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Forestry effects on sediment sources and yields in the Balquhidder catchments, central Scotland

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CONTENTS

Abstract

This study sets out to examine the effects of forestry operations on sediment sources and yields in a Consortium funded, Institute of Hydrology (IH) instrumented, paired catchment experiment at Balquhidder in the southern Highlands of Scotland. A sediment budget approach was adopted incorporating ongoing IH catchment sediment output monitoring of suspended and bedload from the 7.7 km^2 moorland Monachyle catchment and the 6.8 km^2, 40% forested Kirkton catchment. Sediment source inputs from tributary streams and mainstream bank erosion were estimated. There is good agreement between source inputs and catchment outputs in the moorland but not in the forest where tributary inputs seem to be over-estimated. Mainstream channel banks contribute around 5% of the total sediment yield in both catchments. Catchment suspended sediment yield accounts for 97% of the total sediment output (less than 3% is bedload) and is about one and a half times higher in the forested catchment where concentration varies more sensitively with streamflow, suggesting greater availability of erodible sediment. These pre-disturbance sediment budgets based on 1982-5 outputs monitoring and 1984-5 source monitoring are used as a background from which to assess the effects of the land-use conversions which began in 1986.

In autumn 1985 disturbance began in the forested catchment in the form of road regrading, repairs and construction of timber stacking areas. Clearfelling started in January 1986. Between April and July 1986 about 10-15% of the moorland catchment was ploughed and ditched in preparation for planting. Preliminary analysis of suspended sediment data collected in this post-disturbance phase (1986-7) so far indicates that there have been about three and seven-fold increases in suspended sediment outputs from the moorland and forest catchments respectively. No bedload output data is available yet from IH. In the moorland tributaries bedload yields more than doubled but suspended sediment load in the one moorland tributary monitored did not reflect the increased outputs even though the sub-catchment was ploughed and ditched. The greatest impact of forest clearfelling appears to be accelerated erosion of regraded and more heavily used roads and of recently constructed timber loading areas. These 'bare' areas are shown to be capable of supplying much of the observed catchment increases in suspended sediment outputs. The elevated sediment yield in the forested catchment before felling and in both catchments after disturbance is attributed to an increase in the sediment supply from new sources (ditches, roads and stacking areas in the forest; plough furrows and ditches in the moorland) and not to an increase in flood magnitude or frequency. Forestry management implications are discussed in relation to the findings.

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CHAPTER 1: INTRODUCTION

1.1 The Problem

The primary undisturbed forest which once covered the uplands of Britain yielded a steady supply of pure and potable water the year round, protected hillsides from erosion and reduced flooding. Today the 'semi-natural' dominant vegetation types of the uplands include grass and herb species, heather, bracken and scrub forest. The uplands are defined as those areas at an altitude of 300 m or more above sea level. These occupy some 7.3 million hectares or approximately one third of the total land area of Britain. They are associated with high rainfall, low temperatures and short growing seasons and are largely concentrated in Scotland, northern England and Wales. Most of this land is used for low density grazing by sheep with large areas of heather moorland in Scotland devoted solely to grouse and red deer. These grazing activities, along with rotational heather burning have suppressed the regeneration of indigenous forest species. Soil disturbance is minimal and in this 'semi-natural' state most upland streams are still relatively pure and usually carry very low sediment loads.

From the early 19th century the rapid expansion of both industrial and domestic demand for water resulted in increasing utilisation of runoff from the uplands. During the early stages relatively little change occurred in land use in the uplands, but as the 20th century progressed, major changes began to be implemented. During World War I shortages of timber forced the nation to embark on a programme of reafforestation. The Forestry Commission was established in 1919 to implement this programme and since has proceeded to acquire large areas of upland moorland for planting with conifers. Figure 1.1 shows the upland areas of Britain and has the major areas of forestry imposed.

From 1945 to 1983 the area of productive woodland planted by the Forestry Commission increased from 202 000 ha to 909 000 ha and now almost equals the 1 1084 000 ha of forest under private management (Forestry Commission 1984). This represents the largest single land use change in Britain today, being about twice the area lost to urbanisation each year (Best 1976). Recently, overproduction of certain agricultural produce in the UK has led to a reduction or in some cases total withdrawal of existing subsidies for agricultural development. This coupled with low land prices, tax concessions and planting grants makes afforestation an attractive alternative investment and these factors will ensure that it continues to be the major land use change in the uplands in the foreseeable future. In fact, the Centre for Agricultural Strategy report (1980) recommended the planting of a further 1.8 million hectares of forestry in the uplands, primarily in upland Scotland , by the year 2025 increasing the percentage area of Britain's uplands under forestry from 1.6 million hectares (22%) at present to 47% (Forestry Commission 1977). This will necessitate an increase in planting rate from 40 000 ha. yr^{-1} in the 1970's to 60 000 ha. yr^{-1} in in order to meet the recommendation by 2025.

This large and increasing extent of afforestation in upland

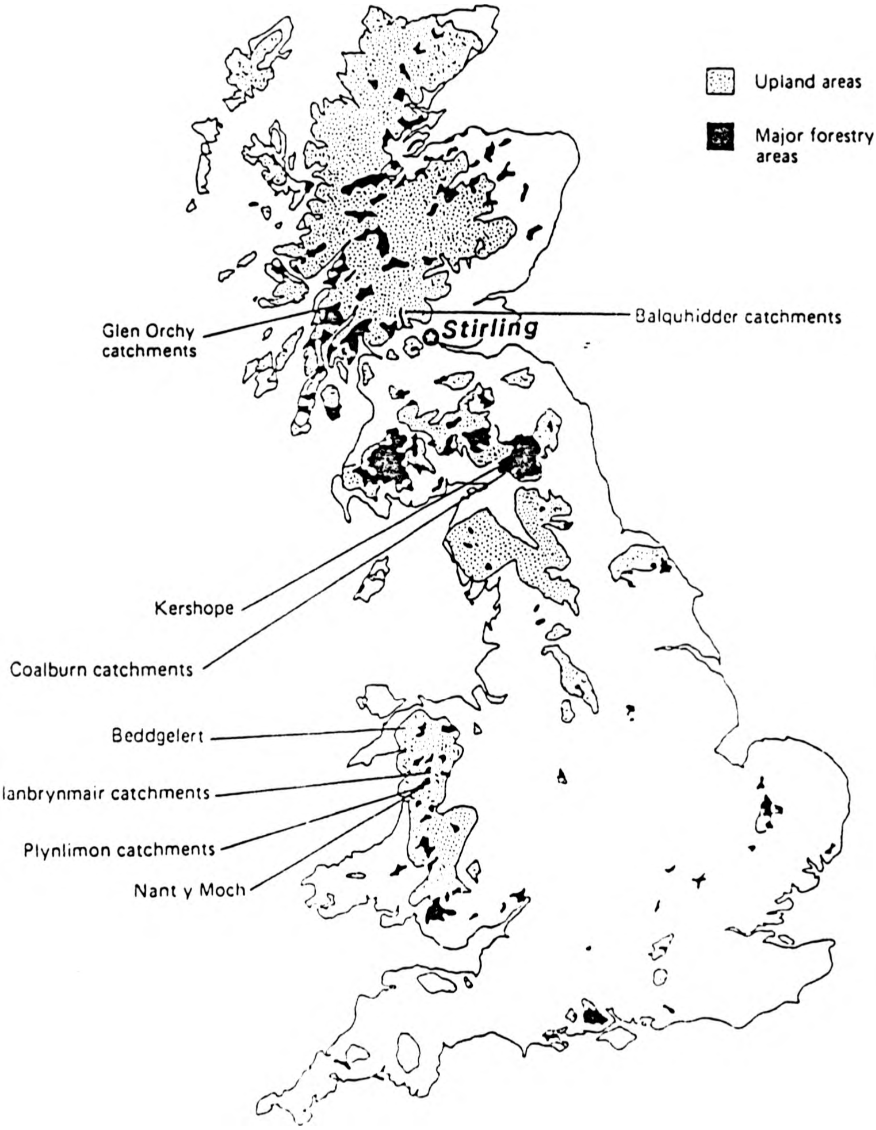


Figure 1.1: Upland Britain showing major areas of forestry and the location of experimental studies mentioned in the text (taken from Blackie and Newson 1986).

Britain, particularly Scotland, has led to concern over the possible effects on downstream water users (Blackie and Newson 1986). Forest establishment in the frequently waterlogged soils of these areas in usually preceded by ploughing up and down what are often steep slopes, and then by ditching obliquely across the slope. Between 1948 and 1967 about 60% of the newly afforested areas were drained prior to planting (Taylor 1970). This figure is rising as forestry is becoming increasingly concentrated on upland areas where land is often poorly drained and peaty.

The managed forests of the British uplands today differ somewhat from our primary forest cover and, in particular, seem to have an adverse effect on water yield and quality. Potential effects of increased sediment yields from the uplands include:

(i) overloading the purification capacity of water supply treatment works. For example, open ditching in 1980 of two small sub-catchments draining to the Homestyles reservoir on a tributary of the river Holme, West Yorkshire (reported by Burt et al. 1984) resulted in a major pollution incident. The loss of a potable water supply due to increased quantities of suspended sediment proved costly to the local water authority, requiring the construction of a new water treatment plant at the reservoir (Austin and Brown 1982). Richards (1985), on behalf of the Strathclyde Regional Council Water Department, has made a detailed investigation of the physical, biological and chemical problems of water quality arising from forestry activities. Richards estimates the increased costs of treating water from afforested supply catchments and demonstrates how for two catchments in the

Strathclyde Water Department Ayr Division, increased treatment costs per hectare exceed the economic return from planting trees some 40-50 years later! Increases in suspended solids and turbidity are reported by Stretton (1983) for the Welsh Water Authorities' Cray Reservoir. In a major and minor input stream suspended solids concentrations reached 1111 and 329 mg l^{-1} respectively during intense rainfall from a background level of 4 mg l^{-1} in both streams. (report also Greene 1987)

(ii) increasing the infill rate of lochs (Battarbee et al. 1985, Ledger et.al 1974) and reservoirs (Ledger et. al. 1980, McManus and Duck 1985, Duck & McManus (in press), Tallis 1981, Winter 1950) thereby reducing their capacity to store drinking water as well as causing operational problems concerned with scour valve releases (Oldman pers. comm.) and arousing complaints of increased turbidity from fishermen.

(iii) detrimental effects on fisheries. Work by Ottaway et al. (1981), Milner et al. (1981) and Carling (1984) on the interrelationships between salmonid fisheries and stream bed sediment dynamics in gravel bed streams of the Pennines has contributed some much needed information on this topic in the U.K. Two main European salmonid species, the Atlantic salmon (Salmo salar L.) and the trout (Salmo trutta L.) in both freshwater and anadromous forms, use the gravel beds of upland streams (many of which in Scotland are now scheduled for afforestation) for egg deposition. Carling (1984) states that "the successful development of the fish eggs is directly affected by the physical nature of the stream bed and the flow hydraulics". The interaction between discharge, stream bed surface and subsurface size composition and sediment movements can have an important influence upon "spawning site choice, survival of intragravel stages, emergence of swim-up fry and the growth and survival of older stages" (Milner et al. 1981). Factors which are known to have a detrimental effect on egg development are gravel movement and the proportion of fine particles in the surface and subsurface layers of the bed. Gravel movement causes washout of eggs which are consequently damaged by crushing, are predated upon by other fish, or are subsequently deposited in environments unsuitable for egg development (Carling 1984). Gravel composition and structure influence the oxygen supply to the eggs by controlling the water movement through the gravel. Many workers have shown that the proportion of fines in the gravel will reduce pore space (Carling 1982) and result in a reduction of the water percolation through the gravel and so have a major effect on egg survival (e.g. McNeil and Ahnell 1964, Hall and Lantz 1969, Turpenny and Williams 1980).

Clearly, the problem has important implications for the Scottish salmon industry (Mills 1986) since the major expansion in afforestation is to be concentrated in Scotland in the next 50 years. On a more local scale Figure 1.2 is an extract from the Stirling Observer (12 September 1986) which makes reference to the concern of the River Forth Salmon Fisheries Board towards scheduled afforestation in the study area of this project. Finally, Graesser (1979) reports on how land improvements can damage Scottish salmon fisheries.

(iv) nutrient losses from the already nutrient poor uplands via particulate organic matter and sediment attached solutes (e.g.

Forestry threat to fish stocks

SALMON and sea trout in the River Forth could be under serious threat if a major forest development goes ahead in the Balquhidder area.

The River Forth Salmon Fisheries Board is claming that plans for 2,000 acres of coniferous forest in remote Glen Buckie and Glen Dubh could kill off the important spawning waters of Calair Burn and its tributaries, writes **GRAHAM CRAWFORD.**

It has written to Stirling MP Michael Forsyth asking him to take up the matter with Mr Michael Ancram, Scottish Office Minister for the Environment.

The board is "gravely concerned" that forestry on such a scale will upset the whole ecology of the area, affecting plant and insect life and ultimately the salmon and sea trout.

Another major worry is increased acidification of the waterways. It is now established that levels of acid are heightened by coniferous trees. Fish life simply ceases when levels are too high.

The application from D. Thow of Ballimore Estate, for 961 hectares (2,000 acres) of predominantly coniferous forest is before Stirling District Council's planning department for consultation.

Final decision on the development lies with the Foresty Commission, which would also give grant aid.

Consultation has been sought from the district council, the salmon fisheries board, the Forth River Purification Board, the Countryside Commission for Scotland and the Nature Conservancy Council.

So far, only the fisheries board has spoken out, but it is clear that some of the other bodies share the board's concern.

Major Fordyce Burke, salmon board superintendent, told the 'Observer' this week: "This area already has two extensive young plantations totalling 1,300 hectares adding to acid production.

"Growing timber also consumes a vast quantity of ground water, changing the amount and content of run-off.

"The gravel base of the streams, so important for spawning, becomes threatened by increased silt. It is also very tempting to use the gravel for road building."

The board uses Calair Burn for its annual stocking of young salmon and trout.

Major Burke said the Forth headwaters were becoming increasingly jeopardised by commercial forestry which had become a favoured source of investment and tax relief for the wealthy.

Mr David Campbell, senior pollutions officer of the Forth River Purification Board, said: "Major Burke has very good grounds for his concern.

"There are a number of possible risk factors in such a sizeable development, and acidification is not easily reversed and would spell the end of fish life.

"Our investigations show the area to be a borderline case. It has a low buffer of alkaline to neutralise an increase in acid."

Mr Campbell said his board recognised a number of pollution risks, which would require strict adherence to the Forestry Commission's code of practice.

Spokesman for both the Countryside Commission and the Nature Conservancy Council said they were not happy about the amount of detail in the application.

Figure 1.2: Stirling Observer newspaper press cutting of 12 September 1986 - 'Forestry threat to fish stocks'.

Harriman 1978). Ongley (1982), Lewin et al.(1977 and 1983) and others have shown that suspended sediments are important in transporting heavy metals and pollutants. Increased sediment yields associated with upland development could assist the dispersion of pollutants further downstream (Macklin and Rose 1986).

(v) channel instability problems further downstream (Newson 1986, Newson and Leeks 1987) which can result in costly erosion or deposition problems.

Thinning and clearfelling of forestry leads to a decrease in interception and transpiration, thus increasing soil moisture levels, runoff (Hewlett and Helvey 1979) and transportation of particulate material (especially pine needles and fine sediment). Rainsplash erosion during heavy rainfall on bare unprotected soil can increase soil erosion and subsequent sedimentation downstream. However, there is as yet very little British data from which to assess the effects of clearfelling. We currently have to draw on experiences largely from North America (e.g. Brown and Krygier 1971, Fredriksen 1963 and 1970) with some recent examples from New Zealand (O'Loughlin et al. 1981).

1.2 Previous work

Prior to the 1970's no accurate first hand information on the effects of forestry on sediment yields had been obtained in upland Britain. Studies in the U.S. (Brown and Krygier 1971), Canada (Roberts 1984), New Zealand (O' Loughlin et al. 1980) and elsewhere had been carried out in very different conditions and could not be readily extrapolated. In any case most of the above studies had been concerned with the effects of logging and clearfelling on sediment yields and not with the effects of forest establishment which was the land use change increasingly affecting more and more of the British uplands.

In the UK the Government Hydrological Research Unit became the Institute of Hydrology (IH) in 1968 and set up two important catchment studies. The first of these was at Coalburn in the Pennines, where a 152 ha tributary catchment of the river Irthing in Northumberland was instrumented and studied for five years from 1967-72. The catchment was ploughed in 1972 following forestry standard practice at that time and the effect of this treatment on the water and sediment yields was investigated by the Institute of Hydrology up to a few months before the saplings were planted and again during the winter of 1978-79 by Robinson (1979) some 6-7 years after the period of disruption. Robinson and Blyth (1982) suggest that the yield of fine sediments peaks rapidly after site preparation and then stabilises at a higher level than observed before the treatment as the figures presented in Table 1.1 suggest.

The second catchment experiment was set up on Plynlimon in mid-Wales where a ten-year study compared the water balances of the upper Wye (entirely upland pasture) with the adjacent upper Severn (68% coniferous forest cover). As part of the experiment the sediment outputs of the mature forested Tanllwyth and the adjacent upland grassland Cyff sub-catchments were compared (Moore & Newson 1986). Under the 30 year old forest of the Tanllwyth sub-catchment, intensively ditched at planting time, suspended sediment yields were double those from the grassland Cyff catchment and bedload yields were five times as high (Newson 1980b). See Table 1.1.

More recently in the southern Pennines, Burt et al. (1984) have compared suspended sediment yields from two small upland catchments following open ditching for forestry drainage. Before ditching,sediment supply was limited and easily exhausted whereas after the treatment a marked increase in the production of suspended sediment occurred from one of the catchments. Ditching took place in early autumn and during the winter large quantities of sediment were carried into a downstream reservoir causing pollution problems. Since the following spring however, sediment yields were greatly reduced mainly due to revegetation of the soil.

Recent results from the Llanbrynmair moor afforestation study in mid-Wales (IH Report 1986, Francis 1987), have confirmed again that 'a significant increase in stream sediment loads occurred during the ploughing phase of forest establishment in both of the two small catchments studied. The magnitude of this increase varied between the catchments, and appeared smaller than that recorded at Coalburn.'

Thus, from our knowledge in British environments so far it seems that following the land preparation phase investigated in the studies above, catchment yields of both fine and coarse sediments increase partly because of the changing flood regime (Acreman 1984, Jones 1975) but mainly because the soil disturbance makes available a large new supply of sediment for transport in the long term. A literature review by Blackie et al. (1980) revealed a wealth of information on the effects of forest management on water quality in North America and other areas, but a noticeable paucity of data from the British uplands or any comparable environments. Consequently a programme of research was initiated to determine the magnitude and duration of the effects of forestry operations on water quality and quantity. With funding and support from the Natural Environment Research Council, the Department of Environment, the Water Research Centre, the Welsh Office, the Scottish Development Department and the Forestry Commission this coordinated programme is being undertaken by the Institute of Hydrology, the Institute of Terrestrial Ecology and the Water Research Centre. Currently, efforts are being concentrated on the "major disturbance" phases of forestry operations: land preparation and planting at Llanbrynmair moor, clearfelling at Beddgelert, Kershope and Plynlimon and ploughing, planting and felling at Balquhidder.

Since the major expansion in plantation forest establishment took place after World War I when the Forestry Commission was set up, forests planted at that time have only been reaching maturity (maximum yield) in the last decade or so. Clearfelling and replanting operations in the U.K are just beginning to take place on a large scale. Consequently, as yet there is a paucity of British data from which to assess the extent to which sediment yields are further modified during the clearfelling and subsequent replanting phase. In contrast, studies on the impact of clearfelling and logging activity elsewhere in the world are more numerous.

Areas of forest clearance and logging activity with associated road construction, heavy machinery operation, and often nearly complete removal of the vegetation cover, have been found in many regions to exhibit increased flooding and particularly increased transport of debris and sediment. Considerable work on this problem has been reported from the Pacific northwest states of the U.S. For example, the influence of two types of logging practice on the response of small catchments in a Douglas fir stand in western Oregon has been studied by Fredriksen (1970). He compared the response of three small watersheds in the H.J. Andrews Experimental Forest: one patch-cut with roads constructed for timber removal, one clear-cut with the timber removed by aerial ropeways, and the third an undisturbed control basin. Total sediment yield from the clear-cut basin was three times higher than the control whereas the patch-cut basin with roads had sediment yields of more than two orders of magnitude higher than the undisturbed basin. The presence of logging roads was found to be the dominant control over increased yields because whereas vegetation removal was more complete in the clear-cut watershed it exhibited a total sediment yield of only 3 per cent of that from the patch-cut catchment where roads had been constructed. The forest roads caused severe mudflows and landsliding which scoured the stream channels and provided a massive source of sediment and debris. There were also contrasts in the relative proportion of suspended load and bedload comprising the total load because whereas the ratio was 1:1 and nearly 2:1 in the control and clear-cut catchments respectively it changed to 1:4.5 in the patch-cut watershed. The increase in the relative importance of bedload in the patch-cut basin was attributed to the landslide activity.

It is apparent from a more recent review of studies by Reid (1981), Madej (1982) and Lehre (1982) summarised by Swanson et al. (1982) in the Pacific northwest and Roberts (1984) in Canada that logging increases sediment delivery to streams. This is due mainly to an increased availability or erodibility of sediment rather than to an increase in runoff. The major sources are surface wash and mass movement failures associated with roads, an increase in the incidence of mass movement failures on steep slopes following forest removal due to decay of the root mat, and an increase in streambank erosion. A major portion of the sediment delivered to the stream channels may be stored so that sediment transport rates observed at the basin outlet cannot be set equal to the rates of erosion (Megahan and Nowlin 1976).

That much can be achieved through careful forest management is illustrated by the example of the H.J. Andrews Experimental Forest where a reduction in the number of logging roads considerably reduced the resulting increase in sediment yields. Table 1.2 shows the effects of timber harvesting in the United States (Sharpe and De Walle 1980) on stream water turbidity levels under two different regimes of forestry management,and contrasts the results with those from an undisturbed control stream. Where no care was taken to protect water quality exceptionally high stream water turbidities resulted. If,

Table 1.2: The effects of timber harvesting on stream water turbidity (from Sharpe and De Walle 1980).

Regime	Stream water turbidity (F.T.U) Base flow (mean)	Storm flow (max)
Undisturbed control	2	25
Commercial harvesting (1)		
During cutting	490	56000
One year later	38	5000
Two years later	2	170
Silvicultural harvesting (2)		
During cutting	6	90
One year later	5	35
Two years later	2	23

(1) No care taken to protect water quality
(2) Exceptional care taken to protect water quality

for example, a small reservoir received such water it would soon become seriously polluted. Where care was taken the deterioration in water quality was minimal and recovery was more rapid.

O'Loughlin et al. (1980) have examined the sediment yield and water quality responses to clearfelling of evergreen mixed forests in western New Zealand and found that clearfelling and removal of logs followed by burning on two steep basins caused marked stream water quality changes. In a basin which was tracked, harvested by rubber tyred skidders and burnt, sediment yield rates increased to eight times the yield from a nearby forested control basin. Most sediment came from the track. In a basin which was clearfelled and harvested by a downhill cable system with no tracking, sediment yields were not significantly different from the control basin.

The effects of logging on sediment yields documented in the Pacific North West states of the U.S. and in New Zealand may not of course be applicable to the British environment since these studies refer to logging of natural primary forest on what are usually steeper slopes, often with higher rainfall intensities and/or a more deeply and thoroughly weathered bedrock. These factors combine to make conditions very different to those in upland Britain and so the validity of direct comparisons is in question. It appears that forest establishment and logging operations can affect erosion and increase sediment yields but that much can be achieved through careful practice (e.g. Mills 1986, Ponce 1986).

