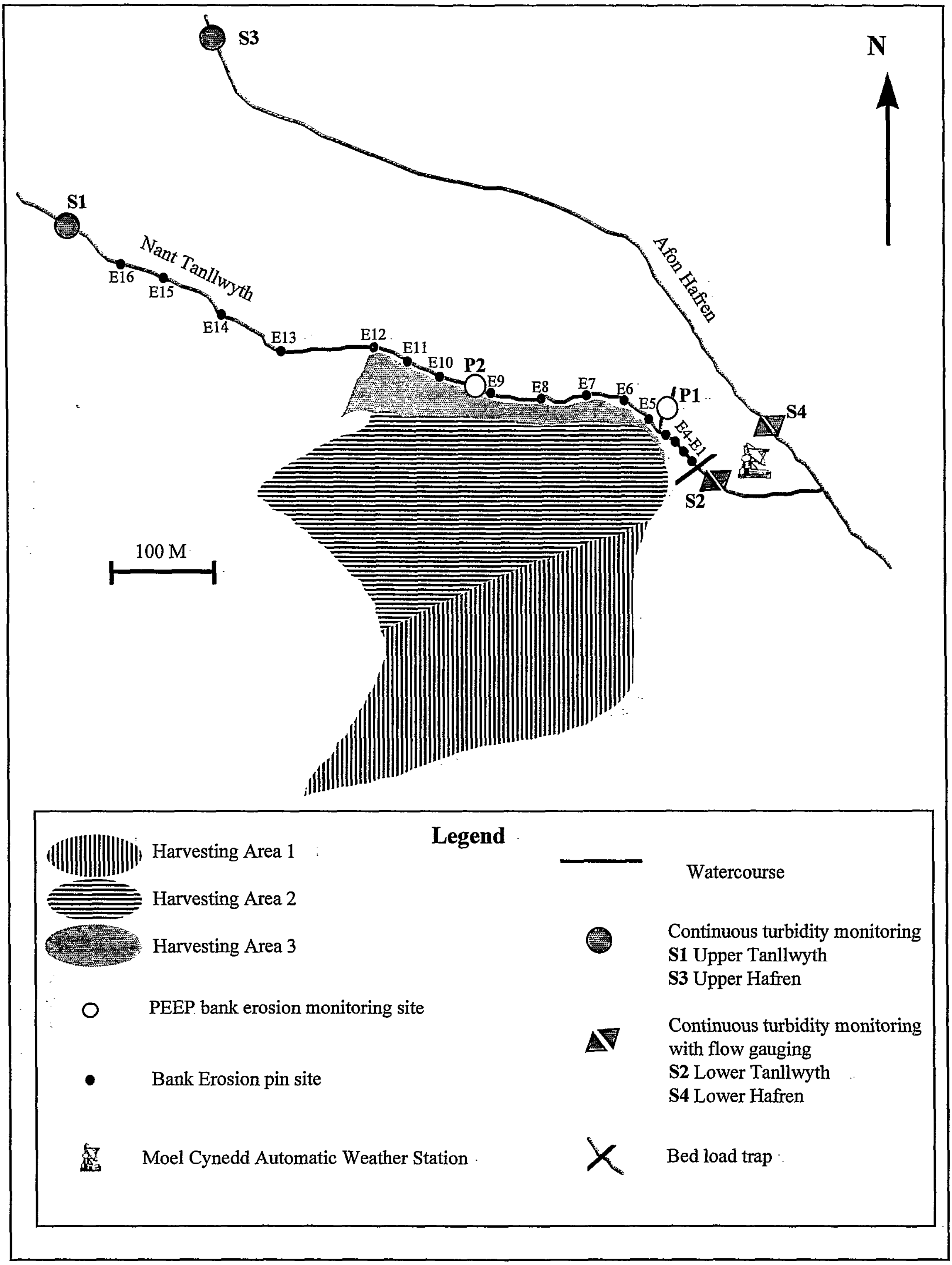


Figure 17 Location of bank erosion monitoring sites in Nant Tanllwyth channel

5 DETAILED MONITORING OUTSIDE THE INSTITUTE OF HYDROLOGY EXPERIMENTAL CATCHMENTS AT PLYNLIMON

5.1 Site Details

Particulate outputs associated with harvesting were investigated at a further site within the Hafren Forest in the Afon Biga catchment directly to the North of the River Severn Experimental Catchment. Figure 18 shows the sampling sites established to study the particulate outputs associated with the harvesting of an area of forestry directly adjoining the south bank of the Afon Biga. A summary of the harvesting site is given in Table 17 below. Due to machine breakdowns, felling was undertaken intermittently between 22 July 1996 and August 1997, and therefore took longer to complete than was anticipated.

Harvesting method	Shortwood (Logma Boom Processor)
Main tree species	Sitka spruce (*P. sitchensis*)
Start date	Bridge building - 11 June 1996
	Felling - 22 July 1996
Finish date	August 1997
Area	6.5 Ha
Timber removed	2600 m^3 (calculated by field survey)

Table 17 Harvesting site summary, Afon Biga

To enable the extraction of felled timber to the forest road on the northern side of the Afon Biga, stone bridge foundations were built at the upper (western) and lower (eastern) boundary of the harvesting site. Small areas of Norwegian spruce (*P. abies*) and Japanese larch (*Larix kaempferi*) were felled on the northern side of the river to enable access from the upper and lower crossings respectively. A single removable bridge platform was used for both crossings. The lower bridge was used first to extract approximately one third of the felled timber.

The Afon Biga site was harvested using the shortwood (Logma Boom Processor) system. After manual felling by chainsaw, the Logma Processor was used to remove the brash and cut the timber into the required lengths on site. Cut timber was then extracted to roadside stacking areas by forwarder.

5.2 Monitoring of Suspended Sediment Outputs Associated with Harvesting Operation

A continuous record of suspended sediment concentration (15 minute interval data) was obtained for river monitoring sites B1 and B2 (see Figure 18) by using the Wallingford Integrated System for Environmental monitoring in Rivers (WISER) instrumentation (see Wass *et al.*, 1997 and section 4.2, this volume). Grid references of these sites and dates of monitoring for this project are shown in Table 18 below.

Site	Grid Reference	Start of monitoring	End of monitoring
Upper Biga B1	SN 847897	01.07.96	30.06.97
Lower Biga B2	SN 855894	01.07.96	30.06.97

Table 18
Grid references and periods of data collection at WISER river monitoring sites within the Afon Biga catchment

All monitoring took place during the harvesting period. A comparison of all continuous sediment concentration data between sites B1 and B2 is shown by Figure 42 in Chapter 4 of R&D Project Record P2/i465/19. As in 4.2, for statistical analyses between mean suspended sediment concentrations, data was normalised by the removal of zero values and application of a logarithmic function. Figures 43 and 44 in Chapter 5 of R&D Project Record P2/i465/19 show the data distributions before (a) and after (b) application of a $\log_{10}$ function. Box plots showing the mean and 0th (minimum value), 1st, 5th, 25th, 50th (median), 75th, 95th, 99th and 100th (maximum value) percentiles for both data sets are shown in Figure 19. As described in 4.2.1 ii., Table 8 summarises how these plots can be interpreted.

Results are summarised in Table 19. As higher suspended sediment concentrations were recorded downstream from the harvesting site, felling may have been responsible for particulate inputs to the Afon Biga. To test if the difference between average suspended sediment concentrations between these sites was statistically significant, both analysis of variance (f) and t-tests were undertaken. Table 19 includes a summary of the statistics between these data sets. Both tests indicate that the means are significantly different at the 0.001 level. As discussed in 4.2.1 ii, high significance levels are, however, likely when dealing with such large data sets.

Two pronounced sources of particulate outputs associated with timber harvesting were identified by field visits to the Afon Biga felling site:

Ground disruption by the operation of harvesting machinery on the steep slopes of the site had resulted in soil erosion where surface runoff was able to erode the exposed soil. Consequently, higher particulate outputs may be associated with the harvesting of steeper sites. The erosion sensitivity of such steep harvesting sites should therefore be recognised before work begins so that careful planning of the harvesting operation can be undertaken to minimise any subsequent adverse impacts. This is recommended in the Forests and Water Guidelines (Forestry Authority, 1993), FE Wales Harvesting manual (Killer, 1994) and FC Soft Ground Harvesting Report (Forestry Commission, 1991b). The latter two documents should be used at this planning stage as they provide specific detail on how such sites can be felled with minimum potential particulate outputs.

The harvesting of trees which had been planted in riparian areas next to tributaries and drains within the harvesting site, and the southern bank of the Afon Biga, resulted in channel bank collapse. As well as the direct introduction of particulate material to the Afon Biga, this also left the affected banks more susceptible to subsequent erosion. This supports the following recommendations in Forests and water Guidelines (Forestry Authority, 1993):

BUFFER AREAS (Pages 13 & 14)

MANAGING RIPARIAN VEGETATION (Page 14)

HARVESTING (Page 17)

- ***Felling in the riparian zone*** *will be an infrequent event once the recommended vegetation has become established....*

No significant source of particulate material appeared to be associated with either of the temporary steel bridge crossings, which were constructed in accordance with guidance in the FE Wales Harvesting Manual (Killer, 1994) and FC Soft Ground Harvesting Report (Forestry Commission, 1991b). Abutments were constructed with rock gabions, upon which removable steel joists were placed with wooden sleepers between. Coarse stone was placed on the tracks at either end of the bridge. These tracks and the bridges were all covered with brash.

	Upper Biga (B1)	Lower Biga (B2)
Maximum suspended sediment concentration (mg l^{-1})	352	507
Mean suspended sediment concentration (mg l^{-1}) Calculated from $\log_{10}$ data #	0.9	1.2
Mean suspended sediment concentration (mg l^{-1}) Log_{10} data #	-0.0631	0.0915
Analysis of variance (F ratio)	1096	
t-Test (t value)	33	

(see Figures 43 and 44 (b) in R&D Project Record P2/i465/18)

Table 19 Summary of suspended sediment monitoring results at Upper (B1) and Lower (B2) monitoring sites and statistics undertaken to test the significance of the difference between mean suspended sediment concentrations