The sediment producing geomorphic processes operating in an upland Scottish glen such as those studied at Balquhidder can sometimes be so slow as to be considered negligible. At other times they can be of a catastrophic nature. At best they are highly variable in both space and time. Clearly, short-term monitoring at a few localities is not easily extrapolated to construct a catchment sediment budget. Designing a monitoring network to measure components of the sediment balance to build a sediment budget can be a daunting prospect especially since little experience of this has been gained in the British upland environment. Many investigators have studied individual sediment production and transport processes operating in the British upland environment (e.g. Slaymaker 1972, Imeson 1974, Lewin et al. 1974, Oxley 1974, Newson 1975b, Lewin and Wolfenden 1978, Robinson 1979, Grimshaw and Lewin 1980, Newson 1980a and b, Arkell et al. 1983, Moore and Newson 1986) but little effort in British geomorphology has been made to integrate the use of the various previously employed techniques to attempt to construct sediment budgets for whole catchment systems. The sediment budget approach has been adopted elsewhere (e.g. Dietrich and Dunne 1978, Duijsings 1987) and in north America it has been used to assess the effects of logging road impact (Reid et al. 1981). Only by learning about sediment budgets will it be possible to assess the long term effects of the increasing land use changes in the British uplands, be they from forestry, agriculture, recreation or water supply undertakings.

CHAPTER 2: THE BALQUHIDDER EXPERIMENT

2.1 The Balquhidder Paired Catchments Experiment

The publication of results in the late 1970's from the Plynlimon Experimental Catchments (Newson 1979) on the headwaters of the rivers Severn (afforested) and Wye (grassland) in mid-Wales concluded that the forested upper Severn catchment intercepted and 'utilised' more water than the adjacent grassland Wye. This caused concern among Scottish Water Authorities. It was claimed that conditions in mid-Wales were not at all representative of Scottish conditions where factors such as geology, topography and relief are different and a much higher proportion of the annual precipitation input is in the form of snow. Catchment experiments are extremely costly to set up and run and studies are not undertaken lightly. Yet the major expansion of forestry planned by the Forestry Commission for upland Scotland over the next 50 years stimulated the interested parties which include the Scottish Development Department, Macaulay Soil Research Institute, Department of Agriculture and Fisheries for Scotland, Forth River Purification Board and the Forestry Commission to form a consortium to fund a catchment scale study of the hydrological effects of afforestation near Balquhidder in the southern Highlands in an area of Scotland where snow input and accumulation are normal features of the climate. In place of the relatively smooth upland grassland of Plynlimon, the natural vegetation cover tends to be a heather, bracken, scrub and grass complex with significant areas of bare rock at the higher levels.

The catchments allow comparisons of the effects of forest with those of the indigenous vegetation on the water balance, stream flow and sediment yield characteristics for a 'calibration' period from 1982-5 (to be referred to as Phase I hereafter). They also offered the prospect of longer term studies into the hydrological effects of all phases of forestry in this environment since clearfelling was scheduled to start in the mature forest in early 1986 and the lower slopes of the moorland catchment were to be ploughed and ditched in spring and early summer of 1986 in preparation for planting (1986 onwards is referred to as Phase II).

2.2 Specific aims and objectives

As part of the Balquhidder catchments' water balance study the Institute of Hydrology have undertaken a sediment output monitoring programme throughout the two phases of the experiment. During Phase I (1982-1985) differences in the sediment output from the two catchments were attributed to land use. This phase also acted as a calibration period before the land use conversions of Phase II took place. Phase II started in early 1986 and was concerned with the effects of ploughing, draining and tree planting in the moorland catchment and of clearfelling and the associated activities in the forested catchment.

The research reported in this thesis was designed to supplement the IH 'black-box' monitoring of sediment output from the catchments by monitoring sediment sources at the end of Phase I and beginning of Phase II of the experiment. The objectives were:

<u>Phase I</u>

a. to identify potential source areas and likely sediment transfer points in the catchment system and measure erosion rates (and tributary sediment yields) in them,

b. to compare erosion rates in source areas with sediment yields at catchment outlets and estimate 'delivery ratios'. Low delivery ratios would imply storage of sediment in the main channels, and so

c. to measure changes in channel storage between source area inputs and catchment outputs,

d. to combine the findings above and to construct sediment budgets to compare moorland and forest land uses before disturbance,

<u>Phase II</u>

a. to identify new sediment sources resulting from the forestry operations and monitor erosion rates and yields from them,

b. to continue monitoring in the same source areas as in Phase I,

c. to construct preliminary sediment budgets for the initial stages of Phase II in the same way as for Phase I.

2.3 Experimental Strategy

The focus of interest concerning the human impact on land use changes which has developed during the present century has led fluvial geomorphologists to study these land use changes within the catchment system as the most convenient landscape unit. We have incomparably more experience with (hydrological) catchment experiments than with any other full scale experimental unit within the discipline of earth science and so the drainage basin or catchment system has provided the fundamental unit for experiments in fluvial geomorphology. Traditionally, hydrologists and fluvial geomorphologists have adopted a 'black-box' approach to relate catchment inputs to outputs and indeed, in small catchments it has proved possible to relate catchment characteristics and form to the rates of water discharged from the basin outlet. However, much less success has been achieved when attempting to predict outputs of sediment from a drainage basin using the 'black-box' approach. Although the drainage basin does provide a functional unit for the study of fluvial processes, many subsystems exist at a variety of scales and these have implications for storage of both water and sediment in particular.

For example, it is conceivable that the effect of a land use change within a drainage basin may result in an immediate change in the sediment output from that catchment. On the other hand, it is more likely that a proportion of the sediment released as a result of the land use change might be transported only a short distance before becoming stored. It may then be some years, decades or even longer before this sediment is remobilised and the true effect of the land use change shows up at the catchment outlet. Measurements made only at the catchment outlet, therefore, could potentially fail to detect changes in erosion and sediment transfer taking place higher up the catchment. The object of this research is to supplement the IH 'black-box' approach to monitoring sediment output from the Balquhidder catchments during a period of land use conversion by monitoring sediment sources. Sediment transfers in the source areas are then compared with yields at the catchment outlets and delivery ratios are computed. Low delivery ratios would imply storage of sediment between source area and the measurement point.

Paired catchment experiments in general, however, require certain characteristics to permit the establishment of experimental control. Establishing experimental control in a short term investigation such as this is crucial and yet difficult to achieve. Church (1983) describes how most geomorphological experiments can be seen at best as 'case studies'; organised programmes of field observations do not usually constitute experiments. Church requires an experiment to include 'a formalised schedule of measurements to be made in conditions which are controlled insofar as possible to ensure that the remaining variability be predictable under the research hypothesis'. In these terms the Balquhidder experiment may prove to be little more than a representative case study. The degree of control is minimal and no specific model is being directly tested. Nevertheless, such case studies continue to be valuable, since as Ward (1971) notes, 'only a wide range of representative catchment studies will allow us to begin to integrate all the complexities of climate, soil and vegetation'.

Church identifies criteria to permit the establishment of experimental control in a paired catchment experiment. For this purpose Church reviews the earliest of all watershed experiments to be concluded, that at Wagon Wheel Gap, Colorado, between 1910 and 1926 (Bates and Henry 1928). This paired catchment experiment examined the effect on runoff of forest cutting and burning. The criteria for choice were:

- that the selected basins be practically contiguous in order that the differences in the amount and timing of precipitation be minimised,
- that the basins be situated on identical geological structure, should have similar ranges of elevation, and

should be as nearly alike as possible in aspect and physiography,

- that the vegetation should be representative of the region (rather than optimum),

At Balquhidder the criteria are met as follows: the two catchments are close to each other, Kirkton being only 5 km east of Monachyle (see Figure 2.1) so that differences in the amount and timing of precipitation are minimal (see Table 2.1); both catchments lie on the Dalradian schists and are therefore geologically similar with the exception of a band of basic rock on the west side of Kirkton which should have little or no implication for sediment studies; topography (slope angles) and relief (250-900 m) are similar; vegetation cover is representative of the surrounding region - the moorland vegetation cover is representative of the adjacent glens and indeed upland Scotland as a whole, while the afforestation in Kirkton is representative of an increasing number of neighbouring and Scottish glens this century. When the Balquhidder Catchments Experiment was first conceived it was originally hoped to find a third catchment (Blackie pers. comm.) which would be left untouched as an overall 'control'. This proved impossible and so the experiment remained a 'paired catchment experiment' but in order to achieve some experimental control over differences in the precipitation inputs a streamflow gauging station was installed on the upper part of

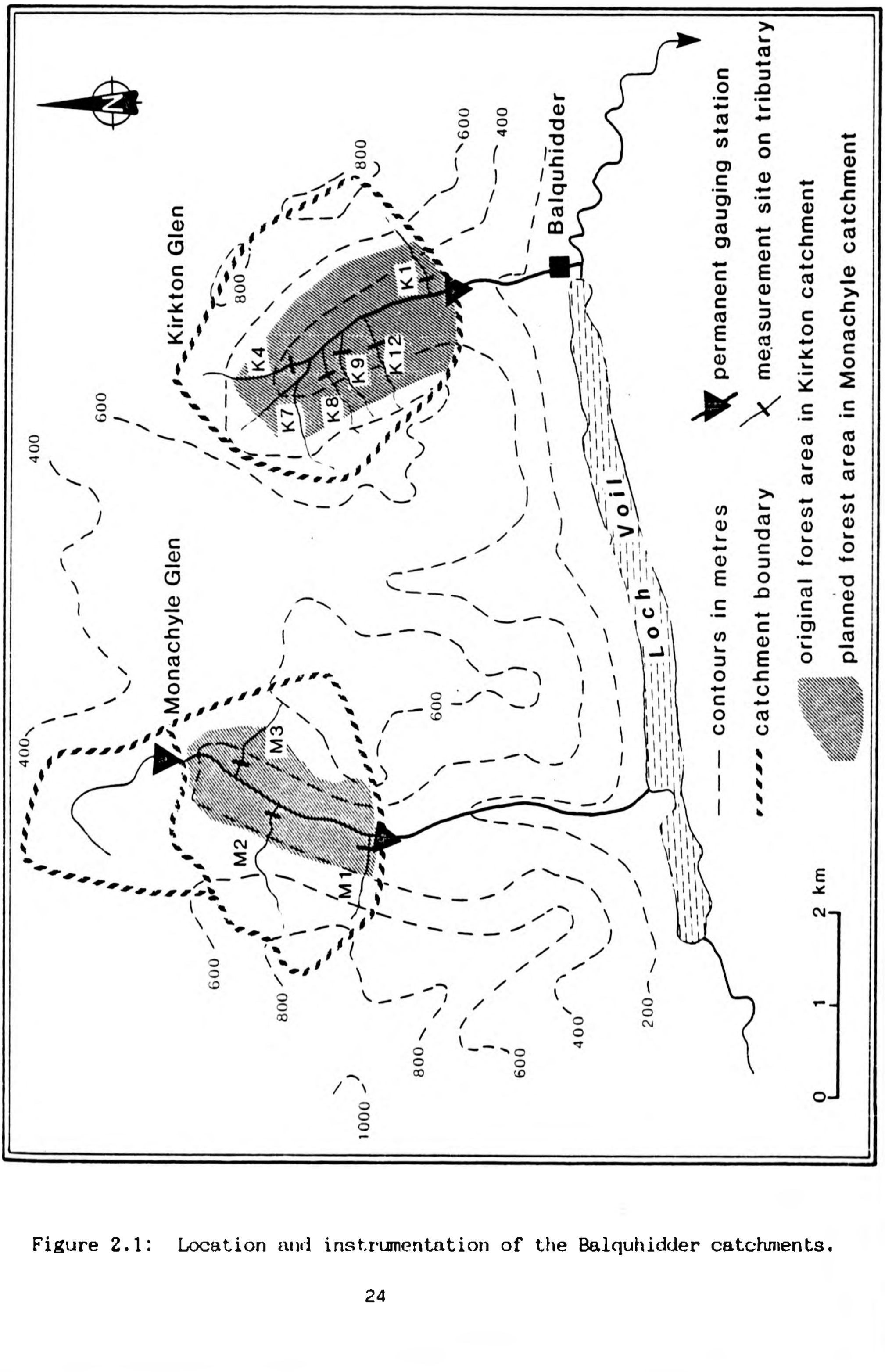


Figure 2.1: Location and instrumentation of the Balquhidder catchments.

Table 2.1: Characteristics of the Balquhidder catchments.

Catchment name	Monachyle	Kirkton
Area (km^2)	7.70	6.85
Forest cover (%)	0	40
Relief (m)	607	623
Stream frequency (km^{-2})	5.1	3.7 (1)
Rainfall (2) (mm yr^{-1})	2636	2236

(1) not including forest ditches

(2) average for 1982-5. For climatic data see Johnson (1985).

the Monachyle mainstream so that an upper Monachyle catchment, which was to remain undisturbed for the duration of the experiment, could be used as a control. The absence of a third separate control catchment is regrettable, however, particularly from the point of view of sediment studies. The choice of the upper Monachyle gauging station was not ideal since the character of this upper basin is very different from the lower Monachyle and Kirkton in that it is a relatively flat area (see Plate 2.1 (a)) of deep peat which seems to act somewhat like a 'sponge'. Access to the gauging station is difficult and as a result hardly any measurements of sediment transport at this site have been made. On the one occasion when coarse sediment monitoring during a flood event was undertaken at the site the observer detected no sediment moving (Johnson pers.comm). The very nature of the channel itself - deep, slow flowing, mud bed - suggest that no bedload transport is occurring and that the coarse sediment yield from this upper catchment is negligible.

A second type of catchment experiment was initiated in the 1890's in the Swiss Emmenthal experimental basins where one of the similar characteristics, that of surface cover, was deliberately varied. This is the case at Balquhidder and it means that the conventional calibration between watersheds before treatment cannot be carried out. Therefore, special precautions are taken in the design of the measurement programme, such as establishing a third separate control catchment (e.g. upper Monachyle), and during analysis, to ensure that extraneous sources of variability do not bias the results. This in particular means that the study should be prolonged in order that short term inconsistencies in the behaviour of the experimental units, introduced mainly by variations in the weather, may be smoothed out. At Plynlimon the experiment ran for ten years and this is the duration planned at Balquhidder. However, the time-span for a Ph.D thesis (normally 2-3 years) is clearly too short to allow variations in weather to be smoothed out. The only approach which can be used to counter this problem is to make use of IH past stream flow records to assess the streamflow variability and the effect that this has on sediment yield variability. In this way some idea of the 'representativeness' of the relatively short time which this study spanned can be gained.

The Balquhidder experiment is a comparison between catchment response from two catchments, similar in all respects except surface vegetation, through the use of paired catchments in which, after an initial calibration period (Phase I) specific treatments (land use conversions) were applied to the catchments. Phase I of the experiment was concerned with initial calibration of the two catchments in their 'semi-natural' state. One has heather moorland land use, the other has mature forest covering 40% of its area (typical of an increasing number of Scottish glens this century). This allowed relationships between catchment characteristics and runoff and sediment response to be determined before the land use changes (treatments) of land draining and forest establishment in the moorland catchment and felling in the forested catchment, started to take place (Phase II).

2.4 Study Area

2.4.1 Catchment characteristics

The catchments selected for the study are the upper Monachyle and Kirkton glens in the Balquhidder area of Central Region, Scotland. Plate 2.1 shows general views of catchments and the locations and relative positions of the catchments are shown in Figure 2.1. Table 2.1 summarises the catchment characteristics and precipitation inputs. Both catchments are in steep-sided glaciated valleys with similar areas and height ranges and are aligned approximately N-S. Drainage networks are similar, both catchments having one mainstream of relatively shallow gradient in the centre of the glen with much steeper tributaries flowing into this. Figure 2.2 shows stream long profiles of mainstreams and tributaries. The similarities are clear. In both catchments shallow peats, peaty gleys and upland brown earths overlie mica schists of the Dalradian assemblage. With the exception of a basic band of rock on the west side of the Kirkton catchment soils and the underlying geology in both catchments are similar. Precipitation annual totals are generally between 2000 and 2500 mm, totals normally being slightly higher in Monachyle. Snow may lie in the catchments any time between December and April. Frosts, measured as grass minimum temperatures at the Tulloch Farm weather station, occurred on 138 days in 1985 for example (see Table 6.3).

(a)

(b)

Plate 2.1 (a) Aerial view of Monachyle catchment in 1983. The arrows indicate the locations of the upper and lower guaging stations (Photograph taken by IH commissioned helicopter).

Plate 2.1 (b) View of Kirkton glen at the start of clearfelling in early 1986. Arrow indicates approximate location of main gauging station and therefore the southern boundary of the catchment.

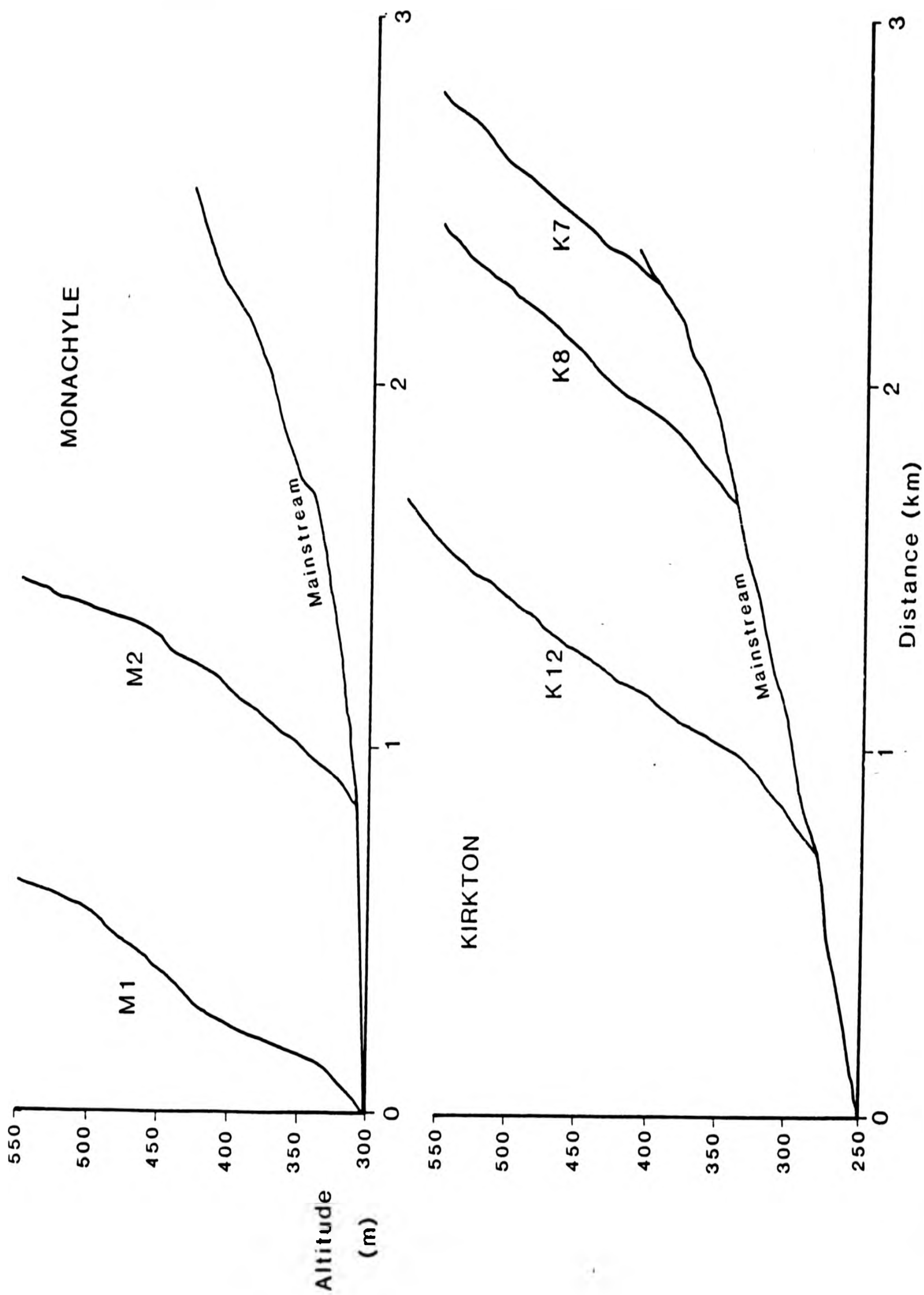


Figure 2.2: Mainstream and tributary long profiles of the Balquhidder streams.

In the 7.7 km^2 area of the upper Monachyle glen being studied, the upland grasses which are dominant in the lower part of the glaciated valley give way progressively to bracken and then to heather as altitude increases. The upper control catchment (2.24 km^2) contains an area of deeper peat and here the channel is deep and very slow flowing because of a very low gradient. In the middle section of the catchment the mainstream gradient steepens (see Figure 2.2) and the channel flows on bedrock. In the alluvium filled lower part of the catchment the channel meanders (see Figure 3.4) and has a gravelly bed and lower gradient. Heather dominates the vegetation on the ridges and in the upper control catchment. Grasses predominate within the lower basin particularly in the area enclosed by the Forestry Commission fence though there is a significant bracken coverage in the north-west part of the enclosed area and some patches of scrub forest below the crags on the western side. There is a considerable area of exposed rock on the western ridge of the catchment.

Above the tree-line in Kirkton glen three lochans provide localised storage and serve to increase baseflow during dry periods. Mixed heather/grass cover dominates above the tree line and is generally similar to that in the Monachyle. The Forestry Commission boundary fence encloses 44% of the catchment area although when unplanted areas, roads and clearings are considered the forest cover is estimated at 35%. Tributaries flow steeply on bedrock into the forest where they merge to form the mainstream which tends to be straighter than in the Monachyle. The channel is mainly gravelly with a few sections where bedrock is exposed. Mainstream channel bank materials are mainly fine with 70-90% finer than 2.8 mm. Typical grainsize curves for tributary channel banks (including a forest ditch) are plotted in Figure 6.4 and again it can be seen that the material is finer than that from the channel bed. Slope angles estimated from contours on 1:10000 maps are similar in both catchments and average 22°.

By March 1981, rain gauge and automatic weather station networks were designed and installed and readings were initiated when the resident observer took up office in August of the same year. Eleven rain gauges are distributed in each catchment, sampling the major altitude, aspect and slope domains. Two automatic weather stations (AWS) are deployed in the catchments, at 300 m in the Monachyle and at 670 m on the western ridge on the Kirkton, whilst a third is maintained alongside a manual meteorological station at an easily accessible, low level site (Tulloch Farm weather station) between the two catchments on the northern shores of Loch Voil. IH streamflow measurement instrumentation is discussed in section 3.1.

To maximise the use of the hydrological data, the catchments are also being used for studies of the effects of forestry on nutrient losses, on water quality and on aquatic biota by the Macaulay Institute, the Forth River Purification Board and the DAFS Freshwater Fisheries Laboratory respectively.

2.4.2 Selection of tributary monitoring sites

At the outset of the study the catchments were divided into two source area zones: the mainstreams and the tributaries. Because of the high density of the stream networks it was practically impossible to undertake measurements in all tributary catchments and so it was necessary to select 'representative' sub-catchments. It was decided to install sediment traps on 6 and 3 tributary streams sampling 38 and 18% of the total catchment area in Kirkton and Monachyle respectively. Figures 2.3 and 2.4 show the locations of these sediment traps, sub-catchment boundaries, roads and also show suspended sediment sampling stations in the stream network for Kirkton and Monachyle. Areas of sub-catchments draining to the monitoring stations, average gradients and approximate forest cover are indicated in Table 2.2. In selecting the sites for sediment traps the following considerations were made:

1. that access to the traps was good (roadside locations were chosen in Kirkton where the lower Forestry Commission road shown in Figure 2.4 was used) since sediment accumulating in the traps needed to be excavated monthly. Ideally, it would be possible to empty all traps in one field day.