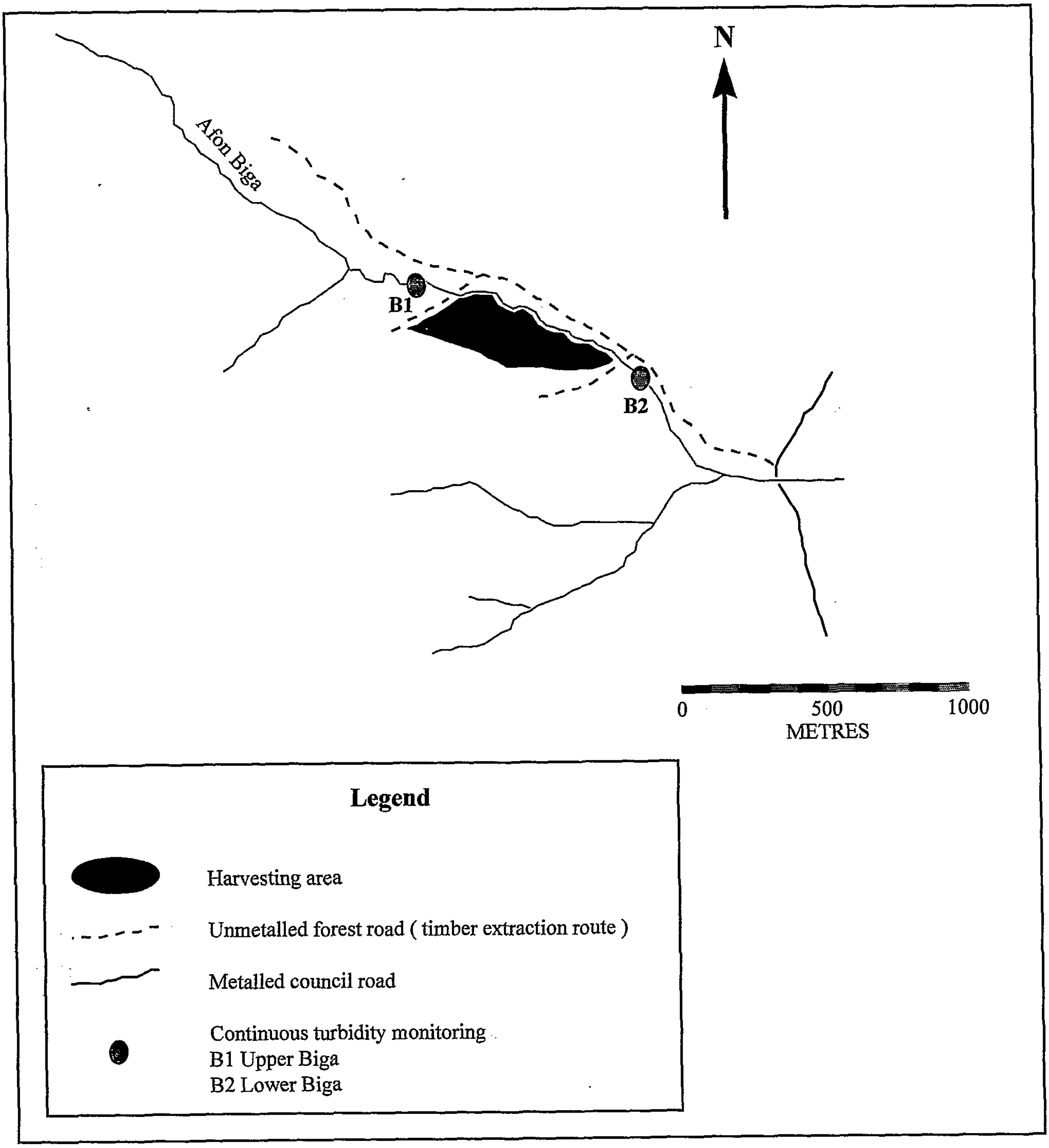


Figure 18 Monitoring network to study suspended sediment concentrations associated with harvesting operation in the Afon Biga catchment

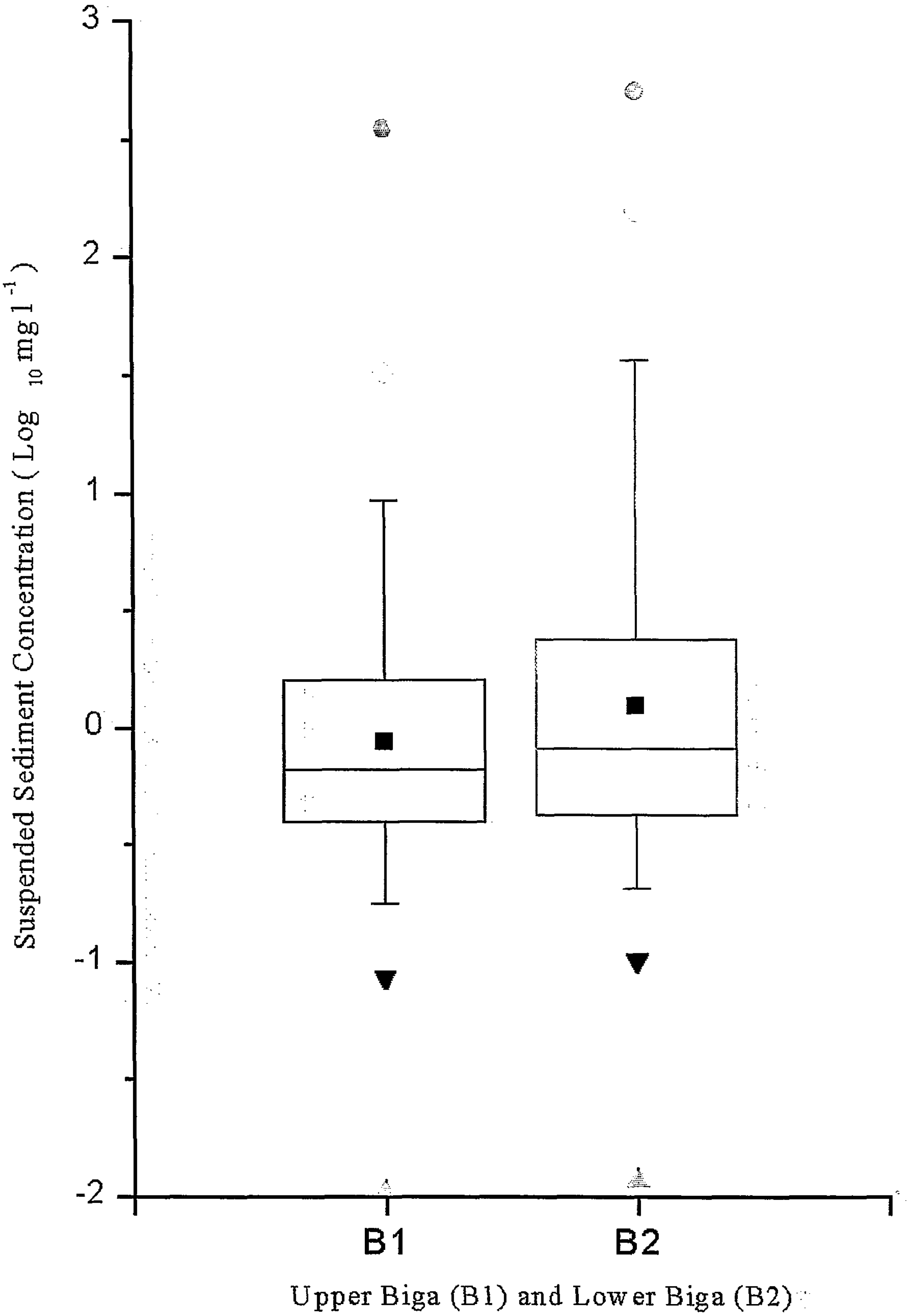


Figure 19

Box charts of continuous suspended sediment concentration data (log $_{10}$) at the Upper (B1) and Lower (B2) Biga sites during timber harvesting

6 SITE SPECIFIC ASSESSMENTS OF THE IMPACT OF PARTICULATE OUTPUTS ASSOCIATED WITH TIMBER HARVESTING

Site specific assessments of the impacts of particulate outputs associated with timber harvesting have been undertaken throughout England and Wales. Correspondence to an extensive questionnaire survey by Pollution Control staff has been collated to report the practical experience within the Environment Agency, leading to an important change in the national Pollution Incident Classification System. Field visits to existing harvesting sites have enabled the identification of the most significant sources of particulate outputs associated with timber harvesting, and some of the methods which could be used to prevent or ameliorate these impacts. Consideration is given to the relevant recommendations in existing Forests and Water Guidelines (Forestry Authority, 1993), FE Wales Harvesting Manual (Killer, 1994) and FC Soft Ground Harvesting Report (Forestry Commission, 1991b).

6.1 Questionnaire Survey of Practical Experience in Environment Agency

In September 1993, for each NRA Region, and each Area / Team within NRA Welsh Region, a questionnaire was sent to a nominated member of the NRA Acid Waters and Forestry sub-group of the Rural Land Use Group requesting information relevant to this research. Through this questionnaire and, where appropriate, visits to Regional offices, a number of examples of practical experience were identified. This information is collated in Chapter 6 of R&D Project Record P2/i465/19.

As many British forests are currently reaching the felling phase of the forest rotation, it was considered likely that further examples of particulate outputs associated with timber harvesting may have occurred since the completion of the First Questionnaire. An Update Questionnaire, requesting relevant information since the initial investigation, was therefore distributed in early 1995 to the officer most involved with forestry within each NRA Region, and Area / Team within Welsh Region. The information from this inquiry is reported in Chapter 7 of R&D Project Record P2/i465/19.

In addition to identifying the areas most susceptible to such impacts, these inquiries enabled the identification of the sources and practices responsible for particulate outputs associated with timber harvesting. In order to identify any positive developments, such as improved liaison between NRA and forestry organisations, and increasing efforts by the latter to prevent and / or ameliorate this environmental impact, brief information from the initial inquiry is also reported in Chapter 7 of R&D Project Record P2/i465/19.

Correspondence relating to both the First and Update Questionnaire recognised that some incidents of sediment pollution associated with timber harvesting may not have been detected. This was attributed to the following:

i. As watercourses draining afforested catchments are often located in remote unpopulated areas, marked incidents of sediment pollution may be less likely to be detected.

ii. When watercourses draining afforested catchments are monitored, this tends to be focused on chemical pollutants, to identify the effects of acidification and the use of forestry agrochemicals.

iii. As sediment transport commonly occurs during flood conditions, incidents of high turbidity are a natural occurrence. The public may therefore be less concerned over events of sediment pollution than those relating to chemical pollution, and may be less likely to contact the Agency concerning this type of environmental impact.

Correspondence relating to both the First and Update Questionnaire has also identified that even when incidents of sediment pollution associated with timber harvesting are detected, follow up investigation may fail to identify the actual impacts. This has been attributed to the following:

i. By the time of follow up investigation, particulate outputs and transport may be less significant than when initially reported. Consequently, sample analysis may reveal low levels of total suspended solids concentration.

ii. If follow up investigation only involves the analysis of water samples, no information on sedimentation will be obtained. The possibility of developing a standard method for the assessment of sedimentation was therefore undertaken for this project (see 7.2). This could go some way to solving the problem described in i. Sedimentation is likely to be associated with incidents of particulate outputs and transport. Although events of suspended solids transport may be short-lived, sedimentation impacts will be apparent for much longer periods. Consequently, follow up investigation might still be able to identify this impact.

Correspondence to the First Questionnaire identified incidents of sediment pollution associated with timber harvesting in the following Regions / Areas and Teams.

South West Region, South West Area. Four incidents.

Welsh Region, South West Area, Team 2 (Haverfordwest). Two incidents.

Welsh Region, South West Area, Team 3 (Lampeter). Four incidents.

Welsh Region, South West Area, Team 5 (Swansea). Two incidents.

Welsh Region, South West Area, Team 6 (Swansea). Three incidents.

Welsh Region, South East Area. Two incidents.

Welsh Region, Northern Area. Five incidents.

Correspondence to the Update Questionnaire identified further incidents of sediment pollution associated with timber harvesting in the following Regions / Areas and Teams.

Severn-Trent Region, Lower Trent Area. One incident.

Severn-Trent Region, Upper Severn Area. Two incidents.

Welsh Region, South West Area, Team 1 (Haverfordwest). Two incidents.

Welsh Region, South West Area, Team 3 (Lampeter). One incident.

Welsh Region, South West Area, Team 5 (Swansea). One incident.

Welsh Region, Northern Area. One incident.

An important point recognised by this work was the difficulty in collating appropriate information due to the absence of a forestry code within the NRA Pollution Incident Classification Systems. As relevant incidents could not be retrieved from the Pollution Archive, past events of particulate outputs associated with timber harvesting are likely to be underepresented in this report. In keeping with a recommendation by this project, a specific forestry code has now been incorporated into the Environment Agency Pollution Incident Classification System within each Region. In early 1996, a further 4 incidents of particulate pollution associated with timber harvesting, since those reported in the Update Questionnaire, were extracted from the Environment Agency, Welsh Region, Pollution Archive using the new FRM25 forestry code. This suggested that subsequent pollution incidents associated with forestry will be more easily identifiable.

Out of a total of 30 sediment pollution incidents associated with timber harvesting, identified through both questionnaire surveys, 24 were within the Welsh region of the Environment Agency. This was expected as the Region contains a high proportion of commercial forestry (see Figure 1). However, Figure 1 also indicates that all Regions contain areas where forestry is considered to be the dominant land cover. Consequently, all may be affected by the impacts of fluvial particulate inputs associated with timber harvesting, but incidents may not always be detected. This is demonstrated by the incidents reported in the South West and Severn-Trent Regions.

The incidents described in Chapters 6 and 7 of R&D Project Record P2/i465/19 identify access tracks, used to extract timber from harvesting sites to the main forest roads, as the major source of particulate outputs associated with timber harvesting. Access tracks are commonly disrupted by the operation of harvesting machinery, particularly if timber is extracted by skidding. Consequently, large volumes of unconsolidated material are often made available for erosion. As access tracks generally form a break in slope and depression in the ground surface, they frequently operate as drains by the interception and concentration of drainage. Flow along the track is then able to transport this material resulting in particulate inputs to watercourses.

Effective measures for the prevention and / or amelioration of particulate outputs from access tracks have been identified. These support the following recommendations in the Forests and Water Guidelines (Forestry Authority, 1993):

__HARVESTING (Pages 16 - 17)__

On soft soils provide and maintain an adequate supporting brash mat for the principal vehicle *routes. Brash may have to be transported from where it is plentiful. Where forest roads have to be used for long distances by forwarders and the like, use brash thatching to prevent damage to the road.*

This is probably the most effective and simplest way to reduce access track erosion during timber harvesting operations. Regularly maintenance by the addition of new brash should be undertaken throughout the harvesting operation .

***When extraction tracks** have been created on slopes, prevent water running down any wheel ruts by digging offlets at intervals. Make this also the standard practice if there is any appreciable break in operations, or during operations if there is a risk of erosion.*

Such offlets could take the form of cut-off drains or soil bunds constructed across the track.

WORKING CHECKLIST, Harvesting (Page 20)

Avoid long ground extraction routes on steep ground, especially in high rainfall areas.

Fell and extract in sensitive areas during dry weather

In this investigation, most of the incidents of serious particulate inputs from forest access tracks used during timber harvesting occurred during wet weather. This latter point is also emphasised in the FE Wales Harvesting Manual (Killer, 1994). Similarly, to enable the utilisation of 'weather windows', the FC Soft Ground Harvesting Report (Forestry Commission, 1991b) states that the choice of season may be critical when planning harvesting operations on very susceptible ground. In British rivers, the critical period when eggs and alevins are living in the spawning gravels, and are therefore vulnerable to the effects of siltation, is normally from October to March (see 3.3.1 i). Avoiding wet winter months when harvesting erosion sensitive sites will therefore also avoid the period when salmonid reproduction is most susceptible to impacts associated with sediment deposition. Erosion sensitive sites which are harvested during dry periods should, however, be monitored after the completion of operations to ensure that particulate outputs do not occur after the completion of operations, when ground disturbed by this activity is subsequently exposed to heavy rainfall.

More detailed guidance on reducing particulate outputs from harvesting tracks is provided by the FC Soft Ground Harvesting Report (Forestry Commission, 1991b) and FE Wales Harvesting Manual (Killer 1994). Within the latter document, additional guidance provided by *3.5.1 Harvesting Tracks, Design and Construction* is summarised below:

The planning and design of harvesting tracks must be done at an early stage to allow for consultation and for deciding if any works will be done in advance of the harvesting operation.

a. As tracks will interfere with land drainage, advice should be sought from the Area Civil Engineer before any tracks are constructed.

b. The minimum number of access tracks should be used.

Over-use of individual tracks should, however, be avoided. Consequently, the FC Soft Ground Harvesting Report (Forestry Commission, 1991b) states that damage levels increase as extraction hauls become longer due to lower roading densities. The optimum number of routes should therefore be identified at the site planning stage based on the volume of timber to be harvested and expected brash route life. Road spacing should be re-examined when more track use proves necessary than was originally planned for.

c. To reduce the risk of long-term erosion, tracks should be designed and constructed to allow for restoration and/or revegetation after use.

d. Access tracks should be constructed on dry ground and avoid wet areas. Any drainage along the track should be diverted using cut-off drains (or log steps, see *38.* below).

e. Tracks should be constructed to the minimum gradient appropriate to the site and safe working limits of harvesting machinery.

f. On sloping sites with a shallow mineral soil overlying impermeable rock, rainfall channelled in wheel ruts will easily erode all of the soil. For forwarder use a heavy brash mat will prevent most erosion. For skidder use or sites with little brash, tracks should be short and located in dry areas with frequent cut-off ditches (or log steps, see *38.* below).

g. A low point should be introduced before tracks approach watercourses to allow any particulates to settle before reaching the water (or enable the drainage to be diverted, see *38.* below).

h. When crossing peat soils it is important to spread the pressure of wheel loads upon the track surface to prevent disturbance of the surface crust. This can be undertaken using overturned root plates or a thick sitka spruce brash mat.

In addition to the measures identified in the Forests and Water Guidelines and FE Wales Harvesting Manual, the following damage control measures for the prevention and / or amelioration of particulate outputs from access tracks are detailed in the FC Soft Ground Harvesting Report (Forestry Commission, 1991b).

38. Log steps can be used to create a barrier across an access route where downhill movement of silt / slurry occurs along ruts. This prevents silty water being moved down the track by the wheels of the machine, and can enable it to be diverted to brash bund lagoons (see below). The effectiveness of log steps can be improved by planning access routes with low points in suitable places for overflow into brash bunds.

39. Brash bunds. Particulate laden drainage diverted from access routes using log steps should be prevented from flowing directly into drains and watercourses by encircling the spillage zone with brash, forming a dam or bund. The brash will help contain the slurry and allow some filtration of particles. Brash may periodically be brought out on top of a load to raise the bund level or reinforce areas of weakness. Bunding is very cheap and the machine operator can be undertake remedial action throughout. In extreme cases the use of an excavator to make a major silt trap may be necessary.

40. Corduroy rafts can be used for temporary reinforcement of short sections of ground with poor bearing capacity that are subjected to high traffic usage. Lengths of timber are placed side by side across the route and are then covered with a thick brash mat. Rafts are particularly beneficial at the approaches to stream-side crossings and roadside stacking sites.

The main preventative measures which can be employed to reduce particulate outputs from harvesting access tracks can therefore be summarised as follows:

i. Access track surfaces should be protected with a thick covering of brash and / or corduroy rafts in sensitive areas.

ii. Any drainage along access tracks should be diverted to areas where provision is made for the removal of particulate material before reaching drains or watercourses. These may take the form of silt traps, brash bunds or riparian / buffer areas.

In addition to the measures identified above in the Forests and Water Guidelines, FE Wales Harvesting Manual and FC Soft Ground Harvesting Report, the following measures for the prevention and / or amelioration of particulate outputs from access tracks have also been identified:

i. If many access tracks are used during harvesting, the phasing of operations should be considered.

ii. If access tracks intercept drainage, bridges or culverts should always be constructed to prevent water from flowing onto the track. The FE Wales Harvesting Manual and FC Soft Ground Harvesting Report give practical guidance on how these crossings should be constructed.

iii. Where drainage from an access track meets the forest road, provision should be made for its diversion to the road drain. In such cases, the road drain may need to be modified to prevent particulate inputs to the watercourse. This could take the form of silt trap construction. The FC Soft Ground Harvesting Report advises the construction of silt traps where particulate outputs are high. Several examples have measured 6m x 6m x 2m deep built either side of a road and linked by a culvert. Primary settlement occurs in the top side pit with secondary trapping of finer particles in the second. On long-term harvesting sites, provision for access must be made for periodic emptying.

iv. Drains, culverts and silt traps should be inspected regularly. If drains or culverts are blocked, they should be cleared. Similarly, if silt traps are full, they should be emptied. After its removal, waste spoil will be easily erodible, and should therefore be deposited away from any drainage where it cannot be entrained and transported to any watercourse.

v. Straw bales can be used to divert and filter surface drainage from access tracks.

vi. Access tracks susceptible to erosion should not be used to extract timber by skidding.

Correspondence to the Initial Questionnaire identified that a number of Regions liaise with the Forestry Commission and private forestry companies regarding operations likely to affect water quality. This may be on an informal basis, as in South West Region where Wardens and Pollution Inspectors contact forest operators on an irregular basis. Severn-Trent, Northumbria and Yorkshire, and Welsh Region, however, have established more formal links, involving direct contact with FE, FA and private forestry companies. Correspondence to the Update Questionnaire identified improved links between the Environment Agency and forestry organisations. Most of this liaison has been with FE and FA. Consequently, there is a need to improve links with private forest owners and felling contractors.

A number of Agency officers reported that FE are receptive towards concern over particulate outputs associated with timber harvesting. This is demonstrated by the FC Soft Ground Harvesting Report (Forestry Commission, 1991b) and FE Wales Harvesting Manual (Killer, 1994). Details of these documents are given in Chapters 8 and 9 respectively of R&D Project Record P2/i465/19.

6.2 Field Visits to Harvesting Sites

6.2.1 Rheola Forest

As described in Chapter 7 of R&D Project Record P2/i465/19, the response to the Update Questionnaire from Welsh Region, South West Area, Team 5, revealed that particulate outputs associated with timber harvesting operations within Rheola Forest, Morgannwg Forest District, were responsible for contamination of the Nant Tyn-y-Cwm, a tributary of the River Dulais. A site visit on 3 February 1995 by IH and Agency staff revealed significant evidence of soil erosion by drainage over ground disturbed by recent harvesting activity.

At one site, an extraction track (with no overlying brash mat) had intercepted drainage, resulting in concentrated flow over disturbed ground along the track. This flow pathway appeared to be responsible for considerable erosion and particulate transport. Extensive particulate deposition, in the form of thick mud up to 35 cm deep, was evident in the unbridged road drain where this eroding track met the main forest road. Mud had then flowed along the road drain and through a culvert under the forest road to a buffer area of thinned mature coniferous trees, where no defined drainage pathway was evident. As the forest had been thinned in this area, the forest floor was not shaded by the forest canopy, thereby allowing the establishment of forest floor vegetation which resulted in particulate deposition. Vegetation has two inter-related influences on drainage. It reduces both flow velocity, and increases lateral flow dispersion. Both lower the ability of surface water to transport material, and therefore encourage deposition (Swift and Norton, 1993). Consequently, no evidence could be found of any particulate transport from the culvert to the River Dulais in the valley bottom.