2. to locate some of the traps where the sub-catchment was

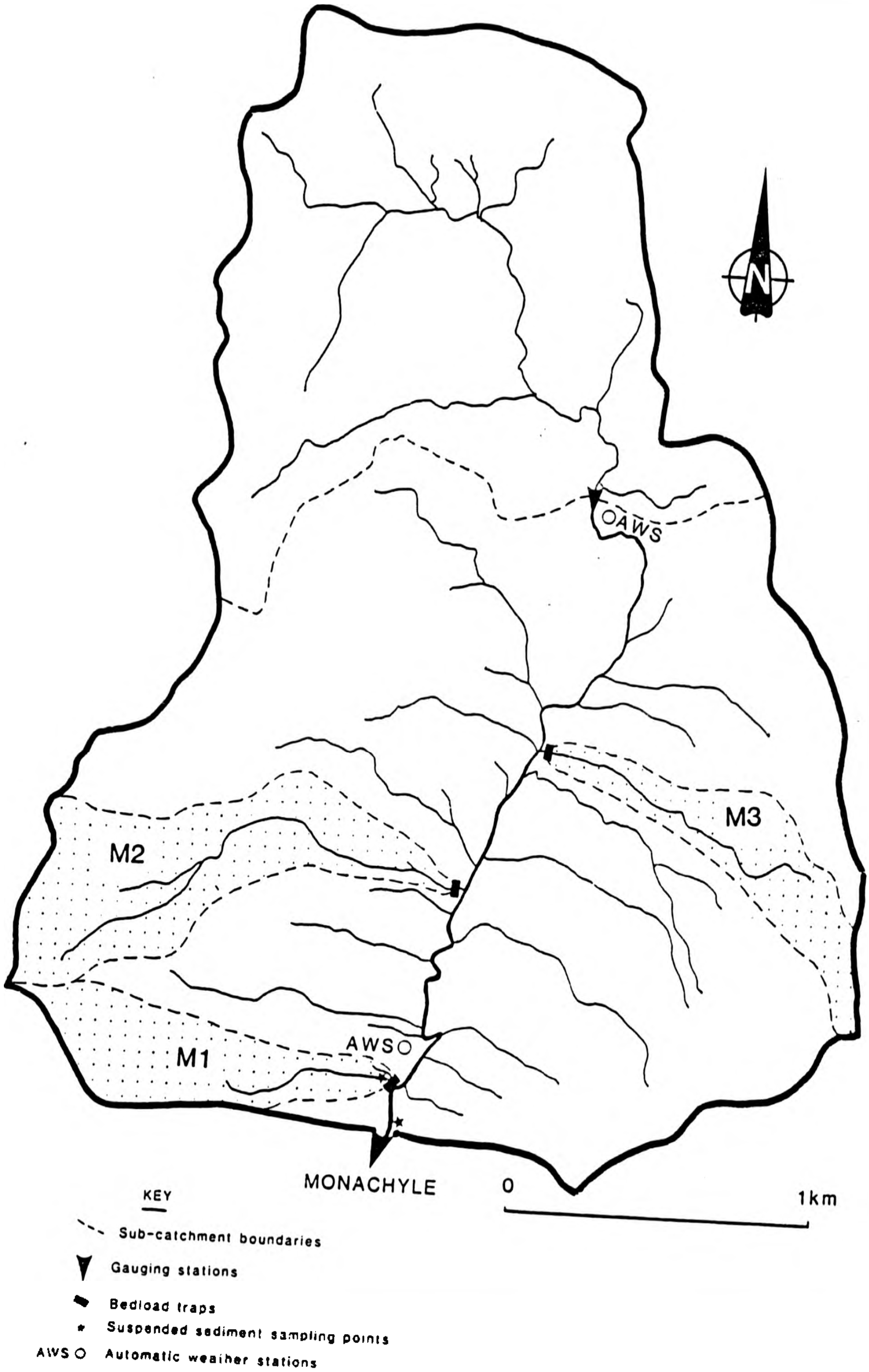


Figure 2.3: Sediment source area measurement sites, sub-catchment boundaries and instrumentation in Monachyle glen.

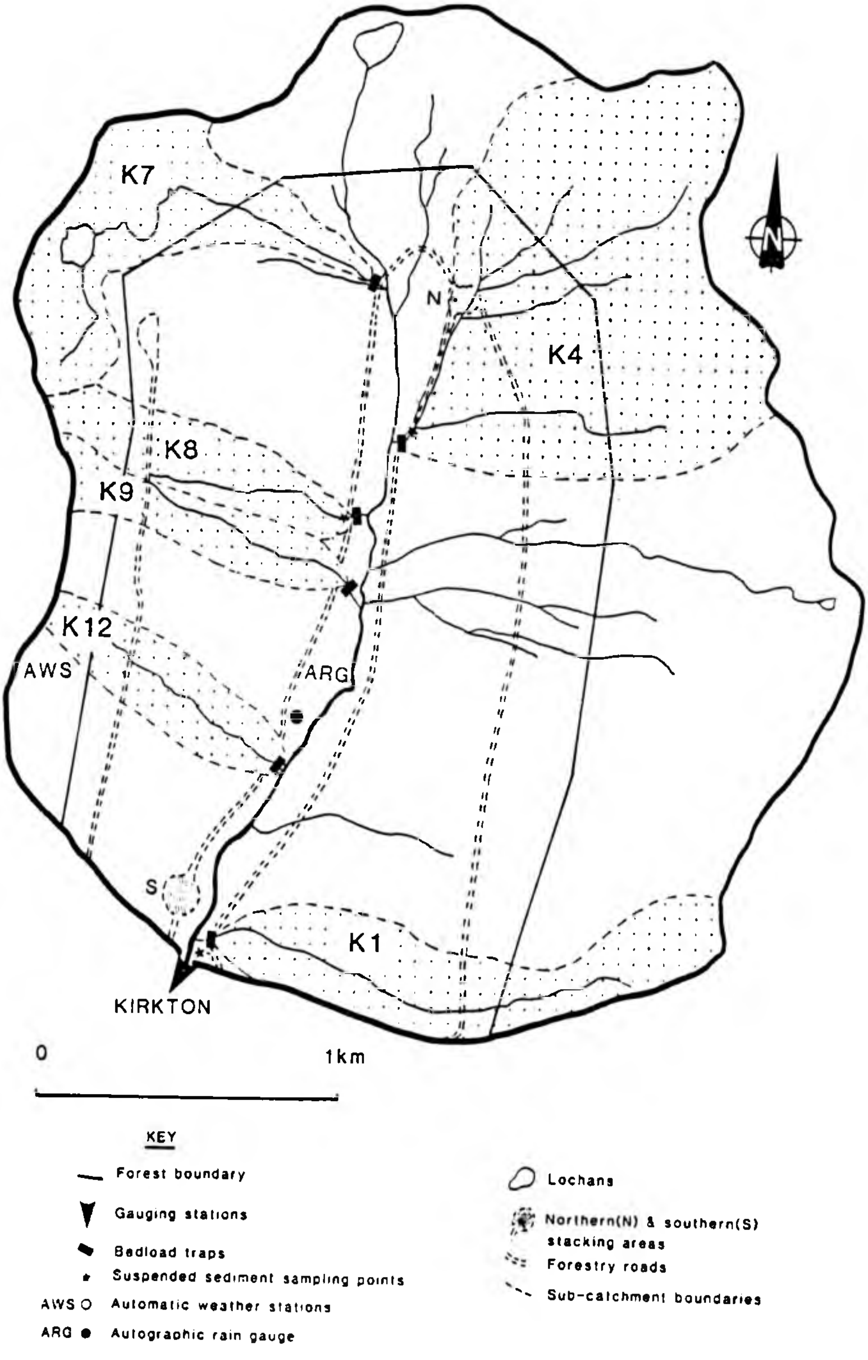


Figure 2.4: Sediment source area measurement sites, sub-catchment boundaries, instrumentation and roads in Kirkton glen.

Table 2.2: Characteristics of Balquhidder tributaries studied.

	Tributary number	Area (km^2)	Average gradient (%)	Forest cover (%)
Forest				
	K1	0.42	40	51
	K4	1.23	22	20
	K7	0.42	38	12
	K8	0.20	29	63
	K9	0.16	29	65
	K12	0.17	40	78
Moorland				
	M1	0.24	42	
	M2	0.55	43	
	M3	0.49	30	

likely to be affected by felling (west side of glen - K8, K9, K12) and ploughing/draining in Phase II of the experiment (M1) as well as positioning others where no change in the land use was scheduled in the two year monitoring period planned (K1, K4, K7, M2, M3).

3. to select tributaries which were 'typical' of others in terms of gradients, water discharge and land use.

At the start of the project areas to be affected and dates for the land use conversions were not available. However, the clearfelling operations were to enter the Kirkton catchment from the south-west boundary and move in a clockwise direction, the whole catchment taking up to five years to clearfell. With this in mind, 4 of the 6 sediment traps were located on the west side of the catchment in order that any effect of clearfelling proceeding up the west side of the catchment (see Figure 2.5) could be monitored. Two further traps were located on K1 and K4 as 'controls' to remain unaffected. In the event, K4 was later affected by the construction of a loading area and a road diversion. Intensive suspended sediment sampling was carried out in K8 (as a sub-catchment which it was hoped would be clearfelled at some point in the two year period, but in the event clearfelling did not affect this sub-catchment) and K4 (where the effect of the road diversions and timber stacking area construction were monitored in Phase II).

At the time of installing the sediment traps in the

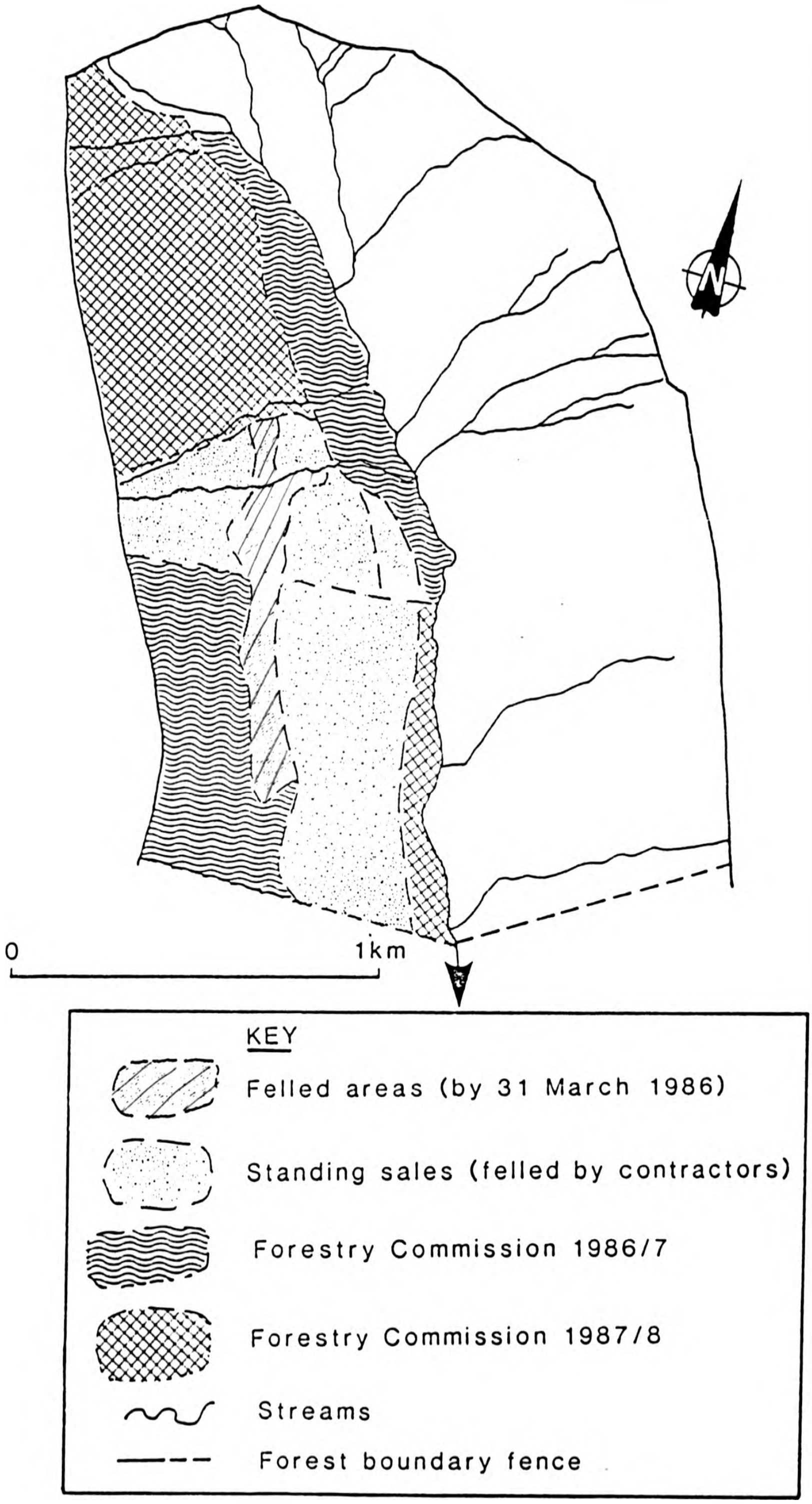


Figure 2.5: Clearfelling progress in Kirkton glen.

Monachyle catchment, the land use conversion plans were that ploughing/draining was to take place in three phases over three years. For this reason, M2 and M3 were located further up the catchment in the hope that M3 (or even M2 as well) would be unaffected after the first phase of ploughing. However, Figure 2.6 shows that all the proposed ploughing/drainage was carried out in one phase (April-July 1986). Intensive suspended sediment sampling was conducted in M1 for reasons of access - there were no roads into the Monachyle catchment and this was the nearest suitable tributary to the end of the road which terminates just inside the southern catchment boundary. Some intensive suspended sediment sampling was carried out in the tributary down which the slope failure had occurred several months previously, but suspended sediment concentrations were very low and not significantly different to samples from M1. Also, M1 had a typical appearance and there was no reason to suspect that it should not be representative of other tributary streams in the glen.

For the purposes of estimating catchment sediment yields from the tributary bedload trap accumulations, all large tributary sub-catchments were delineated in the 1:10000 scale catchment map and their areas measured by digitising. Shaded areas in Figure 2.7 are considered to drain directly into the mainstreams and should therefore not be included when estimating tributary yields. These areas are alongside the mainstreams and generally have low

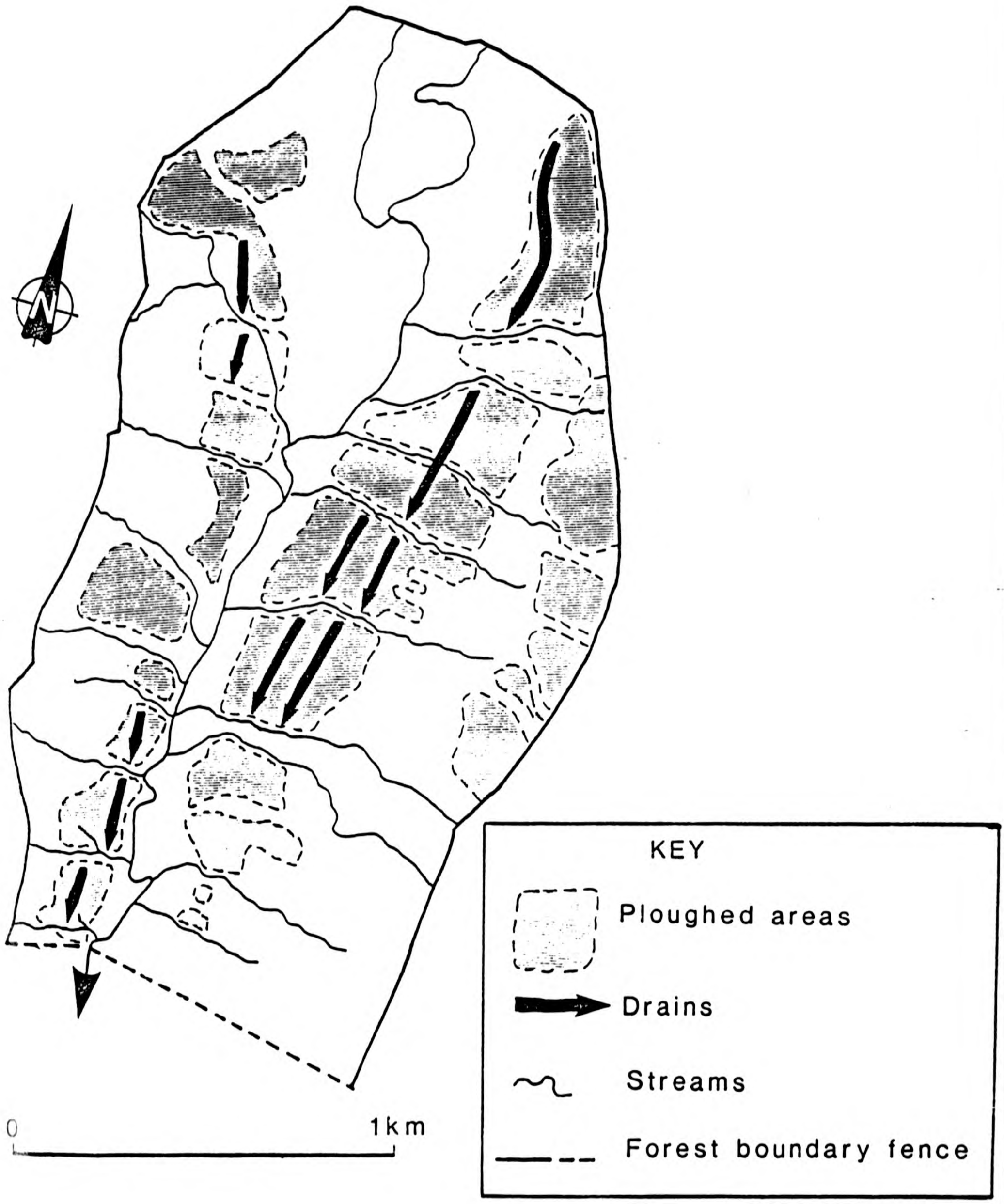


Figure 2.6: Ploughing, drainage and planting areas in Monachyle glen.

gradients and dense vegetation cover. For the purposes of this study the sediment yield from these areas is assumed to be negligible. Sediment yield from the upper Monachyle catchment is also considered to be unusually low (see section 2.3) and therefore is also shaded in Figure 2.7 and not included in tributary yield estimates. Shaded areas corresponded to approximately 60 ha in both catchments which represents 9% of the total Kirkton catchment area and 37% of the Monachyle catchment if the upper Monachyle is included. Thus, the actual areas considered to be drained by tributaries are 630 and 486 ha in Kirkton and Monachyle respectively and these areas are used for the purpose of calculating tributary sediment yields.

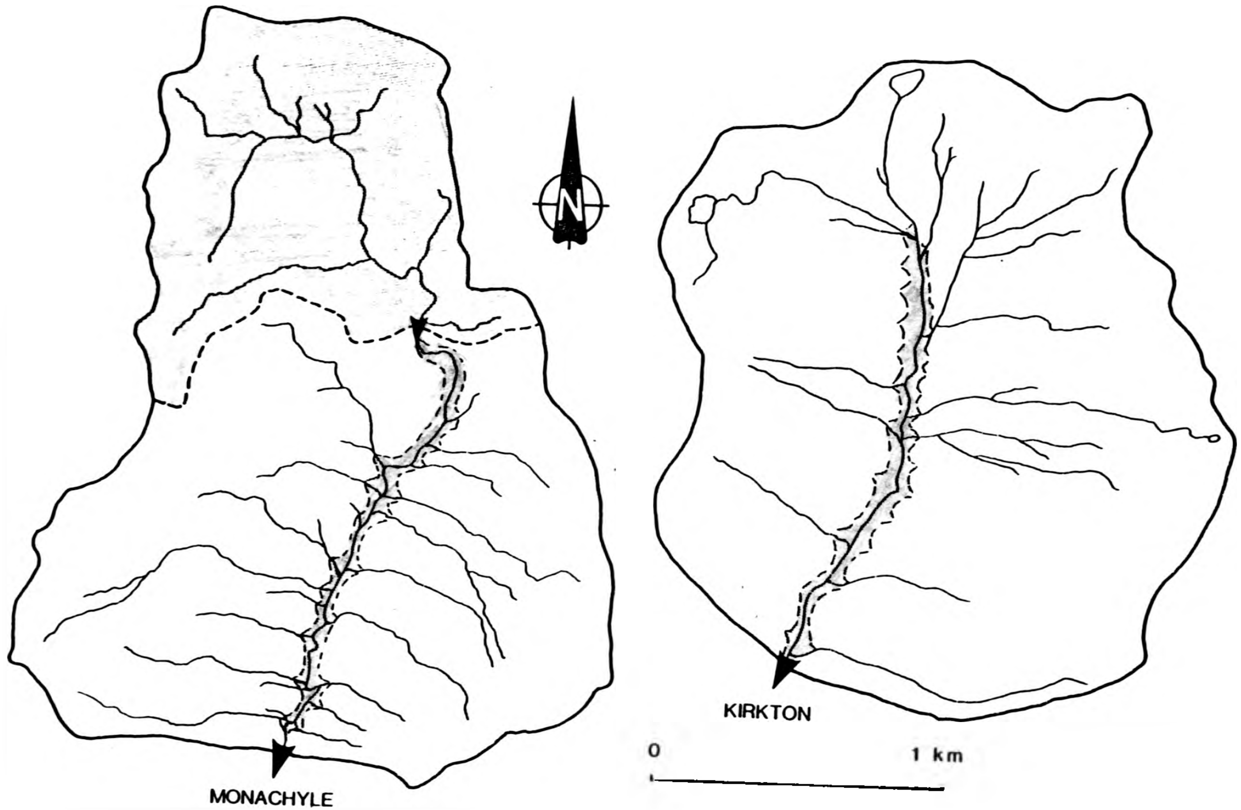


Figure 2.7: Unsampled areas of the catchments assumed to have negligible sediment inputs.

2.5 Land Use Conversion

The Balquhidder Catchments' Experiment entered Phase II to study the effects of deforestation in Kirkton glen from October 1985 and afforestation in Monachyle glen from April 1986.

2.5.1 Afforestation in Monachyle Glen

Before an area of wet, poorly drained upland moor such as that in Monachyle glen can be successfully afforested, a certain amount of ground or site preparation is necessary to give young trees a reasonable chance of survival in their first few years and to enhance the chances of producing a successful crop of trees in the future. This site preparation usually involves some form of ploughing in the first instance usually followed immediately by some form of drainage scheme. According to Taylor (1970)

ploughing is undertaken for the improvement of tree growth by alteration of the site in one or more of the following ways: regulation of water movement, improving soil aeration, reducing compaction, mobilising nutrients (particularly nitrogen), reducing competition from the natural vegetation and providing a favourable planting position. So, the principal objective is to amend adverse soil features in order to encourage root development, and to improve crop stability. Ploughing is carried out in order to help achieve this and a very wide range of plough designs is available to the forester to meet the requirements of the varying soil types and terrain which has to be ploughed. In Monachyle the type of plough used was a D45/T60/m which means that the plough was of the double mouldboard (D) type (i.e. turns turves over on both sides of the plough furrow as opposed to a single mouldboard (S) which only turns over turf on one side), that the depth of the furrow was 45 cm but that the depth of the tine or centre of the furrow (T) was 60 cm. The plough was mounted on a caterpillar tractor (m) as opposed to being trailed behind (t). Thompson (1970) discusses the nomenclature and details of standard and specialised ploughs available. Ploughing within the IH catchment area started in early April 1986 and three-quarters of the area to be ploughed was completed by the end of the month. Ploughing was then interrupted for three weeks on the request of the R.S.P.B due to the presence of a Golden Eagle nest on the west side of the catchment. Ploughing was resumed and completed in the last week of May 1986. Plough furrows ran straight downhill but stopped well before the mainstream leaving wide riparian buffer strips (20-30 m) alongside the mainstream unploughed (see Plate 7.2). Broadleaf regeneration will be encouraged (with some planting e.g. hazel, alder, willow) in this zone. Forestry Commission plans intend that some 235-240 ha (30%) of the 770 ha catchment will eventually be planted of which something like 180-200 ha (25%) would be ploughed and the remaining 5% hand planted. However, the steep slopes and wet conditions meant that only 80 ha (or 10% which is less than half of the originally planned area) was in fact ploughed. A larger proportion will therefore have to be hand planted with the use of herbicides to suppress competition from natural vegetation. Some planting took place in Spring 1987.