In this example, when concentrated drainage with a high particulate load flowed through a vegetated buffer area with no defined drainage pathway, intra-vegetation percolation resulted in particulate deposition, thereby preventing inputs to the river system. Such an approach could be employed in two ways to reduce the impact of particulate-laden drainage on watercourses:

1. As a preventative technique, by designing forest drain pathways to end in vegetated buffer areas with no defined drainage.

2. As an ameliorative technique, by diverting drainage with a high particulate load from a watercourse to such an area.

These observations support the following recommendations in the Forests and Water Guidelines (Forestry Authority, 1993): Reference is made to the relevant page of the latter.

ROAD CONSTRUCTION AND MAINTENANCE. During maintenance (Page 16)

HARVESTING (Page 17)

BUFFER AREAS (Pages 13 & 14)

MANAGING RIPARIAN VEGETATION (Page 14)
This gives guidance on the management of riparian vegetation. As buffer areas include the riparian zone, the management of the latter will be equally applicable to that of buffer areas.

It should, however, be noted that the actual source of particulate outputs identified in this study would have been significantly reduced if the access track had conformed to guidance in the Forests and Water Guidelines (Forestry Authority, 1993), FC Soft Ground Harvesting Report (Forestry Commission, 1991b) and FE Wales Harvesting Manual (Killer, 1994). This should have taken the form of brash matting, and culverting / bridging of the forest road drain where the access track entered the main forest road.

6.2.2 Giedd Forest

A site meeting between IH and FE took place on 7 March 1995 to describe the work undertaken to control particulate outputs associated with harvesting operations. This is detailed below.

i. Access to harvesting area

As the harvested area was located on a plateau above a forest road, excavation was attempted to provide access for harvesting machinery. However, as the plateau consists of unconsolidated glacial deposits, this resulted in slope failure and the exposure of material susceptible to erosion. Further excavation attempts and the use of such a route would undoubtably have led to severe particulate outputs.

An extraction-ramp was therefore built up to the plateau, using 1000 tonnes of 'as-dug' quarry stone, at a cost of £3 per tonne. This stone consists of a range of sizes, with long axes ranging from approximately 4 to 50 cm. Such a composition allows drainage to percolate between the stone. This encourages the filtering out of particulates, and reduces surface run-off which would otherwise transport material. It was, however, recognised that the gaps between the stone may become blocked with deposited material, therefore increasing surface flow. Consequently, cross drains were also constructed on the extraction-ramp. These consist of a slight ramp, constructed at about 45^0 to the direction of the extraction route, which divert any surface drainage into silt traps constructed along the sides of the extraction-ramp.

The total construction cost of this extraction-ramp, including materials and labour etc., was approximately £7500. Due to the large scale of the harvesting site, approximately 400 hectares, it was used to transport 5000 tonnes of timber, with a total value of £100 000. Consequently, the cost of the ramp only represented a small percentage of the timber value (approximately 7%), and was considered to be a practical investment. It should be noted, however, that for smaller scale harvesting sites, such investments may not be economically viable.

ii. Minimise ground disruption by harvesting machinery

Ground disruption by harvesting machinery renders the soil susceptible to erosion, and therefore represents an important source of particulate outputs. To protect the soil within the harvesting site, brash matting had been placed along extraction routes.

iii. Prevention of particulates in drainage from harvesting site entering watercourse

a. Drainage from the harvesting site flows from the plateau to the Nant Cyw and River Giedd. An old stone hedge that exists at the break in slope, where drainage descends to the watercourse, was left standing throughout the harvesting operation. This had been responsible for the ponding of water and dispersion of drainage, thereby preventing flow concentration. As particulate deposition was evident along its upslope side, this structure had been effective in reducing particulate inputs to the watercourse.

b. A number of small established tributaries drain through the harvesting site to the Nant Cyw and River Giedd. Before being culverted under the main forest road, silt traps were constructed on these watercourses. The dimensions of these structures were approximately 1.5m × 1.5m × 1.5m. As one silt trap had completely filled with sediment, this example prevented the input of more than 3 m^3 of sediment to the main watercourse. Clearly, such post depositional evidence gives no information on the amount of particulates which passed through the silt trap into the watercourse. Consequently, the actual efficiency of such structures in removing particulates from contaminated drainage cannot be assessed in this way. The FC Soft Ground Harvesting Report (Forestry Commission, 1991b), paragraph 50, (see Chapter 8 in R&D Project Record P2/i465/19) recommends the construction of larger silt traps measuring 6m x 6m x 2m with access provided for periodic emptying.

iv. Prevention of particulate outputs from main forest road from entering Nant Cyw and River Giedd

The main unmetalled road for the Giedd Forest, connecting timber extraction routes to the County Council road, runs parallel to the Nant Cyw and River Giedd. To prevent particulate outputs from the road from entering these watercourses, a number of measures have been undertaken. These include:

a. **Road drains with silt traps**. A road drain with silt traps has been constructed along the side of the forest road opposite the watercourse. Particular emphasis has been put on silt trap construction where drainage is culverted to the watercourse.

b. **Bund construction along forest road.** A bund has been constructed along the side of the road adjacent to the watercourse. This diverts all surface water to the drain on the opposite side.

c. **Mid-road ramp.** Similar to that constructed on the timber extraction-ramp (see i), a ramp has been constructed across the main forest road to divert any surface water to the road drain.

d. **Bund construction around timber stacking areas.** These areas are associated with large road use during both initial timber stacking by harvesting machinery and subsequent removal by articulated road vehicles. Consequently, the ground surface is susceptible to erosion. Timber stacking areas have been constructed at the side of the forest road, away from any defined drainage. Bunds have been constructed around these areas to contain this potential source of particulate outputs.

These observations support many of the recommendations in the Forests and Water Guidelines (Forestry Authority, 1993), FC Soft Ground Harvesting Report (Forestry Commission, 1991b) and FE Wales Harvesting Manual (Killer, 1994).

With reference to Forests and Water Guidelines (Forestry Authority, 1993), the following recommendations are supported by iii-b and iv-a. As the culverts from the road drain discharge directly into the watercourse, FE have placed particular emphasis upon silt trap construction. (The importance of maintaining these structures is demonstrated by iii-b which describes a trap which had completely filled with sediment, thereby reducing its effectiveness in the removal of further particulates):

GROUND PREPARATION (Page 13)

ROAD CONSTRUCTION AND MAINTENANCE (Page 15)

ROAD CONSTRUCTION AND MAINTENANCE. During maintenance (Page 16)

The following recommendations are supported by i, ii and iv-d respectively:

HARVESTING (Page 17)

6.2.3 Study of river gravel particle size distribution at Giedd site

When the site was visited on 13.04.95, three bulk samples of river gravel, each weighing in the region of 10 kg, were collected from both the Nant Cyw and Afon Giedd, immediately above their confluence. At the sampling points, both watercourses have similar physical characteristics. Each has a similar gradient with a stream order of 3, as calculated by the drainage defined on Ordnance Survey 1:25 000 Pathfinder Maps. The main difference is in catchment land-use. Although both drain afforested catchments, the upper Giedd was unaffected by recent harvesting operations, whereas the Cyw catchment had undergone large scale clear-felling during the preceding year.

Although freeze coring is the preferred method of river gravel sampling for studies of sediment deposition and river gravel fining (see 4.5), it is often too costly and labourious for rapid *ad-hoc* studies. For this investigation therefore, samples were collected conventionally using a shovel. During collection, significant stream water clouding was evident downstream from the sampling point, indicating that large amounts of fines were being mobilised in suspension following bed disturbance. For each of the samples, it was noted that this was considerably more apparent in the Nant Cyw than the Afon Giedd. This suggested that the river gravels in the Nant Cyw contain more fine material than those in the Afon Giedd. Such an approach could be developed as an immediate means by which river gravel sedimentation could be assessed in the field by Agency staff (see 7.2). As considerable quantities of fine material are lost in suspension, resulting in its underepresentation in the sample, this supports the use of freeze core sampling for accurate studies involving analyses of river gravel particle size distribution.

Despite the known underepresentation of fines in conventional grab samples of river gravel, it was decided to analyse the samples collected from the Giedd site. On return to the laboratory, the three samples for each site were combined to give two bulk samples of approximately 30 kg each. These were spread out on plastic sheeting, and allowed to air-dry. Particle size analysis of each sample was then undertaken by dry-sieving the fraction finer than 45 mm.

Figure 20 shows that the river gravels in the Nant Cyw contain a larger proportion of fine particulates than those in the Afon Giedd. Through interpolation, using polynomial regression analysis, it was calculated that fine material (< 2mm) comprises 9.0 % of the Nant Cyw sample, compared to only 3.8 % in the Afon Giedd sample. River gravels in the Nant Cyw therefore contain more than double the fine material present in the Afon Giedd. It is likely that this can be attributed to fluvial particulate inputs associated with timber harvesting.

The proportion of fine material in the Afon Giedd river gravels is, however, lower than the 20 % threshold discussed in 4.5.7 as being sufficient to affect salmonid spawning. Consequently, results from this study appear to indicate that any increase in river gravel fines associated with timber harvesting in the Afon Giedd catchment is unlikely to have a significant impact on salmonid spawning. It should, however, be noted that the proportion of fine material in these samples is likely to represent a significant underestimation of their actual content in the undisturbed gravel due to the wash out of fine material during conventional shovel sampling (see 4.5.3).

6.2.4 Investigation of particulate outputs associated with coarse woody debris removal in River Llwyd catchment

The Forests and Water Guidelines (Forestry Authority, 1993) recommend that riparian areas adjacent to watercourses should be uncultivated and maintained as protective buffer strips. However, during earlier post-war afforestation, trees were planted up to the stream edges, and as a consequence, harvesting within the riparian zone is often unavoidable during current operations. The Forests and Water Guidelines recommend that trees should be felled away from the stream, which should be kept free from branches and tops as far as practicable. It is, however, recognised that an occasional large log may be advantageous in creating a pool. As described in 3.1.5, considerable research has been undertaken into the management of Coarse Woody Debris

(CWD) within the river channel. Furthermore, the Environment Agency, Forestry Commission and NERC Institute of Hydrology, are currently funding a studentship at Birmingham University to investigate the influence of CWD on British headwater rivers.

Unless causing a major obstacle to fish migration, there may be an advantage in leaving stable CWD within streams/rivers rather than removing it. Although smaller brash material should be quickly removed during and after harvesting operations from watercourses which transmit large volumes of water, it could be left within small forest drains to trap any sediment wash-off.

In this example, timber harvesting in the catchment of a tributary of the River Llwyd, within the Hafren Forest District, Forest Enterprise Wales, resulted in sufficient CWD accumulation within the main channel to cause stream blockage, resulting in flow diversion and additional erosion within the riparian area. Such accumulations may be unavoidable during the felling of riparian areas, particularly in steep upland catchments where channel erosion may have resulted in the collapse of mature trees into both watercourses and their valleys. The worst affected area was a 400 m stretch in the headwaters of the catchment. Prior to re-afforestation FE removed this material from the stream channel in two separate phases. The lower 200 m section was cleared in October 1995 using a Hymac forwarder type 'wheeled' machine. Due to the particulate outputs recorded by IH during this operation, the steeper upper 200 m of the site was not cleared until August 1996 when a new Keiser 'walking excavator' machine, specifically designed for operation in steep erosion sensitive areas, was available. This provided an excellent opportunity for a comparative study of the impacts of particulate outputs associated with both methods.

Total suspended solids concentrations in the water samples collected during the River Llwyd CWD removal study are detailed in Table 20. The investigation of both the Hymac and Keiser operation on 25 October 1995 and 27 August 1996 respectively are shown together to enable comparison.

This study reveals that immediately at the operating site the Keiser is responsible for higher particulate outputs than the Hymac. The impacts of the Keiser operation, however, rapidly dissipate downstream, while particulate outputs from the Hymac site are more sustained. Consequently, impacts on the River Llwyd were far more significant during the Hymac operation.

In accordance with the Forests and Water Guidelines (Forestry Authority, 1993) the movement of any machine along a watercourse is bad practice and should not happen. Despite this, as the wheeled Hymac vehicle would not be stable on the valley sides, it was forced to operate within the channel during CWD removal. This resulted in channel erosion and the supply of particulate material to the watercourse which continued after the vehicle had moved on. This is likely to have been responsible for the sustained particulate inputs to watercourses downstream.

The Keiser is designed specifically for use in steep erosion sensitive areas. It moves using four hydraulic legs and can cope with much rougher and steeper terrain than a wheeled vehicle. As the Keiser can operate along the sides of watercourses, it can be used to remove CWD without entering the stream channel. Consequently, during its operation, although CWD removal still results in a considerable point source of particulate outputs, ground disruption caused by its movement supplies limited material to the watercourse. It was therefore found that the limited area exposed to erosion rapidly stabilises, resulting in less significant impacts downstream.

As the daily average discharge from the River Severn IH Experimental Catchment was 51% higher on 27 August 1996, than 25 October 1995, the flow and therefore the erosivity of the headwater stream, in the adjacent River Llwyd catchment was much higher during the Keiser study. This hinders the accurate comparison of the particulate outputs associated with both methods of CWD removal. Due to the higher erosivity of the headwater stream during the study of the Keiser operation, it could be inferred that the contrast between particulate outputs associated with CWD removal using the two different techniques is more significant than indicated by this study. Furthermore, the Keiser operation was undertaken in a much steeper reach of the watercourse, which would have been more susceptible to erosion.

In contrast to the increased erosivity during the Keiser operation, the higher flow would increase the downstream dilution of the affected drainage, and therefore contribute to the rapid downstream dissipation of the impacts of particulate outputs from the operating site. This is demonstrated by samples 3-4 where the total suspended solids concentration in the headwater stream is reduced by 27 % after the confluence with an unpolluted stream. This is, however, the only significant tributary of the affected stream before it reaches the River Llwyd.

The difference in flow conditions between the two studies prevents a quantitative comparison between the impacts of particulate outputs from both methods of CWD removal. The results of this investigation do, however, indicate that during CWD removal in the catchment headwaters, suspended sediment concentrations in the River Llwyd were higher during the operation of the Hymac, 'wheeled' type, machine than the Keiser, ' walking excavator' type, machine (135 and 5 mg l^{-1} respectively).

The Keiser machine was originally designed for use in steep Alpine areas and can operate on slopes up to 100 %, depending on soil type. By moving using four hydraulic legs, it does not produce the ground disturbance and 'wheelings' which may result in erosion and therefore particulate outputs. Due to the minimum disturbance created by the Keiser, FE currently use it in areas where equivalent wheeled or tracked vehicles are unable to operate. It could, however, be used in the threshold areas near the slope limit of other machinery to reduce ground disturbance, and may therefore be appropriate for a variety of forest management practices in erosion sensitive areas. As in this example, it is commonly used for post-harvesting site preparation, as it creates the minimum ground disturbance, and therefore leaves the maximum available area for replanting. The Keiser is not, however, used for felling as its four legged platform may be insufficiently stable to enable the safe lifting of heavy timber.

The use of biodegradable vegetable-based hydraulic oil represents a further advantage of using the Keiser machine in pollution sensitive areas. Furthermore, the machine only holds 25 gallons of hydraulic oil, compared with the 75 gallons used by equivalent tracked or wheeled machinery.

From the viewpoint of its operator, the use of the Keiser is, however, restricted by its increased operating cost. During ground preparation work, it costs approximately £400/Ha compared to £200/Ha by scarification using a forwarder. Biodegradable, vegetable based hydraulic oil is also considerably more expensive than its mineral equivalent at £5/l compared to £1.70/l, but this may be compensated by the smaller volumes required.

The above example of using specialist machinery to reduce erosion of sensitive sites supports paragraphs *57* and *65* in the conclusions and recommendations respectively of the FC Soft Ground Harvesting Report (Forestry Commission, 1991b). These are summarised below. Further details of this document are given in Chapter 8 of R&D Project Record P2/i465/19.

57. Careful choice of harvesting system and machines, coupled with good organisation and control, should always be undertaken. Where possible, the best equipment options must be used to minimise site damage. Specialised machinery may be required on extremely difficult sites.

65. Managers should be able to request specific soft ground equipment by loan or exchange between Districts or Regions.

Sample Number	Sampling Location	Total Suspended Solids Concentration $mg\ l^{-1}$	
		Hymac Machine October 1995	**Keiser Machine August 1996**
1	Experimental headwater stream immediately below operating machinery.	6068	10 632
2	Control headwater stream, which joins the experimental headwater stream 20 m downstream from Keiser operating site.		5
3	Experimental headwater stream immediately above confluence with control headwater stream.		1348
4	Experimental headwater stream immediately below confluence with control headwater stream.		983
5	Experimental headwater stream, 525 m downstream of Keiser operating site at upper road crossing.	2483	436
6	Experimental headwater stream, 675 m downstream of Keiser operating site at lower road crossing. 200 m upstream of confluence with River Llwyd.	458	11
7	River Llwyd, immediately above confluence with experimental headwater stream.	3	0
8	River Llwyd, immediately below confluence with experimental headwater stream.	135	5
9	River Llwyd at Dolydd, 2.1 km downstream from confluence with experimental headwater stream.	9	0

Table 20 Total suspended solids concentrations in samples collected from River Llwyd catchment during CWD removal by both Hymac and Keiser machines

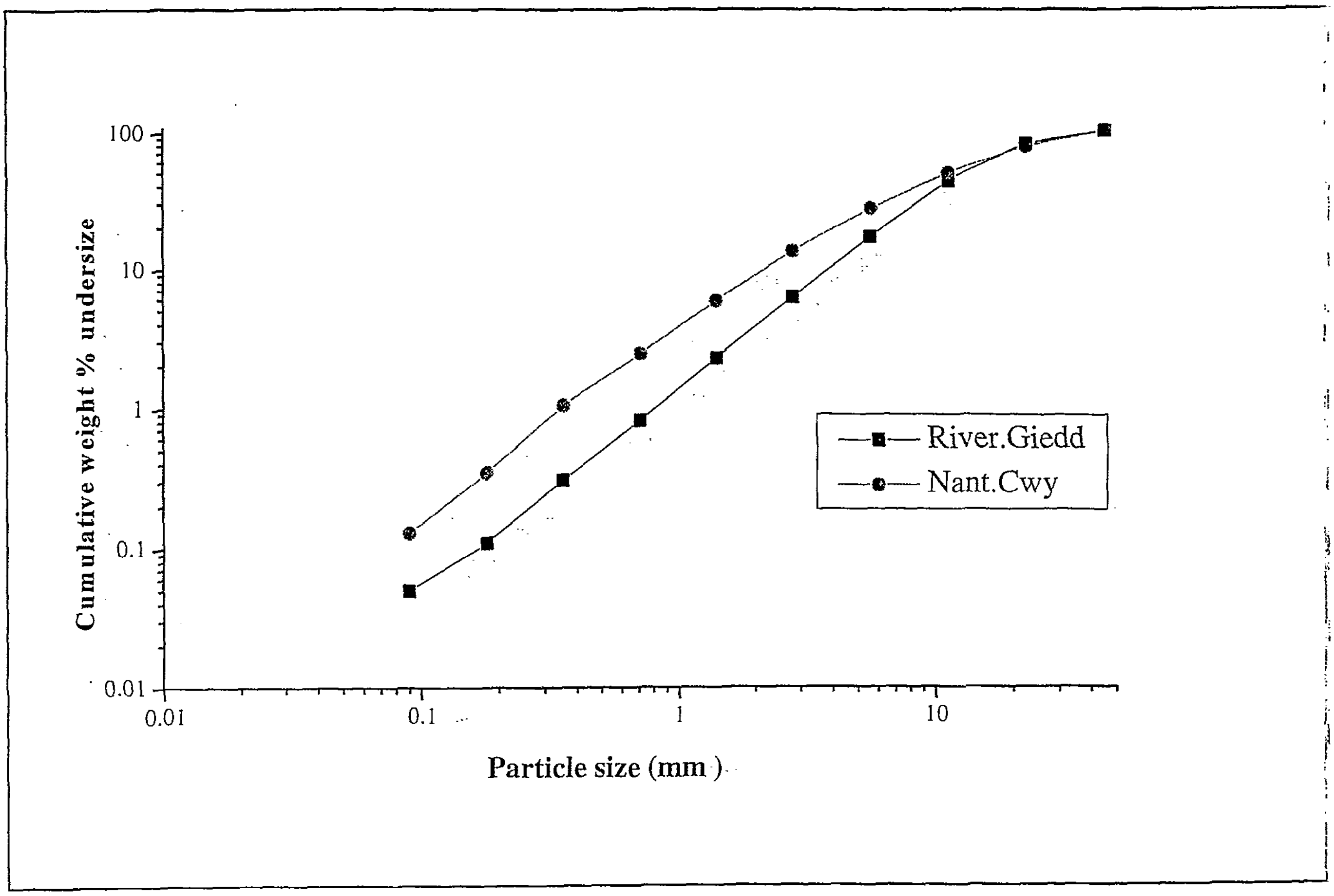


Figure 20 Cumulative undersize particle size distribution in finer than 45 mm fraction of river gravel grab samples collected from Nant Cyw and River Giedd

7 METHODS FOR RAPID PHYSICAL ASSESSMENT OF THE IMPACTS OF PARTICULATE OUTPUTS ASSOCIATED WITH FORESTRY

A standard method for the field measurement of sediment pollution would enable Environment Agency staff to make semi-quantitative rapid on-site assessment of the potential impacts of particulate outputs associated with timber harvesting.

7.1 Suspended Sediment

Although portable turbidity meters are available, a simple extinction technique could also be employed for rapid field assessment of turbidity / total suspended solids concentration in surface waters. A simple methodology is proposed:

A graduated measuring cylinder, with a clearly defined cross marked on the bottom, could be filled with water to the point where the cross becomes obscured. The height of water will be inversely related to turbidity / total suspended solids concentration. There is generally a close relationship between turbidity and the Biochemical Oxygen Demand (BOD) of settled sewage and effluent. Such a technique is already used by Agency staff for BOD assessment in effluent samples. The device used, called a BOD tube, is manufactured by Palintest Ltd. who were therefore contacted to obtain full details of this equipment.