To a large extent ploughing itself gives very intensive drainage of the upper soil layers, but ploughing alone is not usually sufficient to drain these very wet upland areas and so is usually supplemented by an open-ditch drainage scheme which is superimposed on the ploughed area and commonly called cross-draining. In short, a drainage scheme carries water collected by plough furrows to a natural water course in collecting drains or intercepted at strategic points by cut-off drains. Cross-drains are ideally restricted to a gradient of about 3° to reduce severe erosion and their capacity sets a limit to the size of their catchment area. Maintenance (removal of blockages) and remedial work (deepening and widening of existing drains and digging of new drains) are important parts of a drainage scheme. Thompson (1972) gives more details of the design, limitations, maintenance and remedial work for forest drainage schemes. In Monachyle the drainage scheme was installed using standard JCB type diggers in June and July 1986 immediately following ploughing. Some drains were dug by hand on steeper ground after this date. Figure 2.6 shows the ploughed area within the catchment and the approximate location of the cross-drains.

2.5.2 Clearfelling in Kirkton glen

Clearfelling entered the catchment in January 1986 but was preceded by extensive road grading, repairs and construction of timber stacking areas - the IH resident observer who is concerned with changes in sediment output declared 14 October 1985 as the official date on which the road repairs in preparation for clearfelling started. Three main stacking areas have been constructed: the first (southern) is on the west side of the mainstream near the main IH crump weir and this was constructed in March 1984. However, since it lies on the southern limit of the catchment boundary only a small proportion of the runoff from this area actually passes through the main output weir via a small tributary (K14 in Figure 5.16) which is just downstream of the IH suspended sediment sampling point and therefore did not affect suspended sediment outputs. The second stacking area (northern) was constructed in late October and November 1985 (see Plate 5.5 and Figure 2.4) and runoff from this area entered stream K4 and was sampled for suspended sediment throughout the project study period from March 1985 to April 1987. A bedload trap was also located on stream K4 downstream of the northern stacking area. Road repairs in the form of straightening a bend to allow large logging lorries to approach the northern loading area took place in August 1986 and runoff from this also directly entered stream K4. Results of this sampling are reported in section 5.4.2. The third stacking area is to the east of the main IH output weir and was constructed at the same time as the northern one. However, since runoff from this area enters the mainstream downstream of the IH weir its construction has no effect on catchment outputs of sediment and is therefore discussed no further in this thesis. All roads, the three stacking areas, suspended sediment sampling points and bedload traps are located in Figure 2.4.

Clearfelling crossed the southern boundary on the west side of the catchment in January 1986 and proceeded in a northwards (clockwise) direction up the west side of the glen and will continue southwards down the east side in the future. The Forestry Commission works on the basis of five year plans, and details of the present plan were presented to a water quality consortium meeting on 14 November 1985 by the Regional Head Forester Mr. Brian Roebuck. Briefly, the current plan ends in 1988 and it was proposed to fell approximately two thirds of the west side of the glen within the current plan. The aim is to fell each sub-catchment as a whole before moving into the next one by both cable crane (also called 'skyline') and forwarder. Forwarders are large wheeled tractors which in general can remove timber from slopes of up to 55% and are preferred to cable cranes since they move the timber to the stacking areas rather than to piles on the side of roads as is the case for cable crane extraction (see Plate 7.4). Loading timber onto logging lorries on roadsides tends to be more time consuming. The lower roads will be used by forwarder only, the upper east road allowing logging lorry access to the northern stacking area and the upper west road currently being used for stacking and removal of timber extracted from above and below the road by cable crane. Felling progress up to the end of the study period (May 1987) is illustrated in Figure 2.5 which shows that not all felling is done by the Forestry Commission and that some areas are "standing sales" in which felling and extraction is contracted to felling gangs. Felling contracts include statements clarifying that trees must be felled away from streams, any forest litter must be removed from streams and forwarder movement must avoid crossing streams except in specially strengthened or bridged points.

After felling a new stock fence will be erected round the outside and deer populations within the perimeter fence will be controlled by rangers. The land will be left for eighteen months to two years and then replanting will follow the felling pattern, the main species being sitka spruce with some larch and possibly douglas fir. There is the possibility that additional drains on flatter ground will be dug and existing drains cleaned at the time of replanting but otherwise there will be no other cultivation. There will probably be no fertilisation since the soils are rich but there could be a herbicide application after the first year of planting. Strips will be left unplanted along the mainstream up to

30 m wide and some open areas will be left for deer control. Broadleaf regeneration will be encouraged in these areas.

Within the catchment unit monitoring of sediment sources was largely undertaken at the tributary or sub-catchment scale by monitoring tributary yields ('inputs') of suspended and bedload and along the mainstream by measuring 'inputs' from bank erosion and changes in bed storage of coarse sediment. 'Outputs' are monitored for the duration of the experiment by the Institute of Hydrology (IH). Figure 3.1 indicates the points in the system at which sediment transfer is assumed to occur. All transfers were monitored except for hillslope processes and bedrock erosion which were assumed to be negligible over the timescale of the study.

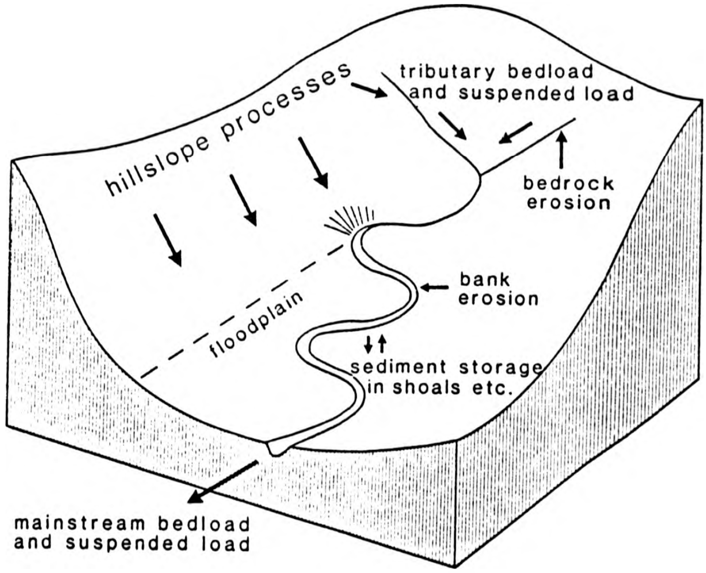


Figure 3.1: Representation of the catchment system sediment sources, stores and fluxes.

3.1 Catchment outputs

Catchment outputs of both water and sediment have been monitored by the Institute of Hydrology since 1982. This task is undertaken by an IH resident observer.

3.1.1 Streamflow measurements

The design chosen for the main gauging structure on each catchment was the Hydraulics Research Station Crump weir. The Monachyle structure is seen in Plate 3.1. This design has the ability to provide accurate estimates of flow over a very wide range. In order that the structures be capable of containing the estimated 50 year flow of 26 and 30 m^3 s^{-1} crest widths of 5 and 7 m in Monachyle and Kirkton respectively were needed. This meant that the dry season base flows would inevitably drop below the 0.3 m minimum stage recommended in British Standard 3680, resulting in poor sensitivity in this range. Therefore, separate low flow structures were installed by the Forth River Purification Board in series with the crump weirs. These were short trapezoidal flumes prefabricated in fibre glass and embedded in concrete and designed to overlap the lower part of the acceptable flow range of the crump weir it complimented. Designs were completed by early autumn 1981 but weather and flow conditions precluded construction until late spring 1982. Forestry Commission access roads made it possible to build the structures by conventional methods, using ready-mix concrete.

Plate 3.1 Crump weir mainstream gauging structure in Monachyle. The stilling well is on the right and the water level logging equipment is housed above it. The weir is 5 m wide.

In addition to flow measurements at the main outfalls, it was agreed that a further structure should be installed on the Monachyle immediately above the area to be ploughed and planted in 1986. The catchment draining to this structure was intended to act as an overall control for the experiment during Phase II. An all-alloy design of a flat Vee weir was evolved for this site because of the need to fly materials to the site by helicopter. The Kirkton structures became operational in July 1982 and the main structure on the Monachyle in December of that year. The Monachyle low flow structure and the upper weir were finally completed and commissioned in summer 1983. The theoretically derived stage-discharge relationships for all the structures have been checked over a range of flow conditions using dilution gauging and current metering. The corrected measured stage-discharge relationships are used in this study. All water level data used in this study is quality-controlled by IH.

All five structures were equipped initially with the standard potentiometric water level recorders used by IH. These have a potential accuracy of +/- 1 mm throughout the flow range. Readings at 15 minute intervals are logged on Microdata cassette recorders. Starting levels for each tape are determined using a 'dipflash' device in which contact with the water surface in the stilling well closes a circuit. This is also potentially capable of an accuracy of +/- 1 mm. Ott paper chart recorders installed and operated by Forth River Purification Board as well as Fisher and Porter punch card recorders are used as backup on the main structures.

3.1.2 Suspended sediment outputs

Discharges past both gauging stations are sampled for suspended sediment by IH personnel using the following methods:

(i) depth-integrated manual sampling using a standard USDH-48 depth integrating sampler which consists of a glass bottle secured to the end of a wading rod with a standard brass inlet valve and exhaust valve. The glass bottle is contained in a steel weighted case. This sampler is most suitable where the stream depth is 0.1-1.0 m (which corresponds to the depth range normally found at the catchment outlets of the Monachyle and Kirkton) and there is the possibility that the suspended sediment load is not evenly mixed in the stream profile. In larger streams suspended sediment concentration can be higher nearer to the stream bed. Lowering the sampler vertically into the stream until it just touches the bed and then raising it back through the water profile collects a 'depth integrated' or average sample. In this way it is hoped to eliminate bias which might result from sampling at a fixed depth which may not sample suspended sediment concentrations representative of the vertical column. This so-called 'hand sampling' is supplemented by:

(ii) automatic sampling using ALS Mk 4 automatic pumping samplers. These time-lapse vacuum operated bottle samplers (manufactured by Automatic Liquid Samplers (ALS), England) pump 24 samples at a predetermined time interval ranging from 30 minutes to 8 hours. Water samples are taken from a fixed point intake located in the stream. In this study the sampling hose was roped onto the top of a concrete block which kept the inlet off the stream bed. The inlet was pointed downstream. By taking samples from a fixed point in the stream cross-section this sampling method does not have the advantage of collecting a depth integrated sample as the USDH-48 sampler does and could therefore be biased. However, it is felt that the turbulent flow conditions during floods (when most sediment is transported) causes suspended sediment to be well mixed in the stream vertical profile and so sampling at a point may not lead to serious bias. For times when the resident observer is not on site,sampling during flood events can be initiated by a float-operated electrical switch which is switched on as the stream level rises. The water/sediment mixture is pumped from the stream by the power supplied by a partial vacuum, produced in the bottles by means of a manually operated bicycle-type pump, and reinforced routinely every two weeks if the float switch had not been activated since the last visit. The quantity sampled in each bottle is a function of the suction head, the original level of vacuum produced, the time since the last evacuation and the length of tube (3 m in this case). The degree of attainable vacuum yields only a moderate pumping velocity, which in many cases may be lower than the fall velocity of medium and even fine sand particles in the vertical part of the intake pipe. The end of the inlet hose in the stream has a nozzle which allows only particles finer than 2.8 mm to pass through. Thus, for the purposes of this study 'suspended sediment' is defined as that fraction of the sediment load which is finer than 2.8 mm, i.e sampled by an ALS (see Table 3.1). The sampling method may therefore fail to sample some of the coarser particles transported in suspension and may be biased towards the finer size classes. Precaution is taken to clear out the sampling hose after each set of samples has been taken by blowing water out of the tubes which is left as part of the previous sample and could cause errors. Each bottle has it own intake tube so that cross-contamination between sampled is prevented. Sediment concentrations were determined by vacuum filtration through GF/C membranes which have a mean pore size of 1.2 μm.

Rating plots of suspended sediment concentration against discharge were constructed separately for autumn, winter, spring, and summer. The seasons correspond roughly to September-December, December-March, April-May, and May-August but were defined subjectively each year by IH's resident observer in the light of rainfall, air temperatures, and snow cover. Data are sparse in winter due to problems of icing and because floods are fewer.

Total outputs of sediment from each catchment in each season were computed by combining log-log rating curves of instantaneous load against discharge with the appropriate flow duration curve based on 15-minute streamflow data. There are some gaps in the winter streamflow record due to freezing but sediment transport is probably minimal at such times. Sediment rating curves were fitted to log-transformed data by ordinary least squares regression, then detransformed. Since this causes a systematic bias in the direction of underestimation (Ferguson 1986) the appropriate correction factor was applied to the estimated loads.

3.1.3 Bedload output

In the Plynlimon study of bedload yields from forest and grassland (Newson 1980b), concrete traps were used to obtain bulk sediment yields, information on sources and stores upstream coming from tracer experiments. However, at Balquhidder there was insufficient capital and labour to construct traps at the outset of the study; instead, careful monitoring of the build-up of bedload in the pools of the rectangular gauging weirs has given an approximate measure of bulk yield. The emphasis on bedload measurement at the outlets of Kirkton and Monachyle has passed to gauging instantaneous sediment movement by a modified Helley-Smith sampler seen in Plate 3.2. Originally a 3-inch (76 mm) orifice was used, as suggested by Helley and Smith (1971) and calibrated by Emmett (1980). At normal flood flows this proved adequate for the

Plate 3.2 Modified Helley-Smith sampler used by IH for bedload sampling in the mainstreams. The sampler is fixed to a wading rod and used from the bridges over the weirs as seen in Monachyle in Plate 3.1 (Photograph by M. D. Newson).

bedload in motion (D_{50} = 1.4 - 11 mm) but because of the coarseness of the bed material in these basins (D_{50} of flood deposits sampled by IH was found to be 64 mm) difficulties were anticipated with the field use of the original design of sampler and a modified sampler was constructed (Bathurst, Leeks and Newson 1985). This has a six-inch (152 mm) orifice but retains the expansion factor of the original design. Its 'box-kite' tail fin and wading rod suspension make it much more convenient for use by a single operator. Its trap efficiency is thought to be near 100% for the sizes of sediment usually transported past the gauging structures. Bedload samples are dried, sieved and weighed in the IH's Balquhidder laboratory. A single rating curve of load against discharge is fitted and then integrated over the flow duration curve in the same way as for suspended sediment. Loads are corrected according to Ferguson (1986).

3.1.4 Sediment accumulation in Monachyle delta

Some 3 km downstream of the Institute's Monachyle gauging station the mainstream ends in a delta seen in Plate 3.3 which divides Loch Voil and Loch Doine. According to the 1899 Bathymetric survey of the Freshwater lochs of Scotland by Murray and Pullar (1910), these two lochs once formed "at no very distant date a continuous loch, which has been divided into two portions principally by the deposition of material brought down Monachyle glen by the river". Previous studies have used volume measurements

Plate 3.3 View of Monachyle delta looking east down Loch Voil. Loch Doine is on the right.

of such lacustrine deltas to estimate sediment yields (Lambert 1982). In summer 1986 an investigation of the structure of this delta was conducted under the assumption that some or all of the delta is composed of sediment derived from Monachyle glen. The investigation was performed using a seismic refraction technique and work was carried out with Dr. Rob Duck of the Department of Geology, University of Dundee.

The technique utilises the fact that seismic waves travel at different velocities in different materials, depending upon their density or degree of consolidation and that the waves become refracted when they pass from material of one velocity to material of another. The instrument used to detect 'shock' or seismic waves was a portable Bison Signal Enhancement Seismograph. Shock waves are introduced to the ground using a sledge hammer to strike a metal plate. When the hammer strikes the plate a mercury switch on the hammer handle closes, sending a signal through a cable that triggers a timer in the seismic instrument which measures time intervals in milliseconds. When the seismic wave is received by the geophone (a metal spike placed in the ground at a known distance from the hammer plate and linked to the seismograph by an electronic cable), it stops the instrument and displays the vibration as a wave form on the oscilloscope of the seismograph. Four geophones were deployed simultaneously and were positioned at 2.5 m intervals from the sound wave source thus minimising the number of hammer blows necessary. One worker strikes the steel plate with the hammer while the other reads the instrument. Traverses of 30 m were made which corresponded to 12 readings along a traverse in each direction. The details underlying the principle of the technique and the advantages of the Bison model over other seismographs are fully discussed by Kesel (1976) and need not be repeated here. The technique made it possible to detect subsurface discontinuities and to estimate the depth of the layers detected.

Figure 3.2 is an example plot of distance from the geophone to the hammer station (m) versus the seismic travel time in milliseconds. After all stations are plotted, the velocity of the subsurface layers is calculated by drawing a straight line through as many points as possible. Velocity is estimated as the reciprocal of the slope. Where all the points fall along a single straight line, a uniform velocity is indicated which represents a layer within the depth range of the survey that consists of homogeneous material. When more than one distinct subsurface layer is detected the points form two or more straight lines from which the velocity for each of the layers can be estimated. Once a discontinuity has been established between the surface and the subsurface layers, the depths of the layers can be computed using the formula below for a two layered case:

$$D = X_c/2 \cdot \sqrt{(V_2 - V_1) / (V_2 + V_1)}$$

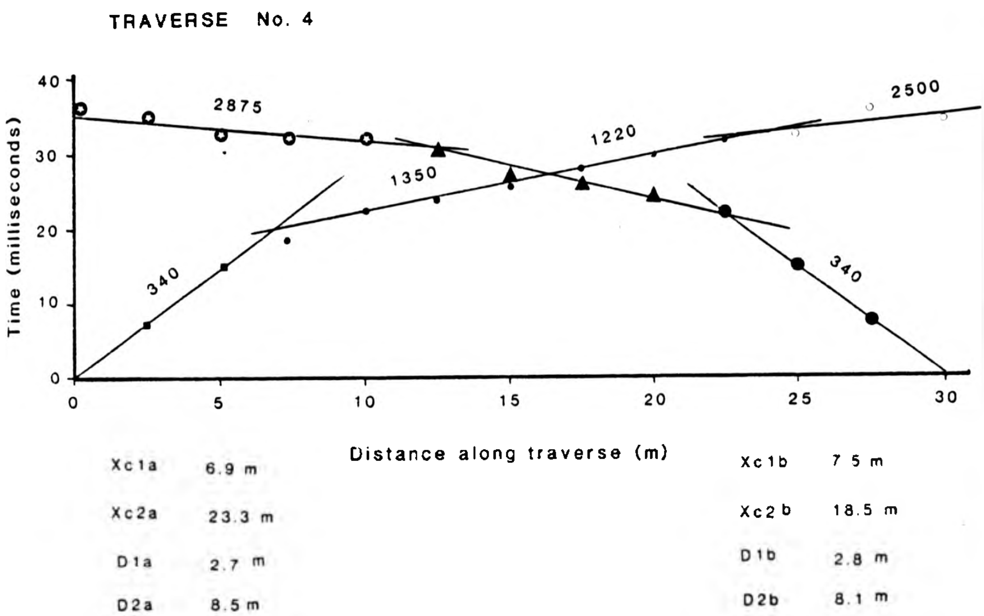


Figure 3.2: Example graph of seismic travel time to first sediment layer or discontinuity (milliseconds) v. distance from hammer for one traverse on Monachyle delta. All speeds on graph are in m s^{-1}. Xc is the critical distance and D is the depth (m) to the interface (see formula in text for calculations from velocities). All traverses were surveyed in both directions so that two estimates to the interfaces are made, one in each direction - 'a' beneath the graph on the left and 'b' on the right.

where D = depth to interface,

V_1 = velocity of upper layer,

V_2 = velocity of lower layer,

X_c = critical distance (see Figure 3.2)

Figure 3.3 shows the locations of the 30 m seismic traverses performed. The estimated depth to the first discontinuity for each end of the numbered traverses is given in Table 4.7 in the results section 4.3.

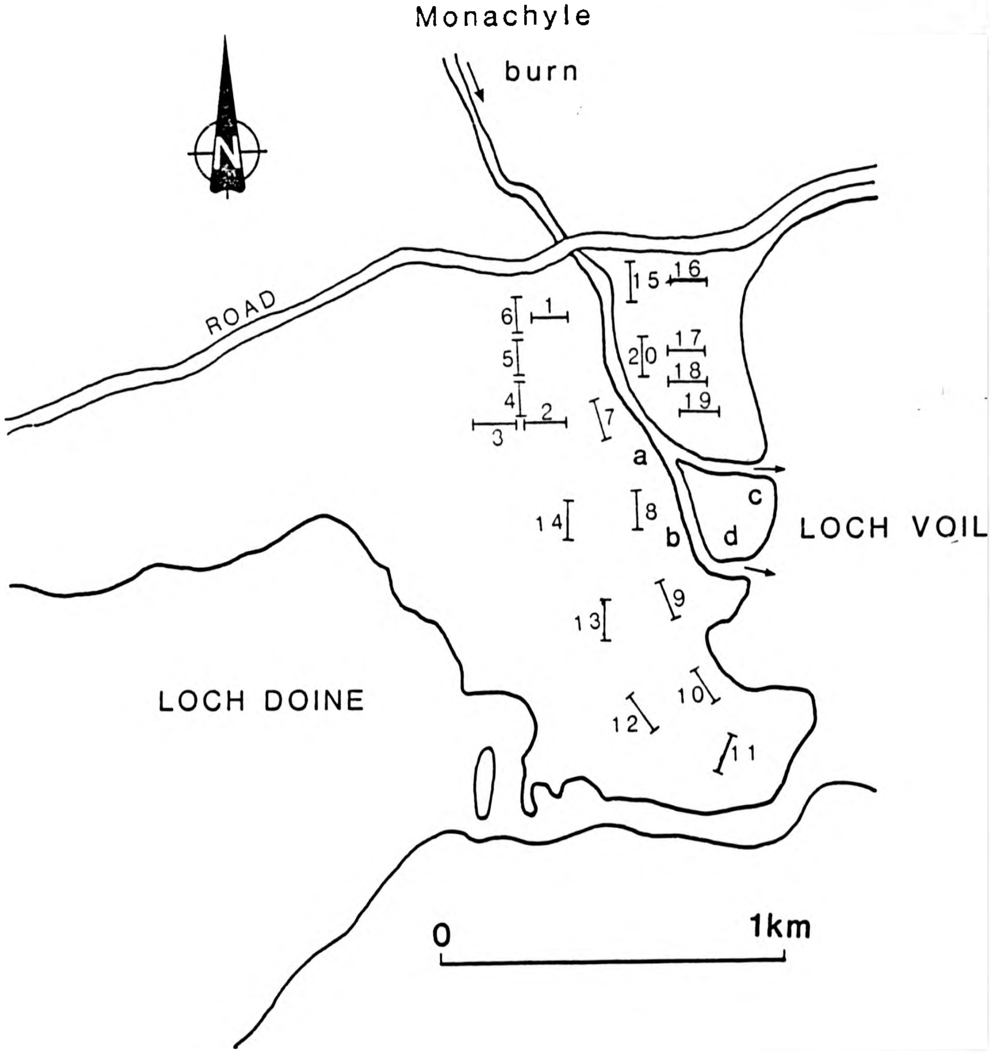


Figure 3.3: Plan of Monachyle delta showing the locations of seismic traverses made in the study. Points a and b are locations of bulk samples taken from the streambank, c and d are samples taken by auger (see text).

3.2 Tributary streams

3.2.1 Discharge measurement

Stage boards graduated in mm were installed in tributary streams in sections that appeared to be stable. No continuous water level recording devices were available for the first half of the study period and so rating curves relating tributary discharge (gauged by the salt dilution method during site visits) to mainstream crump weir discharge (logged at 15-minute intervals by IH) were constructed (see Table 5.1) and used to 'reconstruct' tributary water levels. Tributary discharge at a range of water levels was measured by the salt dilution gauging and corrected for stream temperature (see Appendix I). Log-log rating curves were plotted relating stage to discharge. An iterative process to minimise the standard error of the estimate and obtain the best fit correction factor to the stage board height was used for the latter part of the study period when pressure transducers were in use in tributaries M1 and K4.