The Palintest "turbidity test" operates by measuring the height of water necessary to obscure a cross marked on the bottom of a tube. Tubes have marked graduations, which have been calibrated in Jackson Turbidity Units (JTU) by the Department of Public Health Engineering, University of Newcastle Upon Tyne. This method of turbidity calibration employs the Jackson Candle (JC) extinction method. The JC turbidimeter measures the height of water suspended a certain distance above the JC necessary to just obscure the candle's image. An extinction depth of 21.5 cm is said to have a turbidity of 100 JTU (Ives *et al.*, 1968). Palintest state that JTU values are approximately equivalent to the total suspended solids concentration in mg l^{-1}. Tubes are available in two lengths, one piece 13" and two piece 25". The one piece tube, as used by the Environment Agency for BOD calculation, is calibrated between 30 - 500 JTU. The double length tube has additional calibrations from 5 - 25 JTU.

7.2 Sediment Deposition

Events of suspended sediment pollution are often associated with a limited parameter such as high flow conditions or a finite point source input. They are therefore likely to be of a restricted duration and require a rapid *ad-hoc* measurement technique, as described in 7.1, to investigate any pollution impacts. Site investigation of a pollution incident associated with suspended sediment commonly reveals that the sediment has passed through the water column and deposited on the bed. A rapid assessment method to measure sediment deposition would therefore also be beneficial.

As described in 6.2.3, when gravels with a large fines content are disturbed under flowing water, increased turbidity can be observed in a downstream direction. The possibility of developing such a disturbance technique into a rapid assessment method for the field measurement of sedimentation in river-bed gravels has been investigated.

Such a test could be made semi-quantitative by disturbing river gravel, and then collecting a sample of discoloured water. Analysis of the water sample for total suspended solids concentration, possibly by a rapid assessment method as described in 7.1, could be used to reflect the fines concentration in the gravel. Sample total suspended solids concentration would, however, also be affected by the area of gravel disturbed, water velocity, cohesion of fines and the background suspended sediment concentration. During the freeze coring work undertaken for this project (see 4.5), a 44 cm diameter pipe with a rubber seal on the bottom was used to divert flow away from the core during sample collection. A similar device could be used to obtain uniform hydraulic conditions above a standard area of river gravel, which could then be disturbed using a repeatable method. This should limit the influence of variation in the area of gravel disturbed and water velocity. The other confounding factors would however be harder to isolate. Although useful to give qualitative information on approximate fines concentration in river gravels, it would be difficult to develop this technique into a scientific quantitative test.

Accurate assessment of sediment deposition requires some form of substrate sampling and analysis. This would be difficult to develop into a suitable method for rapid field appraisal. Table 15 indicates that in most cases, freeze core samples contain a higher proportion of fine material than conventional bulk samples. As freeze core sampling is both expensive and labourious, it is unsuitable for rapid investigations of gravel fines content. Figure 20, however, indicates that differences in gravel fines content can be identified by conventional grab sampling. This method of gravel sampling would therefore be more appropriate for rapid investigations of gravel fines content.

As sediment deposition tends to result in longer term sustained impact, it could be studied by subsequent investigation. However, as this material could have been accumulated over a long timescale, it would be difficult to relate deposits to specific periods. It may therefore be more appropriate to focus on the development of rapid survey methods for on-site assessment of suspended sediment pollution.

8 DISCUSSION

8.1 Detailed Monitoring Programme Within the Institute of Hydrology Experimental Catchments At Plynlimon

8.1.1 Impacts of timber harvesting on suspended sediment outputs

Before harvesting, the 1995 suspended sediment yield was 51 % higher from the Nant Tanllwyth (24.3 t km^{-2} yr^{-1}) than Afon Hafren catchment (16.1 t km^{2} yr^{1}). During and immediately after timber harvesting in the Nant Tanllwyth catchment, this difference increased to 90 % for 1996 suspended sediment yields between the Nant Tanllwyth (43.8 t km^{-2} yr^{-1}) and Afon Hafren (23.1 t km^{-2} yr^{1}) catchments. The increase in suspended sediment yield from the Afon Hafren catchment between 1995 and 1996 is most likely to have been caused by particulate outputs from some small areas of felling in the headwaters of the catchment which took place during 1996. If 1995 results are used to represent the background difference in suspended sediment yields between the two catchments, and assuming all other variables are equal, the timber harvesting operation could have led to a 39 % increase in yields from the Tanllwyth, corresponding to 9 t km^{-2} yr^{-1}. This increase in suspended sediment yield from the Nant Tanllwyth in comparison to the Hafren control catchment is not reflected by mean annual suspended sediment concentrations for 1995 and 1996. The difference in mean annual suspended sediment concentrations at the Lower Tanllwyth above those at the Lower Hafren falls between 1995 and 1996 (see Table 9).

Suspended sediment yields are calculated directly from the actual suspended sediment concentration and water discharge data to give an annual suspended sediment load which is then divided by the total catchment area to give values in t km^{-2} yr^{-1}. As upland catchments often contain little in-channel storage of the finer particulate sizes that can be transported in suspension, suspended sediment yields give the most accurate measure of catchment soil erosion and consequent particulate outputs. Mean suspended sediment concentrations can be used to statistically compare the significance of variations in suspended sediment concentrations between different data sets. However, by representing the average of the complete normalised ($\log_{10}$) 15 minute data sets they are statistically derived and may not always reveal the same patterns and relationships as the suspended sediment yields.

The 39 % increase in suspended sediment yields associated with timber harvesting in the Nant Tanllwyth catchment, corresponding to 9 t km^{-2} yr^{-1}, is much lower than that recorded during timber harvesting in the Afon Hore catchment at Plynlimon (see Figure 2) between 1985 and 1989. During this study, suspended sediment yields from the Afon Hore catchment increased by 578 % from 24.4 t km^{-2} yr^{-1} pre-felling (1983 - 1984) to 141.0 t km^{-2} yr^{-1} in 1986, corresponding to an enhancement in catchment soil erosion of 116.6 t km^{-2} yr^{-1} (Leeks, 1992). This harvesting operation was, however, commenced before publication of the 1st Edition of Forest and Water Guidelines (Forestry Commission, 1988) and involved the felling of a large 91 Ha area, corresponding to 29 % of the Afon Hore catchment, which is atypical of modern FE harvesting practice. Current FE harvesting policy favours the phased felling of smaller 10-20 ha plots, such as the 13 ha Nant Tanllwyth harvesting site which represented 15 % of the total catchment area.

The response of suspended sediment concentrations in the Nant Tanllwyth 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. As site investigations indicated low suspended sediment concentrations in surface water drainage within the Tanllwyth harvesting site, this may be associated with lower ground disruption during this harvesting operation. Consequently, in comparison with previous studies of larger felling sites, early results indicate that much lower particulate outputs appear to be associated with smaller plot-scale timber harvesting operations undertaken in strict accordance with existing guidance (Forestry Commission, 1991b; Forestry Authority, 1993; Killer, 1994).

The literature reviewed in 3.3.1 indicates that while suspended sediment concentrations below 25 mg l^{-1} would probably have no harmful effect, serious fishery damage may be associated with chronic exposure to concentrations exceeding 80 mg l^{-1}. The total time when these critical thresholds are exceeded at all suspended sediment monitoring sites within the Plynlimon Experimental Catchments is shown in Table 21. For any complete year, the longest period when the higher threshold is exceeded occurs at the Lower Tanllwyth (S2) site during 1996. This, however, only occurs for 0.5 % of the year, corresponding to 41.5 hours. Alabaster and Lloyd (1980), however, reported that this 80 mg l^{-1} threshold relates to normal levels and that concentrations of several thousand mg l^{-1} may not kill fish during limited exposure of several hours or days. In light of the limited duration of suspended sediment concentrations above this threshold, a significant threat to fish health is unlikely. Although not detected during this study (see 4.5 and 8.1.3), subsequent deposition of this material in salmonid spawning areas may, however, result in far more significant impacts associated with reduced reproduction success (see 3.3.1).

Table 21 does not indicate any impact of timber harvesting within the Nant Tanllwyth catchment in increasing the period when suspended sediment concentrations exceed the 80 mg l^{-1} threshold. During and immediately after timber harvesting in the Nant Tanllwyth catchment the 41.5 hour period when the 80 mg l^{-1} threshold is exceeded at the Lower Tanllwyth (S2) site is only 2.7 hours greater than at the Upper Tanllwyth (S1) control site, and 1.7 hours greater than at the Lower Hafren (S4) site. Furthermore, a more pronounced 30 hour increase in time when this threshold is exceeded occurs within the Afon Hafren control catchment between the Upper (S3) and Lower (S4) sites.

Suspended sediment concentrations should, however, continue to be monitored in the Nant Tanllwyth catchment to identify any lagged post-harvesting impacts which may occur as timber debris and brash breaks down, possibly exposing more of the soil surface to erosion processes. Alternatively, subsequent re-vegetation may stabilise any exposed soil and reduce future particulate outputs from the harvesting site. Since the Tanllwyth harvesting site appears to have been subjected to low mechanical disturbance during the felling operation, particulate outputs associated with this operation may be comparable to areas felled using aerial cable crane extraction. As reported in 3.1.3, in a study of particulate outputs from catchments harvested by cable logging in the USA, Ursic (1991) recorded suspended sediment concentrations 3 and 50 times greater than those observed in an adjacent control catchment during the first and second year after harvesting respectively. A longer series of data will therefore be necessary to assess the full impact of harvesting in the Nant Tanllwyth catchment upon total suspended sediment outputs.

8.1.2 Impacts of timber harvesting on bed load sediment outputs

Between 1995 and 1996, the 1.11 t km^{-2} yr^{-1} increase (8.61 to 9.72 t km^{-2} yr^{-1}) in Nant Tanllwyth bed load yield was only 1.5 % higher than the 0.15 t km^{-2} yr^{-1} increase (1.33 to 1.48 t km^{-2} yr^{-1}) in the Afon Cyff control catchment. This additional increase in bed load yields from the Nant Tanllwyth catchment therefore corresponded to just 0.1 t km^{-2} yr^{-1}. Previous research during the Afon Hore clear-fell experiment revealed an initial fall in bed load yields from 11.8 to 8.3 t km^{-2} yr^{-1} immediately after harvesting. This was attributed to the build-up of sediment behind timber debris within the channel and drains, and was followed by a gradual increase to five times that of pre-felling yields two years later in 1988 (54.5 t km^{-2} yr^{-1}), when these debris dams broke down or reached capacity (Leeks, 1992). Within Harvesting Areas 2 and 3 (see Figure 3), brash was removed where the trees were felled. Consequently, many of the drains within these sites contain timber debris. As the 1996 bed-load yields in the Nant Tanllwyth are similar to those recorded in the Afon Hore after the felling operation, more pronounced increases in bed load yields may become apparent in subsequent years. Similar to the results of suspended sediment outputs, a longer series of data will therefore be necessary to assess the impact of harvesting in the Nant Tanllwyth catchment upon total bed load sediment outputs, allowing comparisons to be made with outputs associated with the Afon Hore experiment.

Previous results from the Afon Cyff and Lower Tanllwyth bed-load monitoring sites report yields of 6.4 and 38.4 t km^{-2} yr^{-1} respectively, representing a ratio of 1:6.0 between the catchments (Kirby *et al.*, 1991). The 1995 and 1996 data in Table 13 indicates much lower yields than the longer term values quoted in earlier papers, possibly due to lower rainfall levels in these years. At the Moel Cynedd meteorological Station (see Figure 3), the 1995 and 1996 rainfall totals (2047 and 1963 mm respectively) were lower than the 2320 mm average annual rainfall for the period 1968-1997. However, the Cyff : Tanllwyth annual suspended sediment yield ratios of 1:6.5 in 1995 and 1:6.6 in 1996 are very similar to previous results.