On 7 May 1986 a pressure transducer stage recorder was installed in tributary M1 and a second was installed in K4 on 1 September 1986. These continuous water level recorders logged water levels at 10 minute intervals onto a Grant Squirrel solid state logger. The system was calibrated using a further rating relationship to convert millivolts (logged by the squirrel) to stage (mm). Since water level is logged to 8-bit resolution (1 part in 250) over a pressure range equivalent to 0-75 cm of water depth, it is estimated that the resolution of the pressure transducers in these streams is 3 mm. Data from the Squirrel loggers was drained into an Epson HX20 portable microcomputer (seen in use in Plate 3.4) weekly and this was used to obtain print-outs of water levels in the field and thereby check that instruments were functioning correctly. Back at the University water level data was then transferred through a BBC microcomputer linked to the University VAX mainframe by means of a special transfer computer programme. Data was then read into MINITAB (a statistical package) and converted from analog form to millivolts and then using rating relationships to convert millivolts to water levels and discharge.

3.2.2 Sediment size classification

The sediment size classification summarised in Table 3.1 was adopted for this study. It was derived in conjunction with IH and uses a combination of the standard boundaries (i.e. sieve sizes) as well as obvious boundaries imposed in the field sampling techniques such as the bedload trap netting mesh size and automatic suspended sediment sampler intake pipe diameter (both approximately 2.8 mm), Helley-Smith bedload sampler mesh size (0.25 mm), and ultimately the GF/C filter pore size (1.2 μm) bounds the lower limit of fine sediment measured. For the purposes of this study 2.8 mm was chosen as the boundary between suspended sediment and

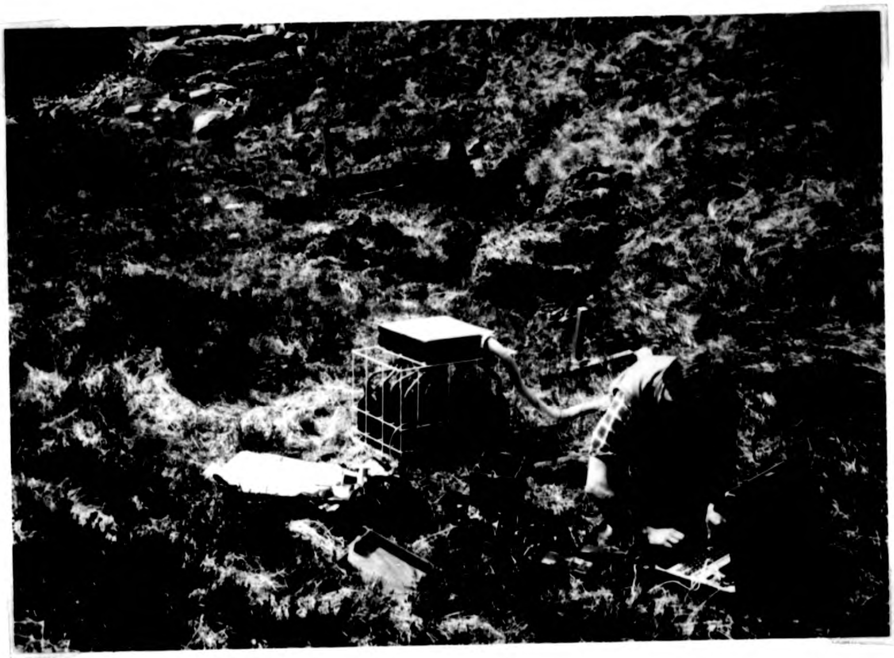


Plate 3.4 Author using Epson field computer for flow data retrieval at moorland tributary M1. Note the automatic liquid sampler and bedload trap in the background (taken by R.I. Ferguson).

Table 3.1: Sediment size classification used in this study

Phi	mm	Sieve boundary	Sediment type	
			Cobbles	
> -5.5	> 45	Pebbleometer board		
-5.0	32			
-4.5	22		Pebbles	
-4.0	16			
-3.5	11	,,		'Bedload'
-3.0	8.0			
-2.5	5.6		Gravel	
-2.0	4.0			
-1.5	2.8	Netlon mesh lining bedload traps and intake tubes on ALS		
-1.0	2.0			
-0.5	1.4			
0.0	1.0		Coarse Sand	
0.5	0.71			
1.0	0.50			
1.5	0.35			
2.0	0.25	Helley-Smith bedload sampler mesh size		'Suspended' sediment
2.5	0.18		Fine Sand	
3.0	0.13			
3.5	0.09			
< 4.0	< 0.063			
			Fine Sand	
	0.001	GF/C filters		

bedload (see section 5.2.1).

3.2.3 Suspended sediment

Some 1200 water samples taken from tributary streams were analysed for their suspended sediment content. The vast majority of these were sampled automatically during flood events by automatic liquid samplers (one is seen in the centre of Plate 3.4) as described for the catchment outlets in section 3.1.2. Samplers were activated by float switches which then sampled through flood events. The first sample was triggered at the time of resetting the sampler (usually low flow). After gaining some experience of flood durations in the tributaries, a 30 minute sampling interval was selected as the most appropriate for sampling both the rising and falling stages of flood hydrographs (see section 5.2.1).

Some samples were collected manually as 'hand' or 'dip' samples. This is a simple method of sampling the water/sediment mixture in small streams in which the suspended sediment is well mixed throughout the vertical profile of the stream. The method involves immersing a wide-necked plastic sample bottle (500 or 1000 ml capacity) into the stream facing upstream and removing it as soon as it becomes full with the water/sediment mixture. Many of the streams in the Balquhidder catchments are only a few centimeters deep (all tributaries flow through road culverts in the forested catchment) and so this method of sampling seemed to be adequate.

The suspended sediment content of water samples was determined gravimetrically by filtration through GF/C (1.2 μm) filters according to the standard method of the Department of Environment (1972) and the same method as used by IH for determining suspended sediment concentrations for samples taken at the catchment outlets. An estimate of the accuracy of this method was obtained by weighing the same filter 20 times on different occasions. The calculated standard deviation was 0.51 mg and so the weighing accuracy or standard error (S.E) determined:

$$S.E. = s/\sqrt{n} = 0.12 \text{ mg}$$

Any changes in filter weight which did not exceed this 0.12 mg error limit were not considered real and were therefore discarded.

3.2.4 Fine particulate organic matter

The fine particulate organic matter (FPOM) content of the stream sediment load in this study refers to any organic material which is likely to be sampled by automatic liquid samplers. Thus, FPOM may consist of pine needles through fragments of leaves, grass, moss to single flakes of peat. FPOM entering mountain streams clearly has very different properties from the inorganic sediment previously discussed. When subjected to the same hydraulic conditions it may be transported in a completely different manner. Organic matter is usually buoyant (pine needles have a waxy cuticle for example) and may float on the water surface and travel considerable distances before becoming waterlogged and sinking. The organic fraction of the stream load is of interest to stream ecologists and fish biologists (Egglishaw and Shackley 1971). Smith (1980) suggests that decomposition of organic material in forested upland streams may be very slow due to low temperatures and shading. However, increases in the amount of organic material entering afforested streams (particularly at times of thinning and clearfelling) which is slowly decomposed by bacteria can result in a reduction in the dissolved oxygen content of the water (Hall and Lantz 1969) and clearly may have implications for fish and stream ecology in general.

In this study the FPOM content of the sediment was estimated by reheating the GF/C filters at 550°C in a furnace for 15 minutes, cooling in a dessicator and reweighing. The organic matter content is taken as that fraction burnt off and is estimated from the change in weight:

$$\% \text{ Organic matter} = 100\ (W_1 - W_2)$$

where, W_1 is filter weight before burning,

W_2 is filter weight after burning.

3.2.5 <u>Bedload</u>

One of the simplest methods of measuring the sediment output of a small stream is to trap the total sediment yield (e.g. Hayward 1980). However, owing to the costly nature of installing and manning sediment traps in remote areas, much of our knowledge of sediment yields for the British uplands has come from *ad hoc* use of data collected by protective traps installed by Water Authorities upstream of stilling ponds, dredged channels or hydro-power intakes such as on the Allt a'Mhuillin on Ben Nevis (Richards and McCaig 1985), the Lake District (operated by Clayton 1951, bedload yields reported by Newson and Leeks 1985) and reservoirs in the Ochil Hills (McManus and Duck 1985). In Japan, Mitzuyama and Watanabe (1981) used sabo dams and reservoirs to estimate bedload yields in mountainous watersheds. With the exception of the weir pools reported in section 3.1 no impoundments were available for *ad hoc* use in tributaries and so simple check dams constructed from logs were used. A typical trap located on one of the larger moorland tributaries (M2) is seen in Plate 3.5. It is difficult to design a suitable trap because the design size required to contain the maximum sediment yield from a single flood event is not known. It is conceivable that a high proportion of the total annual yield could be delivered in just one storm event. Nevertheless, sediment traps constructed from logs were installed in tributary streams at suitable locations and lined with 'Netlon'. This is a plastic netting used in gardening with a 2.8 mm mesh size. Sediment

Plate 3.5 Moorland tributary bedload trap M2. The trap has just been excavated, the sediment piled in a cone on the right and a sub-sample taken from the cone for density and grainsize analysis in the laboratory (taken by R.I. Ferguson).

coarser than 2.8 mm was trapped with confidence and this was demonstrated in the laboratory by placing 2 mm and 2.8 mm sieved fractions on the netlon. Some of the 2 mm fraction fell through whereas all of the 2.8 mm fraction was retained.

The uncertainty about expected sediment yield per flood event affects the methods for detecting this value. The method used was to excavate all the sediment after each flood event where possible and in any case well before the trap filled up. The volume of sediment trapped was measured at the time of excavation by counting the number of 14 litre buckets. The excavated sediment was piled in a cone on a plastic sheet on the bank downstream of the trap (see Plate 3.5) and from this cone a subsample of 5-10 kg was brought back to the laboratory for analysis. Taking a bulk sample from a cone of sediment in this way ensures a more representative sample. After the sample had been taken the remainder of the cone of sediment was returned to the stream downstream of the sediment trap. In the laboratory samples were dried and their weight and volume measured and bulk density estimated. The samples were then sieved at half phi intervals and histograms and cumulative grainsize curves plotted using a FORTRAN computer routine. From these the proportion of trapped sediment finer than 2.8 mm (unknown trap efficiency) could be estimated and subtracted from the total mass of sediment trapped to leave bedload only.

3.2.6 Coarse sediment storage and pebble tracing experiments

As a result of the greater quantity of coarse organic material which enters stream channels in forested environments due either to forestry activities such as thinning or from natural decay and windthrow, streams flowing through forestry tend to become dammed by trees and branches which fall into the channel seldom travel more than a few meters before becoming jammed. Plate 3.6 shows a typical Balquhidder tributary with small organic debris in the channel. Plate 3.7 shows a larger organic debris jam on the Kirkton mainstream. The usual consequence is a build up of sediment behind this organic material which effectively becomes stored until the organic debris jam bursts. The length of time this takes will depend on the size and quality of the material causing the jam, its local position in the channel and the streamflow regime in terms of flood magnitude and frequency. Megahan (1982) finds that most debris jams in forested streams in central Idaho lasted about two years and that even log jams lost 97% of their sediment store in six years whereas Swanson, Janda and Dunne (1982) report that mean residence times of sediment in storage behind log jams are of the order of decades and even centuries. Nevertheless, organic debris jams will tend to increase sediment stored in streams flowing through forested environments and produce a 'stepped' stream profile, sometimes referred to as 'organic stepping' (Ashida et al. 1981, Heede 1972, Keller and Swanson

Plate 3.6 Small organic debris in Kirton tributary K8. Note the stepped nature of the channel.

Plate 3.7 Large organic debris jam in Kirkton mainstream behind which a considerable volume of sediment is stored.

1978, Whittaker and Davies 1982). Just how effective such debris jams are at trapping coarse sediment moving down the streams is unclear - do they simply fill up and then allow sediment to pass over on its course downstream? How much do they increase the sediment storage of a stream? Megahan (1982) working on forested streams in central Idaho finds that on average about 15 years of sediment yield is stored behind organic debris obstructions while Swanson et al.(1976) calculate that less than 5-10% of the sediment in storage is yielded annually. Clearly, moderate changes in the stored volume can account for large changes in the year to year sediment yield even if supply from hillslopes is constant. Conversely, accelerated yields from hillslopes may not show up in the outlet yield for some time. This channel sediment store could therefore act as a buffer which regulates extremes of sediment movement.

In an attempt to answer these questions concerning coarse sediment movements, storage and residence times in forested and moorland channels, two independent painted pebble tracer experiments were conducted. The first was July-October 1985 where approximately 130 pebbles from six size classes in the gravel and cobble size ranges (22 mm - >128 mm) were removed from the tributary beds of one moorland (M1) and one forest (K8) tributary which had similar gradients and discharges. They were all painted yellow and colour coded according to size class and then replaced into the same sites. The purpose of the experiment was to attempt to estimate average rates of movement and potential for storage of coarse sediment in the six most abundant size classes.

On the basis of the results of the first tracer experiment it was decided to conduct a second study, this time aimed as a more detailed investigation into coarse sediment routing. Again some 150 pebbles distributed evenly through six size classes spanning the gravel-pebble-cobble size range were selected from one moorland tributary (M1 upstream of the site used in the previous experiment) and one forested tributary (K8), painted yellow and numbered. The numbering meant that the progress of individual pebbles could be followed and related to streamflow characteristics and sediment stores. This second tracer experiment was conducted from September 1986 until April 1987.

Tape and clinometer surveys of the long profiles of some tributaries were performed noting the locations and approximate sediment store sizes behind debris jams (by measuring the area of the sediment stores and estimating the depth range). Debris jam frequencies were also estimated from these surveys and compared with other findings.

3.3 Mainstreams

3.3.1 Erosion pins

Studies elsewhere have shown that channel banks can be a significant source of sediment in the catchment system (e.g. Coldwell 1957, Dietrich and Dunne 1978) and numerous previous studies (e.g. Wolman 1954, Cummins and Potter 1972, Hill 1973, Lewin and Brindle 1977, McGreal and Gardiner 1977, Hooke 1979, Hooke 1980, Murgatroyd and Turnan 1983 and Lawler 1986) have successfully employed erosion pins to measure channel bank erosion. In this study erosion pins were installed in the mainstream channel banks in both catchments with the aims of measuring bank erosion rates and most importantly, estimating the contribution of channel bank sediment to the overall sediment budget. This involved estimating both the area of channel bank undergoing erosion and the average bulk density of bank sediment in order to estimate the quantity of sediment removed. Erosion pins used for this purpose are seen installed in a typical bank in Plate 3.8 and were made from 5 mm galvanized fencing wire and differ from the traditional 'nail and washer' type proposed by Leopold, Emmett and Myrick (1966) and used elsewhere (e.g. Lewin, Cryer and Grimshaw 1974, Harvey 1974). The fencing wire was cut into 30 - 50 cm lengths, bent at right angles at one end and pointed at the other. This design could be produced in large numbers cheaply and was installed in streambanks by

Plate 3.8 Measuring erosion pins in a Monachyle mainstream bank. The pins are arranged in a vertical line with 10 cm spacing and were spaced at 50 m interval along the entire mainstream in each catchment.

pushing it in perpendicular to the eroding surface thereby causing less disturbance to the bank material than by hammering in larger metal pins. Haigh (1977) and Lawler (1978) have adequately discussed the problems and errors associated with the use of erosion pins and suggest cautionary notes for their use in measuring bank erosion rates. In this study a large number of pins were installed to attempt to sample the spatial variability of erosion rather than to gain a detailed insight into temporal variations as studied elsewhere (e.g. Hooke 1980, Lawler 1986).

A systematic sampling design was chosen in an attempt to obtain adequate spatial representation of erosion along the entire length of the mainstream channel banks (5 km in the moorland stream and 2.2 km in the forest). Pins were installed in verticals approximately 50 m apart on the bank which showed most evidence of erosion or potential for erosion (e.g. on the outside of a meander bend rather than inside). At each site pins were installed in the bank at 10 cm intervals starting from the top of the bank so that variable numbers of pins were used in each vertical according to the height of the bank. The verticals allowed differences in erosion rates at the top and bottom of the banks to be detected. The protrusion of the pins was measured at the time of setting (September 1984) and at 3 monthly intervals for two years (9 surveys in all).

3.3.2 Mainstream scour and fill

Twenty seven channel cross sections were levelled and resurveyed on six occasions over the 30 month period October 1984 - April 1987. Twenty three of these were in the meandering alluvial lower section of the Monachyle mainstream and their locations are marked on the plan of the lower Monachyle mainstream Figure 3.4. Four other cross sections were levelled and resurveyed in a braided gravelly reach of the Kirkton mainstream which was easily accessible and not planted with too many trees so as to make surveying difficult. For the purpose of estimating any scour or fill of coarse sediment across the sections only levelling within the gravel bed of the channel was considered. All height measurements were read to the nearest centimetre and corrected to a fixed baseline and then the data was run through a simple FORTRAN computer program which calculated the area under the fixed baseline for each cross section over each survey period. Increases in area corresponded to net scour whereas decreases meant net deposition. Changes in mean bed elevation (mm) were then calculated as,

$$100.(\text{change in area } (m^2) \ / \ \text{channel bed width } (m)).$$

In order to gain some idea of the errors involved in this method of detecting changes in mean bed elevation a single typical cross section (16 m wide) was relevelled at one metre intervals

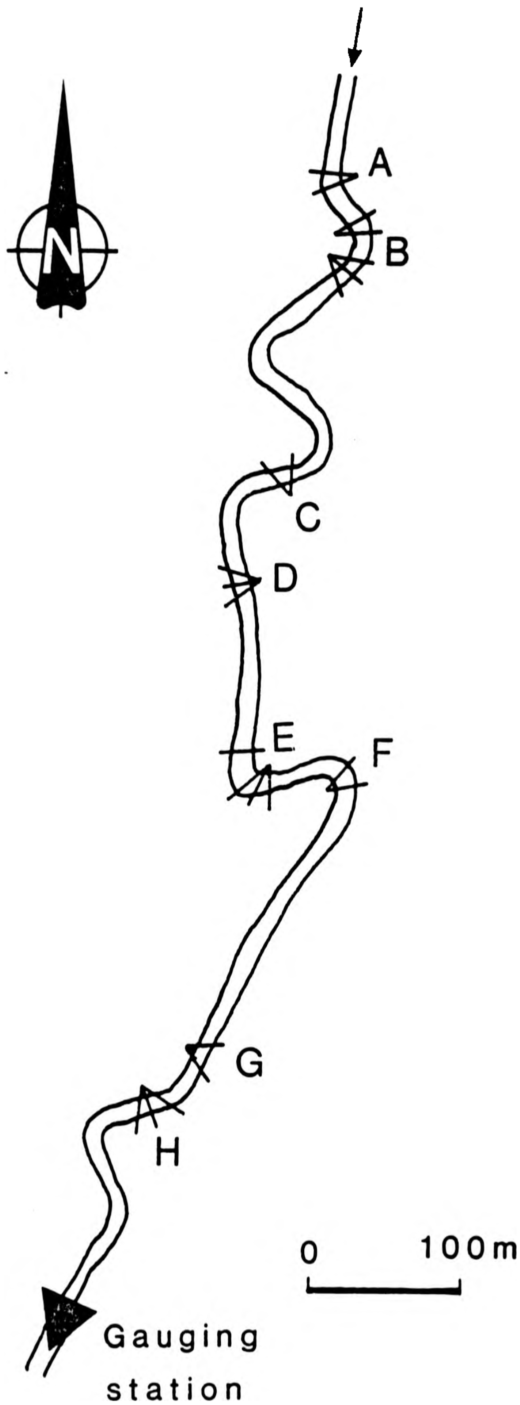


Figure 3.4: Plan of the lower Monachyle mainstream showing the locations of cross sections which were resurveyed.

eight times on the same occasion by two different staffmen. From this exercise the standard deviation (s) of one mean bed height was found to be 0.0083 m. Thus, standard error (se) for a change in mean bed height (2 surveys) is 0.0083 . $\sqrt{2}$ = 0.0117 m (or ~ 12 mm).

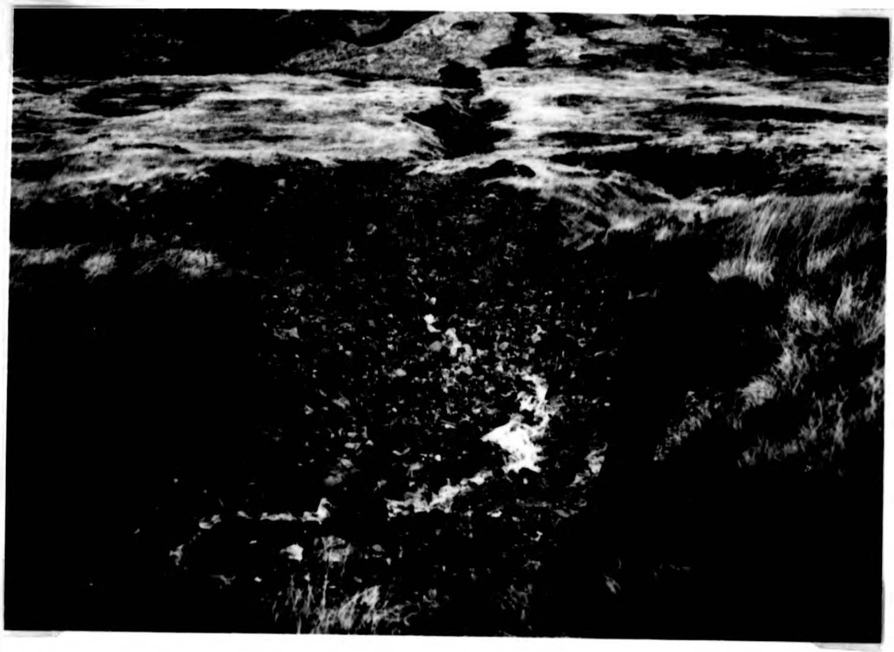
A simple test of how the levelling interval (normally 0.5 - 1.0 m) affected the area calculation was performed on a fictitious cross section by calculating the area on four occasions inputting height readings at 0.5, 1.0, 2.0 and finally 3.0 m intervals to the area calculation program. The results showed that the four areas calculated using the four different input intervals varied by only 0.3 %. It is concluded that recording height readings at between 0.5 and 3.0 m intervals would not significantly affect the calculation of cross section area below a fixed baseline. In practice the sections were levelled at varying intervals between 0.1 and 3.0 m depending on the nature of the bed.

3.4 Hillslopes

The moorland catchment has a vegetation cover of heather, grasses, bracken and mosses. The upper part of the forested catchment is similar, and the forest floor is well covered by conifer needles or, in clearings, grasses and mosses. Sediment transport by overland flow is thought to be negligible and no attempt was made to measure it. Vegetated scars of old landslides were apparent in both catchments at the start of the study, and following intense rainfall in mid-September 1985 material from a slope failure travelled some 500 m down one side of the moorland catchment into the mainstream where a cone of coarse sediment was deposited. The approximate volume of this cone was measured and a bulk sample taken to estimate its bulk density and grainsize distribution. Plate 3.9 (a) shows the slope failure scar and 3.9 (b) shows the cone of coarse sediment which accumulated where the tributary gully entered the mainstream.

Soil creep is a well documented geomorphic process. Bowen et al. (1978) report annual rates for creep ranging from between 9 mm on bare slopes to less than 1 mm on grassed ones. No mention of the effect of slope is made here but logically creep rates will be higher on steeper slopes. However, in this study it is presumed that sediment removed by bank erosion is replenished by hillslope creep processes. Perhaps bank erosion may then be an indicator of the rate of soil creep. Although bank erosion rate in the

(a)



(b)

Plate 3.9 (a) Scar left from slope failure in Monachyle. The view is downslope and the Monachyle mainstrean can be seen some 500 m below (top left). An estimated 65 t of material was removed from this scar on the 17 September 1985 during prolonged rainfall at the end of an exceptionally wet summer.