8.1.3 Impacts of timber harvesting on the river gravel habitat

Enhanced fine particulate loadings in the Nant Tanllwyth were unlikely to have been deposited until a reduction in transport potential following its confluence with the Afon Hafren. Consequently, the largest increase in gravel fines following timber harvesting, in comparison with an unaffected control, was recorded in freeze-core samples between the Upper (G4) and Lower (G5) Hafren sites (see Figure 3). Due to the inefficiency of fine material collection by conventional grab sampling, this relationship was not apparent in conventional bulk samples.

Only the 10-20 cm freeze core sample taken in 1997 at the control site on the River Wye (G6), and therefore the 0-30 cm aggregate, contained more fine particulate material than the 20 % threshold discussed in 4.5.7 as being sufficient to affect salmonid spawning. In light of this, none of the river gravels sampled within the Tanllwyth and Hafren afforested catchments contained sufficient fine material to adversely affect salmonid spawning.

8.1.4 Impacts of timber harvesting on channel bank erosion

Timber harvesting in the riparian zone of the Nant Tanllwyth catchment resulted in a statistically significant increase in the erosion rates of adjacent channel banks. Multiple regression of the main variables controlling bank erosion identified temperature indices as the dominant factor. Comparison of channel bank temperatures within both mature forest and recently felled areas, unaffected by any harvesting activity, identified a larger temperature range at the felled site with lower and higher temperatures during the winter and summer respectively. As 89 % of channel bank erosion is known to have occurred during the winter, the most likely cause of this increase is the reduction in winter temperatures and increase in periods with sub-zero temperatures when channel bank erosion susceptibility is known to be increased through frost action. Other factors may, however, also increase channel bank erosion associated with timber harvesting within the riparian zone. These include increased wetting and drying cycles and the formation of desiccation cracks, increased soil moisture and therefore pore water pressures due to reduced evapotranspiration, and reduced bank stability due to the decay of root systems.

8.2 Detailed Monitoring Outside the Institute of Hydrology Experimental Catchments At Plynlimon

The total time when critical suspended sediment concentration thresholds are exceeded at Upper (B1) and Lower (B2) Biga monitoring sites is shown in Table 22. Comparison of Tables 21 and 22 reveals that results for the Upper Biga are similar to sites unaffected by harvesting activity within the Plynlimon Experimental Catchments. At the Lower Biga, however, the critical 80 mg l^{-1} threshold is exceeded for 2.2 % of the 12 month monitoring period, corresponding to 195.75 hours (8.2 days). This is over 4 times higher than the longest period when this threshold is exceeded within the Plynlimon Experimental Catchments at the Lower Tanllwyth (S2) site during 1996. Although the Afon Biga felling area also represented a small (6.5 Ha) plot, impacts of suspended sediment outputs associated with this harvesting site are likely to be more significant than those associated with the Nant Tanllwyth site. Increased soil erosion within the Afon Biga harvesting site is likely to be related to its steeper gradient and the high number of trees which had to be felled within riparian areas.

8.3 Site Specific Assessments of the Impact of Particulate Outputs Associated with Timber Harvesting

Incidents of sediment pollution reported to the Environment Agency and field visits to harvesting sites have enabled the identification of the most significant sources of particulate outputs associated with timber harvesting. A number of effective measures have been identified for the prevention and / or amelioration of these impacts. Many are recommended in existing guidance (Forestry Commission, 1991b; Forestry Authority, 1993; Killer, 1994).

8.4 Methods for the Prevention and / or Amelioration of Impacts of Particulate Outputs Associated with Timber Harvesting in the Light of Existing Forests and Water Guidelines

The combination of detailed monitoring results from Plynlimon Experimental Catchments with information from elsewhere has enabled the identification of the most successful methods for the prevention and / or amelioration of particulate outputs associated with timber harvesting. These are briefly discussed in the light of the existing recommendations in Forests and Water Guidelines (Forestry Authority, 1993) which have been identified as effective in this project.

GROUND PREPARATION (Page 11-13)

Although not specifically associated with harvesting some of the recommendations under ground preparation may reduce the impact of particulate outputs associated with subsequent felling operations.

- ***Construct silt traps*** *at the ends of drains in areas of high or moderate erosion risk, ensuring that there is machine access for periodic emptying. Spoil should not be dumped on the floodplain or ecologically valuable wetlands.*

After construction, silt traps should be maintained through regular inspection and clearing when needed. Since the Forests and water Guidelines do not recommend how the spoil material from silt taps should be disposed of, this should be addressed in the next revision.

- ***Organise drains maintenance and silt trap cleaning to avoid the spawning season or the period when salmonid eggs and alevins are living in the gravel.*** *The sensitive period varies a little from place to place, but October to May inclusive should cover the main spawning and incubation periods in the uplands. In lowland rivers, consult the local fishery interest.*

This would also avoid the winter months, corresponding to the wettest period when soils are most susceptible to erosion.

ROAD CONSTRUCTION AND MAINTENANCE (Pages 15 - 16)

Road construction and maintenance is often undertaken in association with timber harvesting. The following recommendations may therefore reduce particulate outputs associated with felling operations:

- ***Build roads well clear of riparian zones*** *wherever possible.*

If roads are built adjacent to watercourses, no provision could be made for the diversion of road drainage containing particulate material to buffer areas or silt traps. Enhanced particulate outputs associated with forest road erosion would therefore be able to discharge directly to a watercourse.

- ***Roadside drains*** *should not intercept large volumes of water from ground above. Any watercourse, however small, that is intercepted by a road should be culverted or bridged at that point. If additional culverts are needed to discharge water from the roadside drain, they should be of a size sufficient to avoid overloading, blocking or washout. Roadside drains, likely to carry high sediment loads, must not be allowed to discharge directly into streams, but must discharge to a buffer area of adequate width. Drains on the upper side of the road may need culverts to the lower side a short distance before stream crossings so as to prevent direct discharge.*

Forest road drainage can contain high suspended sediment concentrations, and should therefore drain to buffer areas or silt traps rather than be allowed to directly enter a watercourse. To minimise drain erosion, flow should be kept to a minimum, and contain only the drainage from the forest road.

- ***Where appreciable sediment*** *movement is unavoidable, silt traps should be constructed and provision made for maintaining them. Cleaning should be done in dry weather during May to September, to avoid the salmonid spawning period.*

Silt traps filled with sediment were identified during this project, indicating that they had been effective in removing sediment from contaminated drainage, and preventing it from entering the watercourse (see section 6). Regular emptying is, however, essential to ensure their continued value.

HARVESTING (Page 16-17)

The following recommendations are specific to the prevention and / or amelioration of particulate outputs associated with timber harvesting:

- ***Choose dry sites for stacking timber,*** *well away from watercourses. Do not block roadside drains.*

Bunds can also be constructed around timber stacking areas to further contain this potential source of particulate outputs (see 6.2.2).

- ***Plan felling and extraction*** *to minimise the number of stream and drain crossings. Do not plan a felling coup which includes both sides of a watercourse unless there is road access to each side. Where crossing a stream or drain is unavoidable install a log bridge or piped crossing. Even small runnels which may be dry before felling may flow again during operations; consider them for piped crossings.*

Field visits to harvesting sites revealed large particulate outputs where timber extraction tracks intercepted drainage (see 6.1).

No significant source of particulate material appeared to be associated with either of the temporary bridge crossings used to extract timber from the Afon Biga harvesting site across the river (see 5.2). These involved using a temporary steel bridge in accordance with the Harvesting Manual produced by Forest Enterprise Wales (Killer, 1994).

- ***Choose the best machine combination*** *for the ground conditions including appropriate traction or flotation aids. Avoid ground skidding on soft soils. Avoid long ground extraction routes on steep slopes, especially in high rainfall areas.*

Appropriate choice of three different harvesting methods appropriate to the varying site conditions may explain the lower particulate outputs from the recent Nant Tanllwyth harvesting site (1996) compared with the Afon Hore timber harvesting operation (1985-1989).

The Forest Enterprise Wales, Harvesting Manual gives guidance on the appropriate choice of harvesting system for terrain types differing in terms of slope, soil conditions and ground roughness.

- ***Cable crane extraction,*** *particularly of shortwood, causes much less soil disturbance than skidding or forwarding; consider it for sensitive catchments.*

Identified as being effective in literature review but not tested during this study.

- ***On soft soils*** *provide and maintain an adequate supporting brash mat for the principal vehicle routes. Brash may have to be transported from where it is plentiful. Where forest roads have to be used for long distances by forwarders and the like, use brash thatching to prevent damage to the road.*

At all harvesting sites studied for this project where brash matting had been employed, it appeared effective in reducing soil erosion along vehicle access routes and therefore particulate outputs.

- ***On sensitive sites*** *try to work during spells of good weather.*

Continuous suspended sediment concentration and water discharge data illustrate the importance of the latter in controlling particulate outputs and therefore suspended sediment concentrations. On sensitive sites, the impacts of any operation liable to result in particulate outputs could therefore be minimised by undertaking the work during periods of dry weather and low flow.

Harvesting operations on very susceptible ground should therefore be planned to avoid winter periods. In British rivers, the critical period when eggs and alevins are living in the spawning gravels, and are therefore vulnerable to the effects of siltation, is normally from October to March (see 3.3.1 i). Avoiding wet winter months when harvesting erosion sensitive sites will therefore also avoid the period when salmonid reproduction is most susceptible to impacts associated with sediment deposition. Avoiding winter for felling may, however, increase the impacts of felling upon nesting birds.

- ***Felling in the riparian zone** will be an infrequent event once the recommended vegetation has become established; where it is needed, fell trees away from the stream. Keep streams free from branches and tops as far as practicable. An occasional large log in a stream may be advantageous in creating a pool, provided it is reasonably stable and does not cause erosion by diverting the stream.*

Felling in the riparian zone of the Nant Tanllwyth catchment resulted in a significant increase in the erosion rates of adjacent channel banks. Felling in the riparian zone of the main Afon Biga and its tributaries and drains within the harvesting site appears to have been responsible for increased particulate outputs. Furthermore, although not specifically associated with timber harvesting, increased suspended sediment concentrations in the River Llwyd were associated with the removal of wood debris which had accumulated in headwater channels during the felling of trees within riparian areas.

The effectiveness of buffer areas and riparian vegetation in reducing particulate outputs associated with timber harvesting are further detailed in 6.2. These support the recommendations on buffer areas on pages 13 and 14 in the Forest and Water Guidelines. Although no specific reference is made to the maintenance of buffer areas, recommendations on managing riparian vegetation are detailed on page 14.

- ***When extraction tracks** have been created on slopes, prevent water running down any wheel ruts by digging offlets at intervals. Make this also the standard practice if there is any appreciable break in operations, or during operations if there is a risk of erosion.*

Field investigations at harvesting sites within the IH Plynlimon Experimental Catchments (see section 4.3) and other sites throughout England and Wales (see section 6) has identified the erosion of extraction tracks as the most significant source of particulate outputs associated with timber harvesting. Water should therefore be prevented from running down access tracks by constructing offlets which divert drainage to silt traps or buffer areas rather than allowing it to flow directly into a watercourse.

- ***Make sure that** haulage roads, drains and culverts are adequate and in good repair before work starts. Never let extraction and haulage machines destroy a sub-standard road in the hope that it can be repaired cheaply afterwards - erosion can be very serious, and either expensive or impossible to put right.*

Particulate outputs are commonly associated with poorly maintained eroding roads.

- ***Modify operating procedures immediately** if erosion is occurring and construct silt traps if necessary.*

If significant particulate outputs are identified during operations, ameliorative measures to minimise any impacts should be undertaken immediately. It may be useful if forest operators could employ a rapid assessment technique, as discussed in section 7, to identify when a significant increase in particulate outputs is associated with their activity. This could, however, be as simple as noticing the discolouration of a watercourse below a harvesting site.

If possible, the source of the particulate outputs should be identified and ameliorative procedures undertaken. The most appropriate remedial action should be identified in the light of existing guidance as outlined above in The Forests and Water Guidelines, Third Edition (Forestry Authority, 1993), and also the more specific recommendations detailed in the FE Wales Harvesting Manual (Killer, 1994) and FC Soft Ground Harvesting Report (Forestry Commission, 1991b). If the particulate outputs are particularly pronounced, it may also be necessary for the forest operators to contact the Environment Agency who may be able to offer further advice in controlling both the source of particulate outputs, and also any impacts downstream.

Some of the possible measures which can be employed *ad-hoc* to reduce particulate outputs to watercourses could include:

i. As described in section 6, access tracks, used to extract timber from harvesting sites to the main forest roads, have been identified as the major source of particulate outputs associated with timber harvesting. A number of procedures can be undertaken to control further particulate outputs from an eroding track. These can include the protection of the track surface with a brash or stone covering and/or a change in the harvesting extraction method and type/modification of machinery. An example could represent a change from skidding the timber along the track surface behind a tractor to carrying it out on a forwarder with large balloon tyres to reduce pressure on the ground surface. Specific details of harvesting and extraction methods/machinery in relation to specific site conditions are detailed in the FE Wales Harvesting Manual (Killer, 1994) and FC Soft Ground Harvesting Report (Forestry Commission, 1991b). If water is flowing along an extraction track, it should be diverted. This can be achieved by adopting a stepped profile along the track with ramps and offlets to buffer areas or silt traps. In severe cases, eroding extraction tracks should be closed and replaced by new routes which can be managed and maintained to prevent the enhanced particulate outputs associated with previous tracks.

ii. Straw bales can be placed in watercourses to filter particulate laden drainage.

iii. Polluted drainage can be diverted to buffer areas.

iv. In severe cases of particulate outputs, operations could be stopped completely and re-worked during dry weather.

v. Culvert or bridge construction may control particulate outputs associated with a watercourse crossing.

vi. Where erosion of the main forest roads is responsible for enhanced particulate outputs, routes could be altered to maximise the use of well maintained roads. The eroded roads can therefore be avoided until they can be upgraded.

		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
Time when suspended sediment concentration (> 25 mg l^{-1})	% of monitoring period	3.6	3.9	1.5	3.9	14.5	1.2	1.2	1.3	1.9	0.2	1.3	2.2	1.7	0.3	0.1
	Hours	316	168	132	343	631	106	53	111	171	10	114	189	72	24	6
Time when suspended sediment concentration (> 80 mg l^{-1})	% of monitoring period	0.4	0.5	0.1	0.5	0.9	0.1	0.2	0	0.5	0	0.1	0.3	0.2	0	0
	Hours	38.8	20.3	12.8	41.5	40.5	9.8	6.8	1.0	39.8	0	4.0	23.5	7.8	0.8	0

½ 1997 data (6 months data only, 01.01.97 - 30.06.97)

Table 21
Time when suspended sediment concentrations exceed the critical thresholds identified in 3.3.1 for potential impacts on aquatic life

		Upper Biga (B1)	Lower Biga (B2)
Time when suspended sediment concentration (> 25 mg l^{-1})	% of monitoring period	1.4	6.9
	Hours	126	603
Time when suspended sediment concentration (> 80 mg l^{-1})	% of monitoring period	0.3	2.2
	Hours	29	196

Table 22
Time when suspended sediment concentrations exceed the critical thresholds identified in 3.3.1 for potential impacts on aquatic life at Upper (B1) and Lower (B2) Biga sites

9 CONCLUSIONS

9.1 Technical

Suspended sediment outputs - Nant Tanllwyth harvesting site

The initial 39 % increase in suspended sediment yields associated with timber harvesting in the Nant Tanllwyth catchment is more than an order of magnitude lower than the 578 % increase recorded in the Afon Hore felling experiment. In this example, a limited increase in particulate outputs appears to be associated with a small plot-scale timber harvesting operation undertaken in strict accordance with Forests and Water Guidelines (Forestry Authority, 1993) and the Forest Enterprise Wales Harvesting Manual (Killer, 1994).

In light of critical thresholds for impacts on aquatic life, increases in suspended sediment concentrations observed to this study are likely to have a minimal impact.

Bed load sediment outputs - Nant Tanllwyth harvesting site

Only a very small increase in bed load yields has been recorded following timber harvesting. As much of the harvesting site remains covered in brash with timber debris in many of the drains and ditches, this may correspond to the harvesting response of bed load yields in the Afon Hore catchment which showed an initial decline in bed load yields, with a subsequent peak due to lag effects.

Impacts on the river gravel habitat - associated with harvesting in the Nant Tanllwyth catchment

The limited particulate outputs associated with this harvesting operation only appear to have been responsible for a small increase in gravel fines content in the Afon Hafren below its confluence with the Nant Tanllwyth. This increase in fine material was, however, unlikely to adversely affect salmonid spawning.

Impacts on channel bank erosion - associated with harvesting in the Nant Tanllwyth catchment

Timber harvesting in the riparian zone of the Nant Tanllwyth resulted in a statistically significant increase in the erosion rates of adjacent channel banks.

Suspended sediment outputs - Afon Biga harvesting site

The increase in suspended sediment concentrations associated with harvesting in the Afon Biga catchment were higher than in the Nant Tanllwyth. This is most likely to have been associated with its steeper gradient and the harvesting of trees within riparian areas. In the light of critical thresholds for impacts on aquatic life, increases in suspended sediment concentrations in the Afon Biga could therefore have a more significant impact.

Site specific assessments of the impact of particulate outputs associated with timber harvesting

Information from other harvesting sites can be combined with results from detailed monitoring studies at Plynlimon to identify a number of effective measures for the prevention and / or amelioration of particulate outputs associated with timber harvesting. Many are supported by information in the Forests and Water Guidelines (Forestry Authority, 1993) and FE Wales Harvesting Manual (Killer, 1994). Consequently, good harvesting practice in strict accordance with this guidance, as in the Tanllwyth example, appears successful in reducing the impact of particulate outputs associated with timber harvesting.

9.2 Practical / Management

Much progress has been made in recent years towards developing methods for the prevention of particulate outputs associated with timber harvesting. It is vital, however, that the methods are consistently applied in practice. The Forests and Water Guidelines, Third Edition (Forestry Authority, 1993), FE Wales Harvesting Manual (Killer, 1994) and FC Soft Ground Harvesting Report (Forestry Commission, 1991b) are all excellent documents which should be widely promoted to all involved with timber harvesting, including both FE and private felling companies / contractors. Regular review of this guidance should be undertaken in light of continuing developments in harvesting techniques and available equipment. The methods prescribed should be promoted through extensive and regular training of foresters and Environment Agency pollution prevention staff. A good example of this represented the training / discussion seminars which were held throughout Wales during early 1995 to support the introduction of the FE Wales Harvesting Manual and explain its principles to both Forestry Commission staff, private felling contractors and members of the Agency. The latter made presentations at these meetings to describe the potential impacts of particulate outputs associated with timber harvesting, and explain why it should be controlled. It is important that all forestry staff (including private contractors) are bound by contract specification to adhere to good practice and that there is adequate monitoring of operations by the Forestry Authority and the Environment Agency.

10 RECOMMENDATIONS

1. Suspended sediment and bed load particulate outputs associated with the Nant Tanllwyth harvesting site should continue to be monitored to identify any lagged post-harvesting impacts. These may occur as timber debris and brash on the harvesting site breaks down, possibly increasing the area of the soil surface vulnerable to erosion processes and allowing increased bed load transport from within the site. This work would enable the calculation of total particulate outputs from the Nant Tanllwyth harvesting site which can then be compared with other harvesting studies.

2. Results from both this project, the FE Wales Harvesting Manual (Killer, 1994), and FC Soft Ground Harvesting Report (Forestry Commission, 1991b) should be considered in any future revisions to Forests and Water Guidelines.

3. Joint training of all foresters involved with timber harvesting operations (both FE and private companies / contractors) and Environment Agency staff should be encouraged. Training / discussion seminars were held throughout Wales during early 1995 to support the introduction of the FE Wales Harvesting Manual. This provided the opportunity for staff from forestry operators (representing both FE and private companies / contractors) and the Environment Agency to discuss the methods prescribed to reduce environmental damage associated with timber harvesting. Such a forum of discussion proved effective at encouraging the necessary liaison between all parties so that a pragmatic workable approach could be developed toward controlling the environmental impacts associated with this activity .

4. Consideration should be given to the production of a video on pollution prevention by collaboration between the Environment Agency, the Forestry Commission and private forestry companies / contractors. This could be used for training purposes in colleges providing forestry courses as well as for training foresters and Agency pollution prevention staff as recommended in 3 above.

5. Consideration should be given to the best methods by which the use of best practice can be ensured from all forest operators including private companies / contractors. The use of detailed coup management plans, strict specifications and effective monitoring should all be encouraged.

6. All guidance and training should be regularly reviewed and updated in line with continuing developments in harvesting techniques and equipment.

11 ACKNOWLEDGEMENTS

This research was funded by the Environment Agency and NERC.

The long-term commitment to upland land-use research of all staff at IH Plynlimon is gratefully acknowledged. In particular, Sean Crane provided flow and meteorological data. Alun Hughes and Phil Hill assisted with fieldwork, in addition to Rupert May and a number of other Sandwich Course Students from the University of Luton. Jonathon Evans (IH Instrumentation) provided invaluable help with remote monitoring equipment.

Full details of all harvesting sites were provided by invaluable assistance from a number of Officers at FE Wales, Newtown District. In particular, the authors would like to thank Graeme Clark and Craig Sinclair for the regular supply of recent information, and a number of very useful field visits.

FE Wales, Morgannwg District, and FE South and West England, Cornwall and North Devon District, for arranging a number of field visits to harvesting sites.

D.J. Killer of FE Wales, Aberystwyth, for allowing the reporting of the FE Wales Harvesting Manual.

In addition to a number of very useful field visits to harvesting sites, considerable relevant information was provided by Environment Agency pollution prevention staff.

Dr Tim Stott, of Liverpool John Moores University for allowing the reporting of his research on channel bank erosion.

Adam Sawyer, of Liverpool John Moores University, for his involvement in research upon coarse sediment fluxes within the Plynlimon Experimental Catchments.

In addition to a number of staff from the Environment Agency and Forest Enterprise Wales, invaluable comments were made on draft project outputs by Dr Tom Nisbet of Forest Research, Alice Holt Lodge.

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