Plate 3.9 (b) Cone of sediment containing an estimated 14 t of coarse sediment deposited in the mainstream which took about 18 months to be removed.

tributaries was not measured directly (as along the mainstreams), the tributary sediment yields were measured as an indirect measure of sediment supplied by channel banks. Section 7.2 demonstrates that by applying measured bank erosion rates to estimated tributary channel bank area the total catchment sediment yield in the Phase I can be explained as coming from this source. It must be creep processes that supply this sediment if we assume that channel bed erosion is not significant.

CHAPTER 4: SEDIMENT OUTPUT RESULTS

4.1 Institute of Hydrology Monitoring

The Institute of Hydrology has monitored both streamflow and sediment leaving both catchments since 1982. Table 4.1 below summarises the streamflow characteristics for each catchment outlet.

Table 4.1: Summary streamflow data ($m^3 s^{-1}$) for IH main weirs, 1983-85.

Year	Q_{mean}	Q_{max}	Q_{min}
Kirkton (6.85 km^2)			
1983	0.37	11.36	0.02
1984	0.39	8.79	0.03
1985	0.43	8.22	0.06
Monachyle (7.7 km^2)			
1983	0.51	14.27	0.01
1984	0.50	15.19	0.01
1985	0.53	16.25	0.02

4.1.1 Suspended sediment

Some 326 and 335 samples were collected by IH (using the method described in section 3.1.2) at the Monachyle and Kirkton catchment outlets respectively in Phase I (1982-5) of the experiment. All samples were analysed for their suspended sediment content and concentrations (mg l^{-1}) were assigned discharge values

(m^3 s^{-1}) estimated from the stage at the time of sampling. All data was logarithmically transformed and suspended sediment rating curves produced. The first estimate of annual sediment yield was made by dividing the data set according to season (as described in section 3.1.2) and applying the seasonal ratings to the appropriate portion of the flow duration record. The second estimate was made by combining a single rating curve for all data with the flow duration records. The rating equations used are presented in Table 4.2. The loads estimated by this method were then corrected for logarithmic detransformation bias (Ferguson 1986). The estimated seasonal and total loads and average Phase I yields of suspended sediment from the two catchments are given in Table 4.3, with and without correction for logarithmic detransformation bias in the rating curves.

Clearly most suspended sediment is yielded in autumn with summer surprisingly showing the next highest yields with spring and winter having the lowest yields. It must be born in mind that spring, for the purposes of these estimates, is only April and half of May, whereas the other seasons are at least three-months. Autumn is four months (see section 3.1.2). Rating curves are for individual seasons and for when the seasons are pooled, as in Figure 4.1, the steeper trend and smaller scatter in the Kirkton rating indicate a more sensitive link between streamflow and suspended sediment load. This can be explained by a greater availability of sediment within the plantation forest. This would confirm the Plynlimon findings (see Table 1.1) and those of the source area studies of this thesis (see Chapter 5). It seems that

Table 4.2: **Seasonal and annual rating curves for Monachyle and Kirkton catchment suspended sediment concentration on discharge for Phase I of the Balquhidder experiment (1982-5).**

	Monachyle (moorland)					Kirkton (forest)				
Season	n	a	b	r	s	n	a	b	r	s
Winter	93	0.890	0.344	.26	.41	20	1.210	0.537	.11	.35
Spring	16	0.849	0.184	.09	.71	36	1.070	2.050	.27	.66
Summer	41	0.357	0.825	.26	.52	58	0.818	0.813	.11	.66
Autumn	176	0.850	0.530	.12	.53	221	0.934	1.380	.68	.41
All	326	0.837	0.375	.13	.53	335	0.934	1.350	.57	.50

Key: n = sample size, a = intercept constant and b = slope in $\log_{10} C = a + b \log_{10} Q$, where C = suspended sediment concentration in mg l^{-1} and Q = discharge in $m^3 s^{-1}$, r = correlation coefficient and s.e = standard error of estimate.

Table 4.3: **Phase I (1982-5) suspended sediment loads and yields for the Balquhidder catchments.**

	Monachyle (moorland)			Kirkton (forest)		
1985 Season	Load (t)	Correction factor	Corrected load (t)	Load (t)	Correction factor	Corrected load (t)
Winter	16	1.56	25	20	1.38	28
Spring	8	3.80	30	10.5	3.17	33
Summer	21	2.04	43	28.5	3.17	90
Autumn	94	2.12	199	141	1.56	220
Total	139		297	200		371
All data	138	2.12	293	187	1.94	366
1982-5 Average Yield ($t\ km^{-2}\ yr^{-1}$)	18		38	28		54

Note: the seasonal division is for 1985 only, other estimates are averages for the three years (1982-5).

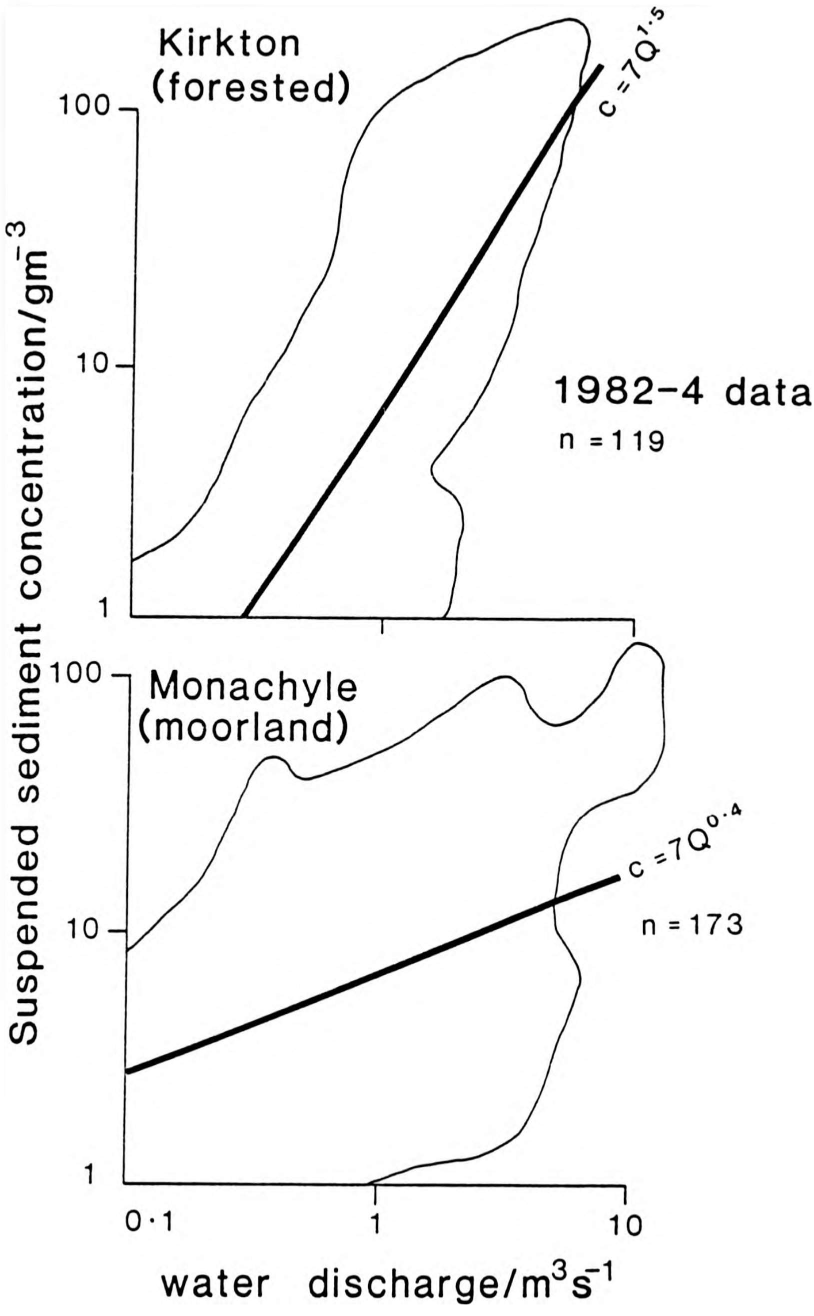


Figure 4.1: Log-log suspended sediment vs. discharge rating curves for Phase I Balquhidder catchment outputs with data envelopes.

fine sediment in forest ditches and organic debris jams is flushed out by high flows so that there is less scatter in the relationship between load and flow and a steeper growth of load with rising flow than in the moorland catchment where there are fewer obvious sources of fine sediment.

The totals are equivalent to uncorrected sediment yields of 18 t $km^{-2}yr^{-1}$ from the moorland catchment and 28 t $km^{-2}yr^{-1}$ from the forest catchment, or corrected yields (corrected according to Ferguson 1986) of 38 and 54 t $km^{-2}yr^{-1}$ respectively.

4.1.2 Bedload.

Bedload transport past the weirs was sampled using the modified Helley-Smith bedload sampler described in section 3.1.3. Samples were dried and weighed and a discharge value assigned. Data were logarithmically transformed as for the suspended sediment and since there were not as many samples as for suspended sediment (about 150 in all) a single bedload rating curve was developed for each year and was applied to the annual flow duration record. The estimates were again corrected for logarithmic detransformation bias according to Ferguson (1986) and the estimates for each year (1983-5) and the Phase I average loads and yields are presented in Table 4.4. The corrected estimates of total 1982-5 outputs are 2.5 tonnes for the Monachyle catchment and 10.8 tonnes for Kirkton, corresponding to yields of 0.3 and 1.6 t $km^{-2}yr^{-1}$ when corrected for detransformation bias. These totals are consistent with observations of infill of the gauging station weir pools. The forested catchment appears to have a much larger yield of bedload, but in each catchment bedload makes up no more than 3% of total

Table 4.4: Balquhidder catchments Phase I (1982-5) bedload yields estimated from IH Helley-Smith sampling of bedload transport past the weirs. All loads estimated from rating curves and are corrected for logarithmic detransformation bias (Ferguson 1986) and are expressed in t yr^{-1}. Yields are in t km^{-2} yr^{-1}.

Year	Monachyle (moorland)	Kirkton (forest)
1983	4.464	20.988
1984	*	3.752
1985	0.576	7.518
Average	2.520	10.752
Yield	0.3	1.6

* = no data available from IH (November 1987).

sediment output.

4.2 Preliminary effects of disturbance

At the time of writing only a preliminary analysis of the post-disturbance suspended sediment output data collected by IH can be presented. Data collection and analysis are still being undertaken by IH catchment resident observer Mr. Dick Johnson who is currently preparing an M.Sc thesis concerned with the catchment sediment outputs throughout the whole of the experimental period and this thesis will be presented to the Department of Environmental Science, University of Stirling in the future. Clearly, this will be based on more data than are available at present and should contain a far more comprehensive analysis than is possible at the time of writing. However, some preliminary analysis has been carried out by the author on the data supplied by Mr. Johnson at this early stage.

No bedload data are available for Phase II (1986 onwards) but since the Phase I results show that bedload only accounts for less than 3% of the total catchment sediment output any changes in bedload yields resulting from the land use changes are not likely to have a drastic effect on the overall sediment yield. It is the suspended part of the load which is clearly more important.

4.2.1 Ploughing and ditching in Monachyle

Ploughing in the Monachyle catchment took place in March - May 1986 and was followed by drainage ditching in June and July of that year (see section 2.5.1). At this stage it is useful where presenting results to include the Phase I results alongside for immediate comparison.

The maximum sampled suspended sediment concentration in Phase II so far is double that sampled in Phase I. Figures 4.2 (a) and (b) are rating plots of concentration (mg l^{-1}) vs. discharge (m^3s^{-1}) for the pre- and post-disturbance periods respectively. The Phase II rating curve is parallel to the Phase I rating but higher up the concentration axis. Statistical tests on the slopes of the curves showed that they were not significantly different at the 0.05 probability level whereas tests on the intercepts showed that they were significantly different at the 0.05 probability level, i.e. there is less than a 5% chance that the slopes of the rating curves are different and less than a 5% probability that the upward shift in the rating could occur by chance. Thus, there has been a real parallel shift upwards.

Unfortunately the continuous streamflow data for 1986 were not checked for either catchment at the time of writing and so actual 1986 sediment loads can not be calculated. However, in the absence of the 1986 streamflow it is possible to get an approximate idea of how the new Phase II rating curve translates into total catchment suspended sediment yield by applying both rating curves to the 1984 and 1985 continuous streamflow records for comparison. The results of applying a single rating curve to the 1984 and 1985 flow duration records are presented in Table 4.5 where they are referred to as 'Phase II equivalents'. Both raw and corrected estimates are given with figures corrected for logarithmic detransformation bias shown in brackets. From tables produced by Ferguson (1987) based on sample size, scatter and slope of the rating curve, it is possible to estimate that the sediment

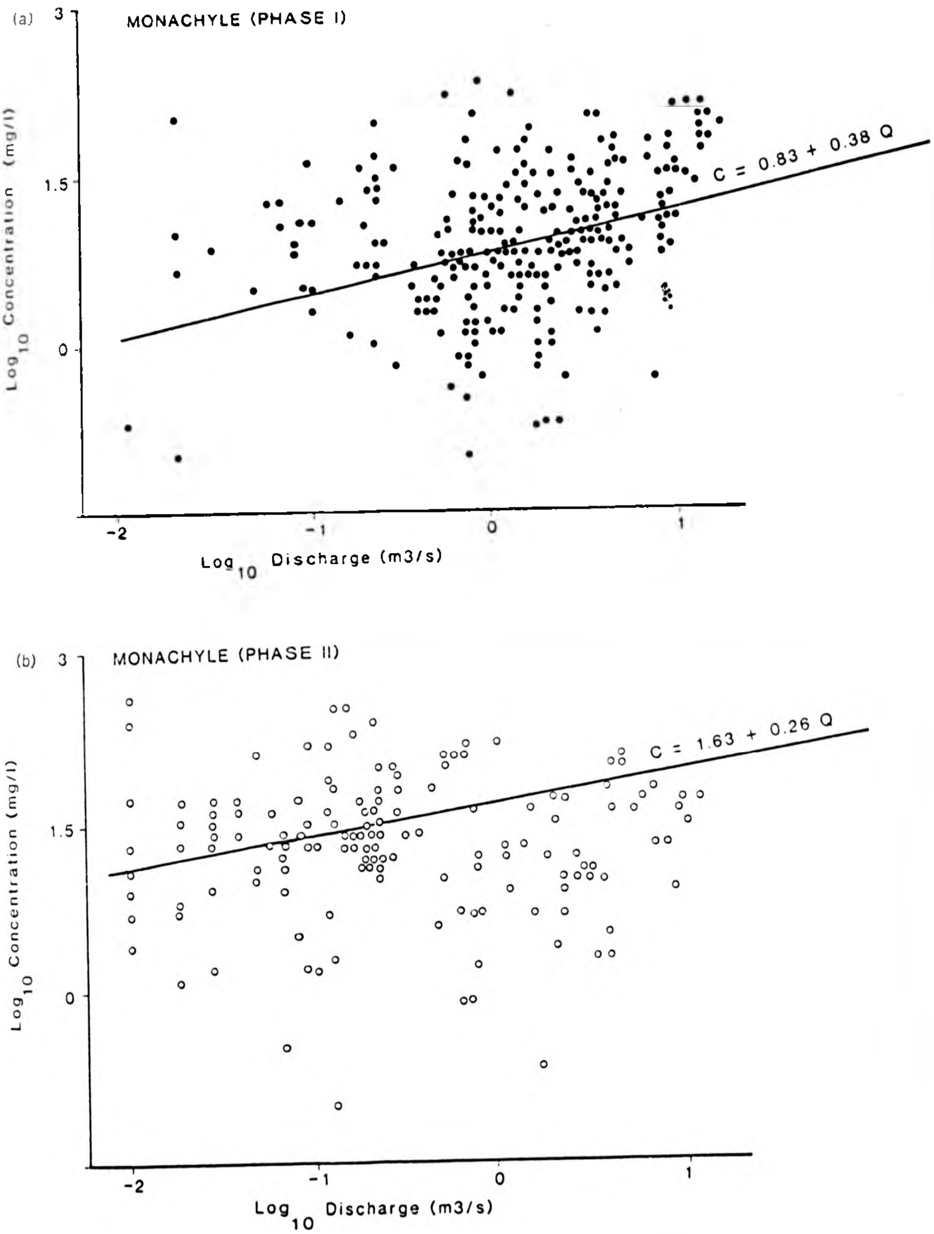


Figure 4.2: Monachyle catchment output log-log suspended sediment vs. discharge rating plots, (a) Phase I, (b) Phase II (preliminary). Least squares fitted rating curves are drawn in with the rating equation. Institute of Hydrology data.

loads calculated from these rating curves should be prone to errors of no more than +/- 20% of the true load in both the pre and post-disturbance phases.

Table 4.5: Suspended sediment load and yield estimates for Monachyle catchment before (1982-5) and after (1986-7) ploughing and ditching of the catchment. All bracketed figures are corrected for logarithmic detransformation bias (Ferguson 1986). Phase II estimates are for the single rating curve applied to the Phase I flow duration records and are referred to as 'equivalent loads', corrected in the usual way.

Year	Phase I (1982-5) actual loads		Phase II (1986-7) equivalent loads	
	t	$t\ km^{-2}$	t	$t\ km^{-2}$
1983	134 (284)	17 (36)	728 (1497)	95 (194)
1984	132 (279)	17 (36)	717 (1475)	93 (192)
1985	147 (311)	19 (40)	798 (1641)	104 (213)
Average	138 (293)	18 (38)	748 (982)	97 (200)

It appears that the ploughing and draining operations carried out in 1986 have caused suspended sediment outputs to increase by a factor of 3.4 i.e ploughing and ditching seem to have caused a trebling of suspended sediment output. This type of increase seems to be consistent with the findings of other British studies (e.g. Francis 1987, Robinson 1978 and Burt et al. 1984). Table 1.1 in Chapter 1 summarised these findings.

4.2.2 Clearfelling in Kirkton glen

Clearfelling in the Kirkton glen catchment began in January 1986 on the west side. Some 30-40% of the forest, all on the west side of the catchment (see Figure 2.5) had been felled by the end of the study period in May 1987. The clearfelling has been accompanied by extensive road regrading, local road straightening and repairs and construction of timber stacking areas (see section 2.5.2).

The highest sampled suspended sediment concentration in Phase II so far is almost an order of magnitude higher than in Phase I. Figures 4.3 (a) and (b) are the logarithmically transformed concentration vs. discharge rating plots for Phase I and Phase II. The Phase II curve again shows an upwards shift, but this time not a parallel one as in the case of the moorland. Statistical testing showed that the slopes and intercepts of the rating curves are significantly different at the 5% level confirming that there has been a real upward and non parallel shift in the rating. When the ratings are applied to the 1983-5 streamflow record the estimated catchment suspended sediment yields are shown in Table 4.6. As for the Monachyle yields, estimates for the kind of errors to expect are obtained from Ferguson's (1987) tables as reported for the moorland rating curve estimates. Again, the loads presented can be expected to be within +/- 20% of the true load.

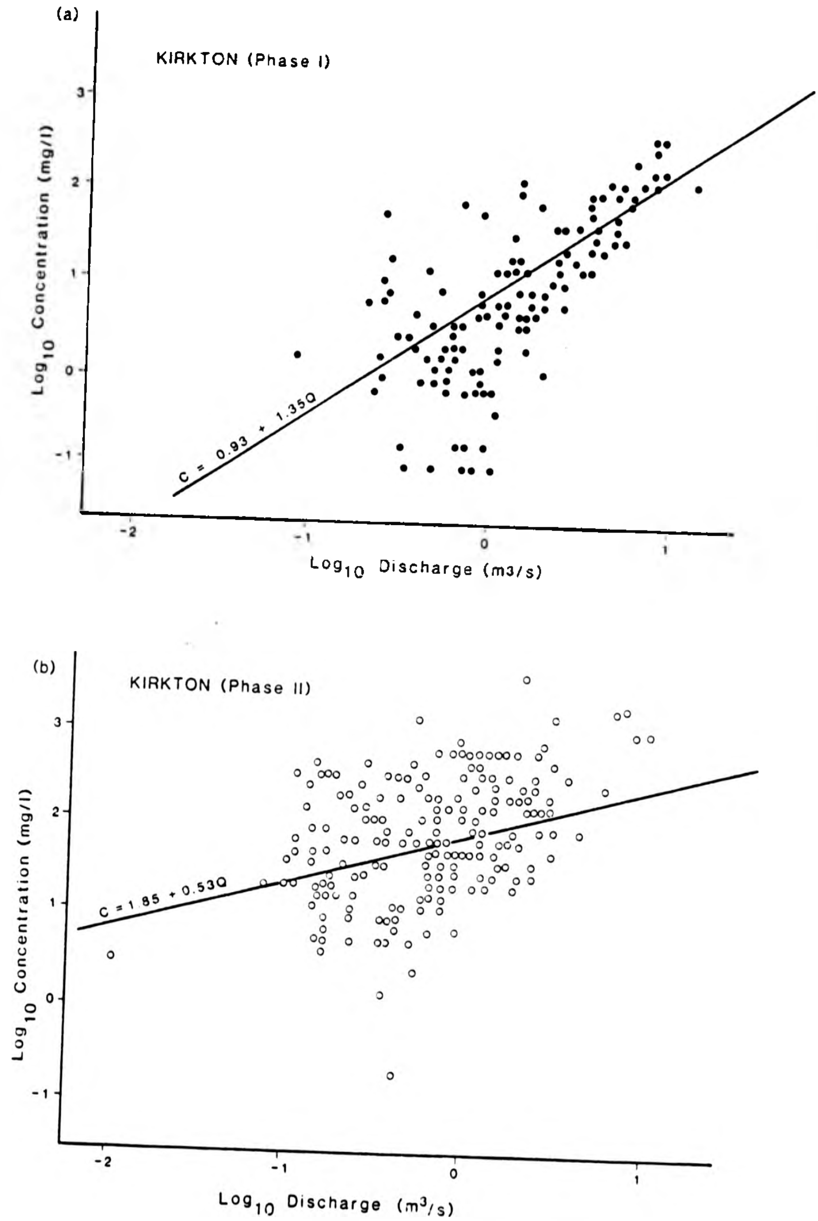


Figure 4.3: Kirkton catchment output log-log suspended sediment vs. discharge rating plots, (a) Phase I, (b) Phase II (preliminary). Least squares fitted rating curves are drawn in with the rating equation. Institute of Hydrology data.

Table 4.6: Suspended sediment load and yield estimates for Kirkton catchment before (1982-5) and after (1986-7) the start of clearfelling and associated activities. Figures in brackets are corrected for logarithmic detransformation bias (Ferguson 1986) and Phase II loads are estimated by applying the single rating curve seen in 4.3 to the Phase I flow duration record, corrected in the usual way.

Year	Phase I (1982-5) actual loads		Phase II (1986-7) equivalent loads	
	t	$t\ km^{-2}$	t	$t\ km^{-2}$
1983	197 (382)	29 (56)	838 (2366)	122 (345)
1984	163 (316)	24 (46)	833 (2352)	122 (343)
1985	206 (400)	30 (58)	957 (2702)	140 (394)
Average	187 (366)	28 (54)	876 (2473)	128 (361)

These preliminary yields of suspended sediment appear to show a dramatic increase by a factor of 6.7 in the Phase II period so far. Although these figures are preliminary they nevertheless form some of the first British data on the effects of clearfelling operations.

However, owing to the recent aquisition of the Phase II data by the author it has only been possible to make first approximations of the suspended sediment yield increases for the first part of Phase II. More work needs to be done by way of sub-dividing the ratings for season at least, and perhaps even into smaller time periods since it is to be expected that the rating relationship is and has been changing constantly since the start of the forestry 'disturbance' operations. This sub-division of the data should help to reduce the scatter about any one rating relationship (currently se= 0.63 and 0.52 in Kirkton and Monachyle respectively !). One danger inherent in using a single rating relationship as done here is that if, for example, some particularly high sediment concentrations are sampled either during or soon after a particular disturbance operation such as ditching, but that concentrations at that particular discharge are never as high again, then it is conceivable that an 'artificially' upward shifted rating curve dominated by the early high concentrations is applied to the whole year, instead of just a few weeks perhaps, of the flow duration record. Without a detailed analysis of the times of sampling (with respect to such factors as the timing of the disturbance operations) which was not possible at the time of writing, it will not be possible to detect this type of effect.

Nevertheless, what <u>is</u> clear even at this early stage, is that <u>there have been considerable increases in the production of fine sediment from both catchments in the first part of the post-disturbance phase of the experiment</u>. However, it must be stressed again that the Phase II yield estimates are strictly <u>provisional</u> at the time of writing and are not likely to be as reliable as the Phase I estimates for the reasons given above. Therefore, any quotations or use of these figures outside of this thesis should qualify this uncertainty beforehand, at least until more data have been collected and further analysis has been carried out.

4.3 Results of Monachyle delta investigation

The objective of this particular part of the research was to use a completely different approach to attempt to produce a second, independent estimate of the sediment yield of Monachyle glen by carrying out an analysis of a lacustrine delta. The degree to which this was successful is described.

Figure 3.3 shows the locations of the 30 m seismic traverses performed and the estimated depth to the first discontinuity at each end of the traverse is given in Table 4.7. In a number of cases the velocity of the lowest (third) layer indicated that it was bedrock. The mean depth of sediment estimated by this method was found to be 2.2 m.

The total catchment area draining to the delta is 17.2 km^2 (digitised from 1:50 000 O.S sheet 57). The upper 7.7 km^2 of this has an estimated present suspended sediment yield of 38 t km^{-2} yr^{-1} and bedload yield of 0.3 t km^{-2} yr^{-1}. Making the assumption that this yield applies to the whole catchment and also that the contemporary sediment yield has operated since the termination of the Loch Lomond stadial of the last glaciation ($\sim 10^4$ years ago) it is possible to make an estimate of the mass of sediment which would be deposited in Lochs Voil and Doine and the delta assuming a 100% trap efficiency (not unreasonable since the loch outlet is 6 km from the delta):

Total sediment output = catchment area x measured sediment yield x number of years accumulation

Table 4.7: Depths in m to first sediment discontinuity for traverses on Monachyle delta estimated by seismic refraction.

Traverse number	North end	South end	East end	West end
1			2.1	2.8
2			3.5	2.5
3			2.5	3.0
4	2.8	2.7		
5	2.4	3.2		
6	0.8	2.4		
7	3.3	2.6		
8	2.6	2.2		
9	1.8	1.6		
10	2.9	1.1		
11	2.5	1.8		
12	2.3	1.7		
13	2.1	1.9		
14	2.0	2.0		
15	1.8	1.0		
16			2.3	2.7
17			2.2	2.2
18			1.8	0.8
19			0.8	1.8
20	2.2	2.1		

Mean depth = 2.2 m (n = 40, sd = 0.6)

$= 17 \times 38 \times 10^4$

$\sim \underline{7 \times 10^6 t}$

From the seismic refraction work a discontinuity between layers of sediment was detected at depths ranging from 0.8 to 2.9 m with a mean depth of 2.2 m (n=40, s.e=0.1), see Figure 3.3 and Table 4.7. Without the availability of augering equipment to take sediment cores we assume that this discontinuity represents a boundary between glacially deposited till and fluvially deposited sediments from Monachyle glen as suggested by the velocities measured by seismic refraction. The possibility of this discontinuity being the water table was discarded since the difference between the height of the loch surface and the delta surface is less than 2.2 m. The surface area of the delta estimated from the 1: 10 560 scale O.S map (surveyed in 1863, second edition 1901) is 85 400 m^2. Assuming that the average depth of fluvially deposited sediment is 2.2 m over the whole delta then the volume is the product of the area and average depth. The average bulk density of sediment accumulating in bedload traps in the upper part of the Monachyle catchment has been estimated as 1.37 t m^{-3}. However, it is reasonable to suppose that sediment accumulating in a delta such as this will become compacted over time and therefore have a higher average bulk density. Reid and Frostick (1986) use an average bulk density of 1.6 t m^{-3} for similar deltaic calculations on a delta in northern Kenya. This value seems more reasonable and so using this estimated density a crude estimate of the sediment mass can be made:

Mass of sediment on delta surface = area x depth x density

$$= 85\,400 \times 2.2 \times 1.6$$

$$\sim \underline{0.30 \times 10^6 t}$$

This represents a sediment yield of almost 2 t km^{-2} yr^{-1} from the whole of Monachyle glen averaged since the last ice retreat ($\sim 10^4$ years) and therefore only accounts for about 5% of the contemporary sediment yield. This represents approximately 460 years of sediment accumulation at the present rate of production of sediment from the gauged catchment in the upper part of the glen.

If alternatively we assume that the whole of the delta is composed of sediment derived from Monachyle glen since the last ice retreat, a simple calculation of the whole delta volume can be made: the maximum depth of lochs Voil and Doine as surveyed by Murray and Pullar (1910) near the delta is 15 m (converted from feet). A method of predicting delta profiles has been derived (Matyas 1984), but for the purposes of a first approximation a slope angle of 30° is assumed from the surface of the delta to the deepest point in the loch either side. In this way the volume of the delta cone was estimated as 1.29×10^6 m^3 which represents 2.06×10^6 t of sediment (using an average sediment density of 1.6 t m^{-3} as before). This corresponds to a sediment yield of about 12 t km^{-2} yr^{-1} when averaged over the last 10^4 years or about 30% of the present sediment yield and would represent around 3000 years accumulation at the present rate of sediment production from the catchment in the upper part of the glen.

These estimates are very approximate indeed but nevertheless it seems that measured contemporary sediment yields in the upper part of Monachyle glen do not match estimated yields reconstructed from sediment deposited in the delta downstream. There are two possible explanations. First, more than 97% of the contemporary sediment yield is suspended sediment as reported in sections 4.1 and 4.2 and by Stott et al. (1986) - it is probable that only the coarser fraction of this is actually deposited on the delta, the remainder travelling in suspension to more distant parts of the loch before becoming deposited or possibly even leaving the loch as part of the sediment load of the outflowing river Balvaag at the east end of the loch. Two bulk samples taken with a trowel from the banks of the stream flowing across the delta (at points 'a' and 'b' on Figure 3.3) had median grainsizes of 0.125 and 0.18 mm and two samples from the delta surface at points 'c' and 'd' (Figure 3.3) using a standard soil auger (depth 30 cm) both had a median grainsize of 0.125 mm. The fine nature of these samples will to some extent reflect the sampling methods, but nevertheless do indicate that the surface layers of this delta are composed of quite fine fluvially deposited sediments which have been brought down Monachyle glen in suspension and deposited more recently in the form of overbank sedimentation.

A second, but less likely explanation for the mis-match of present sediment yield with delta accumulation is that contemporary sediment yields are lower than in the past and so the delta represents sediment deposited in a time of higher sediment yields.

There is no onshore evidence for the delta aggrading at present, its area not having changed significantly since the 1863 Ordnance survey. However, evidence from elsewhere (e.g. Battarbee et al. (1985) study of loch sediments) indicate that contemporary sediment yields are higher than in the past.

More work in the form of augering to depths of at least 3 m is required if the nature and composition of the sediments in this delta are to be related to the sediment yield from Monachyle glen. Offshore work using echo sounding to investigate the delta profile, possibly combined with some loch bed coring could prove worthwhile. In the past five years the Monachyle glen has undergone progressive ploughing and drainage ditching in preparation for afforestation, the last phase of this being a subject of this thesis. It appears that this ground preparation is associated with at least temporarily increased sediment yields. Future work coring the loch sediments at the mouth of the Monachyle mainstream could reveal layers of sediments corresponding to the ploughing phases (Battarbee et al. 1985, Duck 1985). However, this type of work lies outside the scope of this thesis which aims primarily to investigate sediment sources.

CHAPTER 5: SEDIMENT SOURCES - TRIBUTARIES

5.1 Discharge estimation

Intensive suspended sediment sampling was conducted in three tributaries - one in the moorland catchment (M1), and two in the forested catchment (K4 and K8). At the start of the study period no tributary streamflow recording devices were available. Instead stage boards graduated in mm were installed in the tributaries and stage/discharge relationships were derived for each tributary by the method of salt dilution gauging described in Appendix I. Water level at the main weirs was noted at the time the dilution gauging was performed and this was converted to discharge using the rating relationships below:

$$\log_{10}KWQ = -3.8481 + 1.7214.\log_{10}KWstage \quad (r^2 = 0.996)$$

where, KWQ = Kirkton weir discharge, KWstage = Kirkton weir stage

$$\log_{10}MWQ = 2.3330 + 0.6334.\log_{10}MWstage \quad (r^2 = 1.000)$$

and MWQ = Monachyle weir discharge, MWstage = Monachyle weir stage.

Thus, relationships between tributary discharge and mainstream discharge could later be derived. Institute of Hydrology 15 minute streamflow records for both catchment outlets were available on computer disk on the IBM Wallingford Oracle system. The discharge data for 1983-1985 were transferred to the VAXA mainframe computer at Stirling University via the JANET network. Synthetic tributary streamflow series were then reconstructed in the MINITAB statistical package using the following rating relationships indicated by the numbered arrows in

Figure 5.1, i.e. equations (i),(iii) and (iv) were used to reconstruct streamflow records for M1, K4 and K8 respectively.

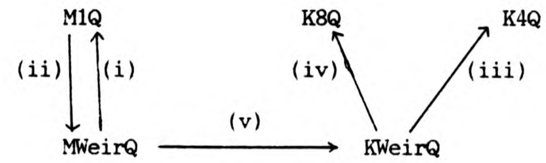


Figure 5.1: Relationships between outlet and tributary streamflow. Equations for the arrows are given in Table 5.1.

Table 5.1: Rating relationships between instantaneous mainstream discharge (at weirs) and tributary discharge. All relationships are statistically significant at the 1% level.

Rating Equation	n	a	b	r^2	s.e
(i)	11	1.5118	0.6678	0.835	0.1785
(ii)	Reverse of (i)				
(iii)	14	2.2707	0.8892	0.877	0.1084
(iv)	14	1.4275	0.9329	0.791	0.1697
(v)	9	-0.0753	0.5995	0.937	0.0615

This method of estimating tributary discharge from mainstream discharge had to be employed until 7 May 1986 when a pressure transducer stage recorder was installed in M1. A second was installed in K4 on 1 September 1986 and so when these were in operation these were used to give a more accurate estimate of the tributary discharge regime.

IH streamflow records for 1986 were unfortunately not available at the time of writing. Thus, for the first part of the year up to 7 May (when the M1 pressure transducer was installed), IH streamflow charts were digitised at one hour time intervals using a Hipad digitising pad linked to an Apple IIe micro-computer. The coordinates were then then transferred to the University VAXA mainframe computer using a transfer package called KERMIT and then read into MINITAB files for the subsequent analysis. Synthetic streamflow series were reconstructed for M1 and K4 using equations (i) , (iii) and (iv) for tributaries M1, K4 and K8 respectively. From 7 May the M1 streamflow variation was recorded by a pressure transducer, the method by which the data were collected in the field and later transferred via a BBC micro-computer to the University VAXA mainframe computer was described in section 3.2.1. A second pressure transducer water level recorder system became available and was installed in K4 on 1 September 1986. Thus, for the period 7 May - 1 September the K4 and K8 streamflow series were estimated from the M1 pressure transducer record using equations (ii), (v) and (iii) for K4 and (ii), (v) and (iv) for K8. The K8 record was estimated in this way until the end of the study. This was thought to be more reliable and much less time consuming than digitising the charts. From 1 September to the end of the study K4 records were maintained by the pressure transducer.

For the latter part of the study period when the pressure transducers were installed in M1 and K4 the rating equations below (all statistically significant at the 1% level) were fitted to relate mV (recorded by the pressure transducer) to discharge (Q in $l\ s^{-1}$) in M1 and K4:

For M1:	r^2	s.e
M1 mm = -10.3 + 19.5 mV	0.999	2.1
$\log_{10}$ M1Q = -4.73 + 2.87 . $\log_{10}$(mm + 100)	0.814	0.2

Merging these so that Q can be computed using mV directly,

$$\log_{10} M1Q = -4.73 + 2.87 \cdot \log_{10}(19.5mV + 89.7)$$

$$\therefore M1Q = 10^{-4.73}(19.5mV + 89.7)^{2.87}$$

$$= (10^{-4.73} \times 19.5^{2.87})\ (mV + 89.7/19.5)^{2.87}$$

$$= 0.0938\ (mV + 4.60)^{2.87}$$

for K4:	r^2	s.e
K4 mm = -27.5 + 21.3 mV	0.978	10.5
$\log_{10}$ K4Q = -6.63 + 3.74 . $\log_{10}$(mm + 100)	0.858	0.2

Merging these,

$$K4\ Q = 10^{-6.63} \cdot 21.3^{3.74}\ ((-27.5 + 100) + mV)^{3.74}$$

$$= 0.0218\ (mV + 3.40)^{3.74}$$

where,

mm = tributary water level in mm as read from stage board

mV = pressure recorded by pressure transducer (millivolts)

Flow duration curves for 1983-85 for each of the tributaries are shown in Figure 5.2. Mean discharge is indicated on each curve as well as the maximum and minimum discharges actually gauged by the salt dilution method. Table 5.2 summarises the streamflow characteristics for each year and for each tributary.

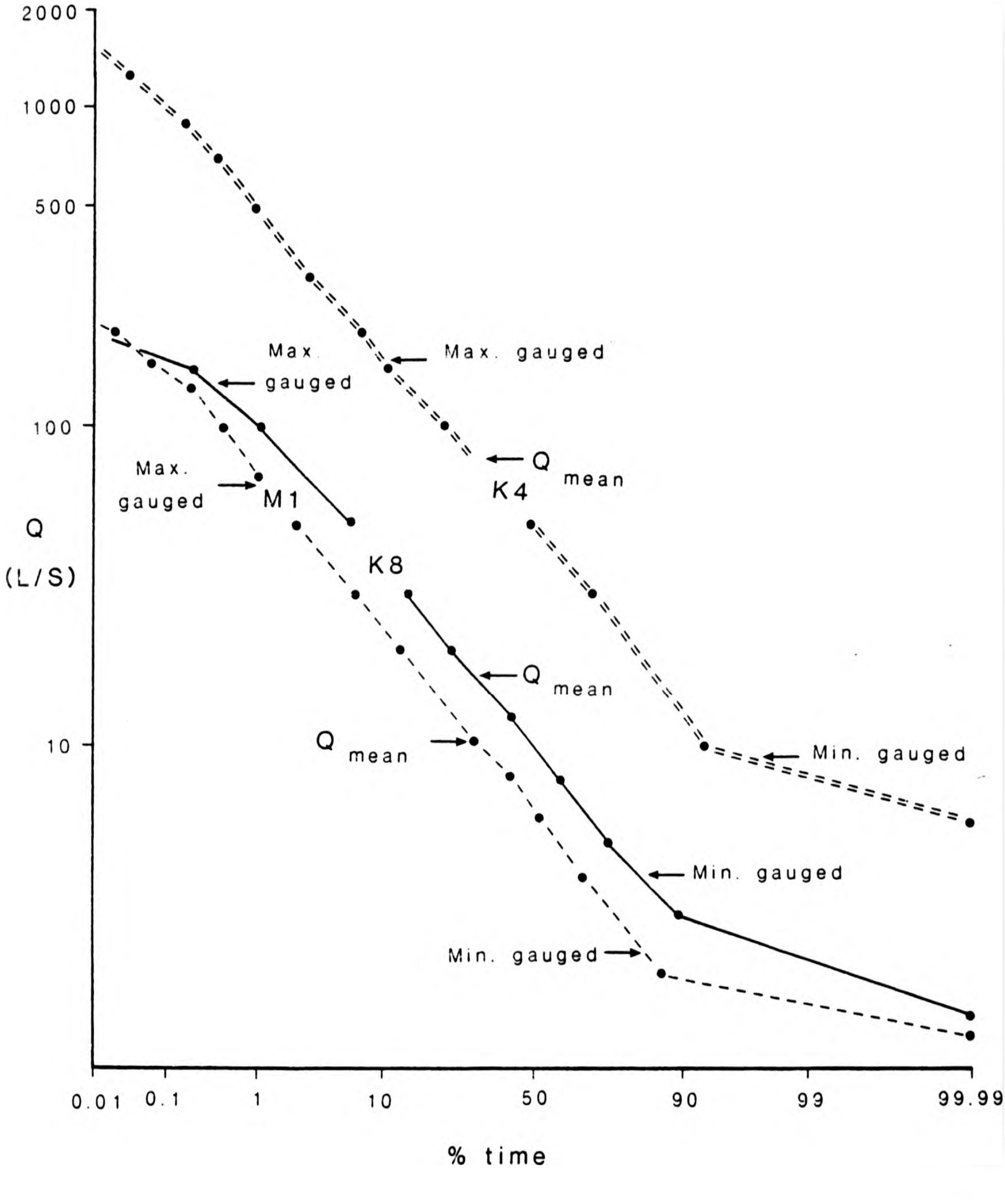


Figure 5.2: Flow duration curves for tributaries M1, K4 and K8. Maximum and minimum gauged discharges and the mean annual discharge (Q_{mean}) are indicated next to the curve. Curves are for 1983-5.

Table 5.2: Table summarising streamflow characteristics for three monitored tributaries (streamflow in l s^{-1}, Q_{total} in l x 10^8, runoff in mm over whole sub-catchment).

Year	Stream	Q_{mean}	Q_{max}	Q_{min}	Q_{total}	Runoff
1983	M1	16	192	2	5.10	2125
	K4	73	1619	6	23.07	1876
	K8	10	258	1	3.24	1620
1984	M1	16	200	2	5.13	2138
	K4	75	1289	8	23.72	1928
	K8	11	203	1	3.34	1670
1985	M1	17	209	2	5.41	2254
	K4	83	1214	15	26.10	2122
	K8	12	191	2	3.68	1840
1986	M1	17	213	1	5.04	2100
	K4	75	1301	22	22.68	1844
	K8	11	207	3	3.19	1595

5.2 Suspended sediment

Suspended sediment is defined as that portion of the sediment load of a stream which is carried in suspension, i.e. not in contact with the stream bed. For this reason it is the 'fine' fraction of the sediment load. However, it is well documented that suspended sediment concentration in a uniformly flowing stream increases towards the bed (e.g. Colby 1963) and that the size of the particles carried in suspension also increase towards the bed. It is in the zone close to the bed that it becomes difficult to distinguish between sediment in suspension and bedload. The size of the particles which can be carried in suspension will vary depending on their shape, density and surface characteristics as well as on localised streamflow characteristics such as turbulence, eddying and bedform. In the light of the difficulty of rigidly defining the boundary between suspended sediment and bedload it was decided to choose an arbitrary boundary of 2.8 mm. This was convenient in this study since it corresponded approximately to the mesh size of the netting used to line the tributary bedload traps (see section 3.2.5) and also to the diameter of the inlet holes on the automatic liquid sampler intake pipes by which the majority of suspended sediment sampling was carried out (see Table 3.1)

5.2.1 Suspended sediment dynamics

The concentration of suspended sediment in a stream is highly variable in space and over time, particularly during periods of storm runoff. Much work has been dedicated to understanding the factors which control the measured variations in suspended sediment. The first and most obvious control seems to be stream discharge - increasing streamflow usually increases sediment concentrations. This fact has led to the extensive use of sediment rating curves to predict sediment concentrations in streams. However, the sediment concentration associated with a given flow will commonly vary by several orders of magnitude (Walling and Webb 1982). Several workers have isolated a seasonal effect whereby sediment concentrations are higher or lower during a particular season (e.g. Guy 1964, Hall 1967, Temple and Sundborg 1972, Walling 1974, Paustian and Beschta 1979 and Beschta 1981). A second factor, that of hydrograph slope or rate of rise in streamflow also has an important effect, sediment concentrations typically being higher on the rising limb of the hydrograph and lower on the falling limb. This phenomenon known as hysteresis operates both during individual events (e.g. Arnborg et al. 1967, Walling 1974, Wood 1977, Bogen 1980, Beschta 1981), during a sequence of events (e.g. Negev 1969, Walling 1974, Wood 1977, Beschta 1981) and even at a seasonal timescale (e.g. Ferguson 1984) and has been attributed to temporal variations in sediment availability. Sediment readily available for transport can be removed from its source areas early in a storm or season and the supply therefore becomes exhausted in the latter part of the storm, storm sequence or year. Lower sediment concentrations have been measured on the falling limb of the hydrograph or after a frosty or rainy season. Klein (1984) has reported anticlockwise hysteresis effects for suspended sediment also. Walling and Webb (1982) propose a simple mixing model wherein suspended sediment generation is essentially limited to storm events and in a situation where sheet or rill erosion is the dominant source, sediment will be transported to the stream by surface runoff. Suspended sediment concentrations would then reflect the mixing of sediment-laden storm runoff with the prevailing baseflow. Wood (1977) reports sediment concentrations for a given discharge becoming progressively reduced when storm events occur in rapid succession and Beschta (1981) relates the storm sequence to the "memory" of the system. Clearly since storm sequences vary throughout the year a seasonal effect on sediment concentrations operates which is explained in terms of Walling and Webb's mixing model by storm runoff being diluted in a greater volume of baseflow during successive and multiple events such as may occur during a typical British autumn for example.

Figure 5.3 shows typical patterns of suspended sediment variation through selected floods sampled in three Balquhidder tributaries. Positive or clockwise hysteresis is apparent in each of the three tributaries. For example, in tributary K4 (Figure 5.3) the floods of 14 and 28.10.86 show positive hysteresis, on 05.07.85 and 04.11.86 in K8 (Figure 5.3) and on 15.05.86 in M1 (Figure 5.3) this phenomenon is apparent. However, other floods plotted show large variations in suspended sediment concentrations through the sampling period and little or no obvious

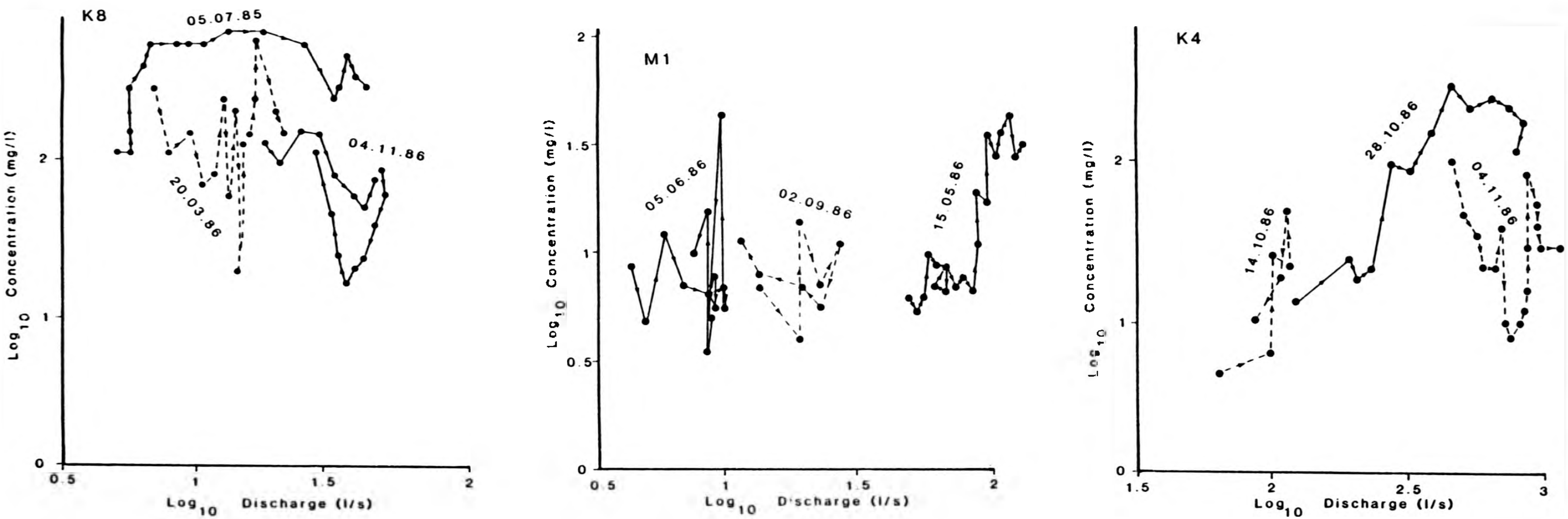


Figure 5.3: Suspended sediment vs. discharge log-log plots for selected floods in tributaries K8, M1 and K4 showing hysteresis and exhaustion effects. Arrows indicate the next sample. Time interval between samples is 30 minutes. Note the different concentration scale for M1 and discharge scale for K4.

pattern (e.g. flood of 20.03.86 in K8 and on 05.06.86 in M1). The early part of the sampling in floods on 04.11.86 in K4 and on 20.03.86 in K8 indicate that exhaustion is beginning to take place right at the start of the sampling period since concentration starts high and then decreases. This could indicate that the start of the flood had been missed since all sampling through flood events was triggered automatically by electronic float switches. If the float switch had been set too high for example (very likely if the stage was high at the time of setting), then an initial pulse of sediment may in some cases pass the sampler before the float switch was triggered. Several other problems are associated with this type of automatic sampling, not least, is the sampling interval chosen. Flood events in these steep mountain streams tend to be flashy and short-lived. Experience showed that typically single events in tributaries could last from as little as four hours to as long as 12 hours, with multiple events lasting even longer. On this basis it was decided to select a 30 minute sampling interval which it was hoped would sample the full range of discharges through flood events (12 hours of sampling). However, this was a compromise since although a much shorter sampling interval would have given a better insight into suspended sediment dynamics and patterns, only 24 samples could be taken automatically during one event. A shorter sampling interval of less than 10 minutes, for example, may well have finished sampling before the flood had peaked. Since hysteresis and exhaustion effects appear to be operating, sampling on the rising limb of the hydrograph only would clearly result in rating curves and subsequent load estimates being biased upwards. Sampling on the falling limb of hydrographs was therefore necessary and the 30 minute sampling interval was chosen to achieve this.

From a total of 38 flood events, 17 in the moorland stream (M1) and 21 from the two forested streams (K4 and K8), four types of pattern were selected. Table 5.3 summarises the patterns observed and the proportion of floods in which they occurred. There appears to be little difference between the patterns observed in streams under different land uses except that in one case a negative linear relationship occurred in a flood in the moorland stream which probably indicates an exhaustion effect due to a greater sediment supply limitation. Otherwise all streams are similar with 'no pattern detected' and positive hysteresis being the dominant effects with the linear relationship (as used in the rating curve model to estimate sediment loads) detected in only one of the 38 floods. It is therefore no surprise that the rating curves presented in the next section and previously (sections 4.1 and 4.2) exhibit scatter.

Summary data for all suspended sediment sampling in each of the three streams M1, K4 and K8 are presented in Tables 5.4, 5.5 and 5.6. Mean suspended sediment concentration for each flood sampled is plotted against the mean of the sampled discharges in Figure 5.4 for each of the three tributaries (note that dates indicated by a '*' in the tables were not sampled during flood events and are not plotted in Figure 5.4). The points on the graph are assigned different symbols according to whether they are floods before (open triangles) or after (solid triangles) disturbance i.e. stacking

Table 5.3: Flood event suspended sediment patterns observed in Balquhidder tributaries.

Type of pattern	Moorland stream (M1) (% of events)	Forest streams (K4, K8) (% of events)
Positive hysteresis	35	42
Positive linear relationship	6	5
Negative linear relationship	6	0
No pattern detected	53	53

Table 5.4: Mean suspended sediment concentration and discharge summary data for moorland tributary M1. (C = suspended sediment concentration (mg l-1), Q = discharge (l s^{-1}) and * = not sampled during flood events).

Event Number	Sampling date (Samples collected)	n	Cmean	Cmax	Cmin	Qmean	Qmax	Qmin
	30.05.85 - 05.06.85*	14	30.2	65.1	3.0	4.7	7.9	3.2
	14.06.85 - 20.06.85*	20	15.6	48.3	4.8	4.1	6.5	3.2
1	17.07.85	22	13.3	43.1	4.6	49.6	62.9	25.6
2	08.08.85	21	15.6	63.8	1.0	45.1	82.3	9.7
3	12.09.85	17	49.9	321.3	11.2	47.2	67.2	26.6
4	06.11.85	22	21.3	45.9	10.1	85.5	120.5	38.4
5	22.03.86	23	25.5	102.3	9.2	58.9	75.6	38.0
	Phase I Total/mean	139	23.4	321.3	1.0			
	P L O U G H I N G							
	30.04.06 - 01.05.86*	23	43.8	110.5	10.4	59.4	104.1	31.6
6	07.05.86	23	10.1	23.7	3.4	107.1	113.0	82.0
7	15.05.86	23	14.6	39.0	3.1	79.0	118.2	22.8
8	21.05.86	23	4.6	20.8	0.5	49.6	69.1	13.1
9	22.05.86	22	8.8	25.4	2.8	42.9	66.6	11.8
10	05.06.86	16	8.7	39.6	3.1	8.2	10.1	4.8
11	19.06.86	22	8.9	21.5	3.5	44.6	73.3	25.0
	D I T C H I N G							
12	29.07.86	21	6.0	31.9	0.3	33.0	56.8	2.9
13	30.08.86	23	8.6	81.1	1.1	33.1	62.9	4.4
14	02 09.86	10	7.3	12.7	3.5	7.2	8.7	4.0
15	28.09.86	20	16.9	57.9	4.9	26.4	41.3	2.2
16	07.10.86	15	1.8	4.0	0.5	6.9	8.7	3.7
17	21.10.86	24	3.3	10.4	0.7	24.2	35.2	16.9
18	28.10.86	22	3.1	5.9	0.6	28.0	46.3	16.0
19	04.11.86	24	8.0	25.2	4.1	40.1	53.0	16.9
20	18.11.86	24	10.7	26.1	3.8	33.3	46.2	16.9
21	26.11.86	24	10.2	30.0	2.4	41.5	53.0	13.7
22	09.12.86	15	8.8	21.8	3.5	64.9	115.1	31.3
23	08.05.87	16	11.4	37.4	1.6	6.0	11.4	2.0
	Phase II Total/mean	366	8.5	81.1	0.3			
Upper M1 (control upstream of drainage ditch)								
	29.07.86	20	17.2	54.0	4.1	38.5	56.8	12.1
	30.08.86	23	9.2	38.8	2.2	36.0	65.0	4.4
	02.09.86	9	39.9	88.0	13.7	7.3	8.7	4.0
	Total/mean	51	17.6	88.0	2.2			

Table 5.5: Mean suspended sediment concentration vs. discharge summary data for forest tributary K4 (C = suspended sediment concentration ($mg\ l^{-1}$), Q = discharge ($l\ s^{-1}$) and * = not sampled during flood events).

Event Number	Sampling date (Samples collected)	n	Cmean	Cmax	Cmin	Qmean	Qmax	Qmin
	10.05.85 - 17.05.85*	17	117.8	701.2	10.8	38.7	51.5	26.3
	17.05.85 - 25.05.85*	20	34.4	51.5	26.3	123.7	973.2	38.3
	24.05.85 - 01.06.85*	12	19.0	74.5	4.3	34.6	178.5	2.5
1	21.06.85	15	27.3	103.8	13.0	217.8	286.6	18.9
2	05.07.85	16	94.2	382.9	11.8	704.4	984.6	19.0
3	17.07.85	24	42.8	140.0	6.9	564.4	1043.3	61.2
4	08.08.85	8	42.2	116.5	8.0	411.8	643.9	41.1
5	14.09.85	22	168.3	714.4	12.8	426.6	726.8	241.6
6	30.09.85	15	61.9	502.3	5.1	293.5	324.1	86.0
7	11.10.85	10	108.3	263.1	24.7	644.1	1120.7	333.0
8	04.11.85	22	27.0	89.0	7.4	204.9	234.7	135.1
9	06.11.85	23	41.4	269.3	6.4	702.5	1021.6	218.0
	Phase I Total/mean	219	61.8	714.4	5.1			
S T A C K I N G A R E A C O N S T R U C T E D								
K4 upstream of road gully input								
	14.10.86	18	10.0	40.5	2.5	48.7	54.7	34.7
	21.10.86	21	26.8	139.4	4.0	60.3	70.0	57.7
	28.10.86	13	122.4	277.6	10.8	319.2	542.8	116.6
	04.11.86	23	71.9	301.3	17.6	126.1	145.3	92.1
	11.11.86	19	37.7	94.7	11.0	226.3	299.8	64.0
	Total/mean	94	50.0	301.3	2.5			
K4 downstream of road gully input								
10	14.10.86	9	16.3	40.8	3.4			
11	21.10.86	20	10.4	20.7	2.6			
12	28.10.86	6	93.5	225.6	14.2	As for K4 above		
13	04.11.86	23	59.3	421.4	9.8			
14	11.11.86	20	24.1	44.5	10.0			
15	02.12.86	12	29.2	93.3	3.5	160.6	185.9	134.7
16	09.12.86	14	109.6	197.8	29.3	262.4	536.9	187.4
17	08.05.87	15	6.4	14.0	2.6	130.3	223.0	51.0
	Total/mean	119	39.9	421.4	2.6			

Table 5.6: Mean suspended sediment concentration vs. discharge summary data for forest tributary K8 (C = suspended sediment concentration (mg l^{-1}), Q = discharge (l s^{-1}) and * = not sampled during a flood event).

Event Number	Sampling date (Samples collected)	n	Cmean	Cmax	Cmin	Qmean	Qmax	Qmin
	30.05.85 - 03.06.85*	16	17.0	138.2	0.6	70.2	131.5	2.5
1	05.07.85	20	310.0	563.2	11.6	60.3	80.0	2.0
2	17.07.85	22	101.3	334.7	34.5	102.5	147.8	3.3
	17.07.85 - 18.07.85*	23	14.9	41.1	3.2	40.6	128.7	4.6
3	08.08.85	11	12.3	19.5	5.0	63.7	113.5	5.5
4	30.09.85	22	130.7	295.7	8.9	46.7	55.0	24.0
5	10.10.85	22	96.4	395.4	32.1	51.3	68.9	4.4
6	04.11.85	19	68.9	167.9	14.7	38.2	49.1	13.8
7	06.11.85	22	60.2	185.2	5.0	32.7	36.0	23.9
8	20.03.86	16	160.2	564.7	14.5	41.7	67.6	4.8
	26.04.86 - 01.05.86*	19	244.4	712.7	30.9	82.4	114.1	3.6
9	02.05.86	16	189.9	980.7	62.0	91.1	107.5	16.6
10	10.05.86	14	77.7	239.9	21.6	114.1	128.0	85.0
11	18.11.86	23	21.2	74.5	7.1	39.0	55.7	13.2
12	09.12.87	23						
13	08.05.87	21	16.7	51.4	2.3	22.4	36.8	5.6
	Total/mean	336	104.6	980.7	0.6			

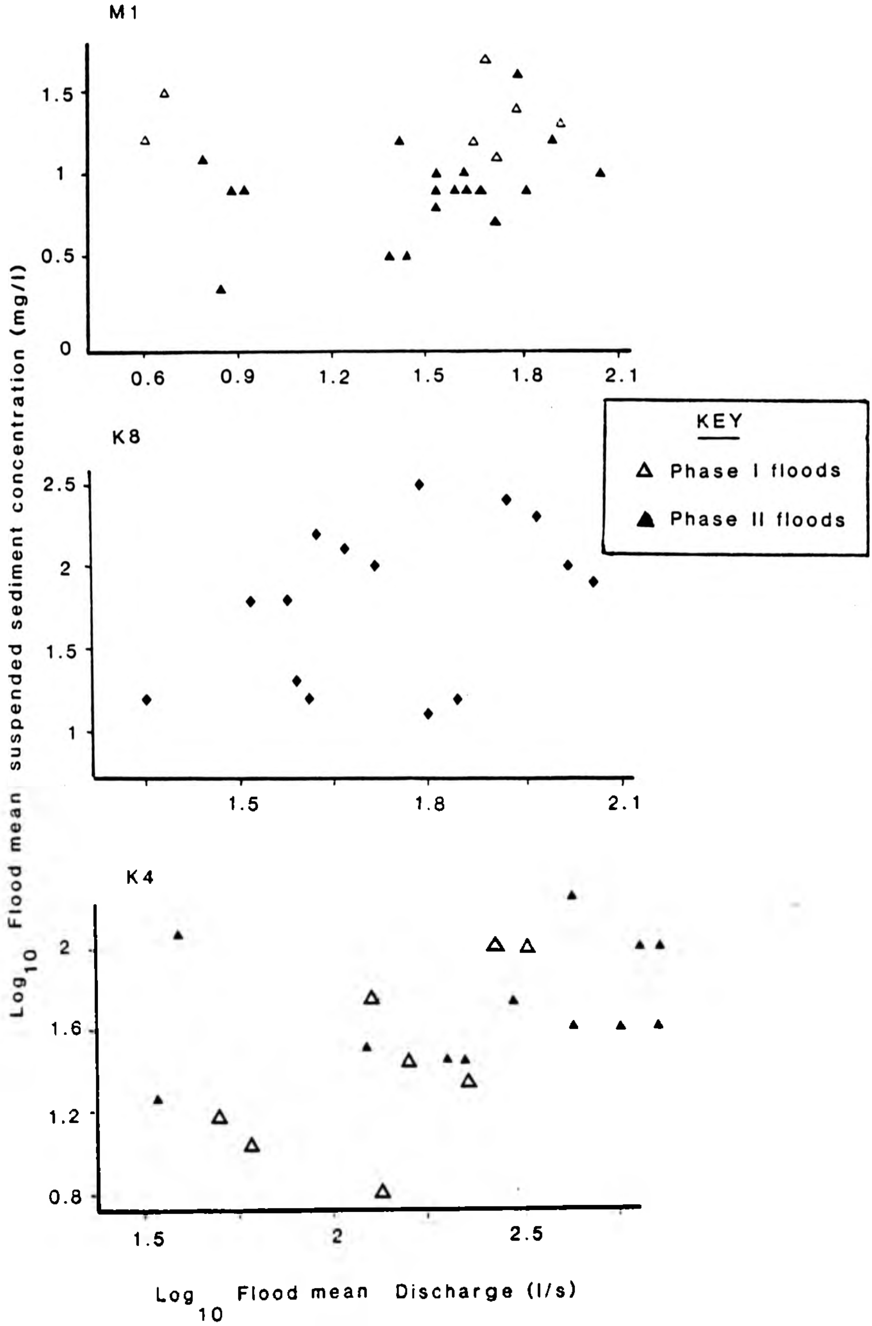


Figure 5.4: Flood mean suspended sediment concentration vs. flood mean discharge for M1, K4 and K8.

area construction in K4 sub-catchment and ploughing and ditching in M1. K8 did not undergo major disturbance and all floods are plotted as solid diamonds. The forested streams tend to show higher flood mean concentrations for larger floods but the relationship is by no means good with mean concentrations differing by up to an order of magnitude for floods with the same mean discharge. However, phase II flood mean concentrations for the period after construction of the northern Kirkton stacking area (solid triangles) are generally higher than the phase I mean concentrations reflecting an increased availability or supply of suspended sediment. In M1, flood mean concentrations appear to bear little or no relationship to flood mean discharge, but what is clear is that mean concentrations for floods sampled in Phase I (open triangle) are consistently higher than mean concentrations in Phase II. An explanation for this surprising observation is offered in section 5.4.1. The overall pattern is reflected in the suspended sediment/discharge rating curves in Figure 5.5.

5.2.2 Suspended sediment loads

Due to the highly variable nature of suspended sediment concentrations in streams as indicated in the previous section (5.2.1) the problem of estimating total stream sediment loadings is a particularly difficult one. In the vast majority of cases it is not feasible to trap the total stream load (as done for bedload in this study) due to the very large quantities of sediment involved (suspended sediment loads can sometimes constitute more than 95% of the total stream sediment load). Therefore, the alternative is to estimate the load from continuous discharge data and intermittent samples of suspended sediment. The most common way of combining these intermittent concentration data with the continuous discharge data is to use a rating curve to predict unmeasured concentrations from the measured discharge at the time. However, it has been demonstrated that sediment load estimates made using the rating curve technique can in some cases result in errors of up to +/- 50% (Walling 1977a and b, Walling and Webb 1981b). More recently Ferguson (1986) has shown that estimating unmeasured concentrations from discharge using least squares regression for the logarithm of concentration has an inherent statistical bias which increases with the degree of scatter about the rating curve, the underestimation resulting from which can reach 50%. Ferguson proposes a simple correction factor which was tested successfully on real and simulated data sets. Therefore, in the absence of a more appealing alternative method all suspended sediment load estimates in this study are computed using rating curves and corrected according to Ferguson (1986).

Some 1165 suspended concentration values collected largely automatically during flood conditions (but with a few sampled by hand and ALS at low flow) were assigned discharge values and divided into pre- (Phase I) and post-disturbance (Phase II) periods. The number of samples in the period and the computed rating equations for the three tributaries are shown in Table 5.7 and the relative positions of the ratings and their confidence intervals (one standard error) are shown in Figure 5.5. Multiple linear regression analysis using both rising/falling stage and season as extra predictors failed to increase the explained

Table 5.7: Tributary suspended sediment vs. discharge rating equations used for estimating suspended sediment loads. All equations take the form $\log_{10}C = a + b.\log_{10}Q$, where C = predicted suspended sediment concentration and Q = discharge, n = number of samples, n.s = not significant, * = significant at the 5% level, ** = significant at the 1% level.

Stream	Sampling Period	n	a	b	r^2	s.e	Significance Level
M1	Pre-ploughing (before April 1986)	139	1.2129	0.0044	0.00	0.3624	n.s
	Post-ploughing (May 1986- April 1987)	418	0.6469	0.1212	0.01	0.3785	*
K4	Pre-construction (before November 1985)	219	0.6133	0.4341	0.12	0.4946	**
	Post-construction (March 1986 - April 1987)	135	-0.8463	1.0693	0.35	0.4216	**
K8	All study period (March 1985 - April 1987)	254	1.1089	0.4728	0.85	0.6064	**

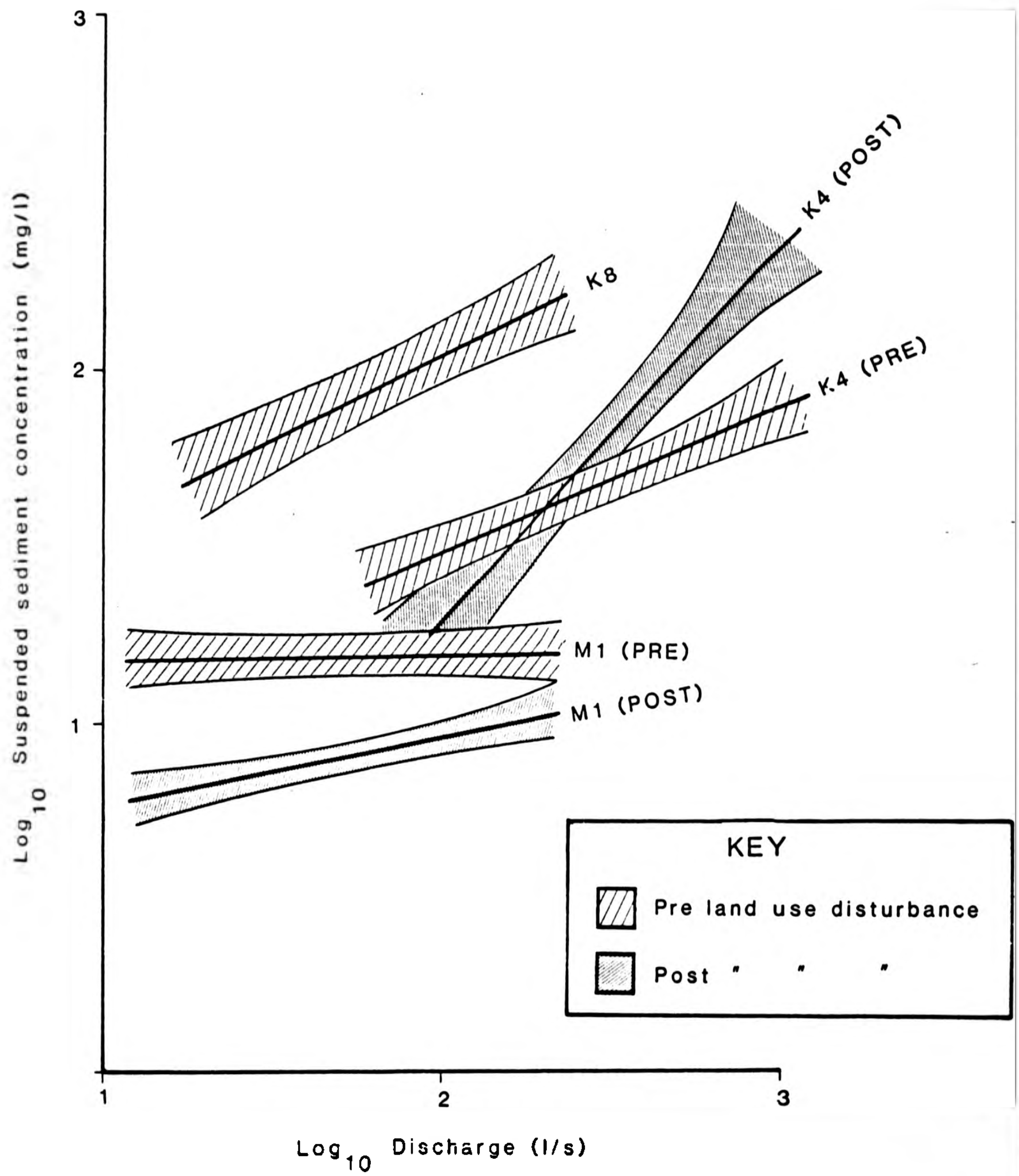


Figure 5.5: Tributary suspended sediment/discharge log-log rating curves with 95% confidence limits for the pre- and post-disturbance phases of the experiment.

variance (r^2) in most cases and so just one rating curve (Table 5.7) was used to estimate total loads and the estimates are corrected according to Ferguson (1986). In order to test the reliability of the estimates over the actual sampling periods during floods the rating curve estimate (Lr) and the corrected rating curve estimate (Lcr) was compared to both La and Ls where

$$La = \overline{CQ} \cdot t$$

and

$$Ls = \bar{C}.\bar{Q}.T$$

where C = instantaneous sampled suspended sediment concentration ($mg\ l^{-1}$),

Q = instantaneous discharge at which sample was taken ($l\ s^{-1}$)

T = time in seconds over whole sampling period,

and,

t = time in seconds between samples.

The load estimated is in milligrams and is divided by 10^6 to convert to kilograms or by 10^9 to convert to tonnes. It was found that both La and Ls were nearly always in good agreement whereas the raw rating curve method systematically underestimated loads. Applying the correction factor proposed by Ferguson (1986) increased the rating curve estimates and made them comparable with the La and Ls estimates.

Table 5.8 presents the Balquhidder tributary suspended

Table 5.8: Tributary suspended sediment yields (t km^{-2} yr^{-1}) estimated by rating curves in Table 5.7 (corrected according to Ferguson 1986).

		Tributary name		
	Year	M1	K4	K8
Phase I	1983	55	131	195
	1984	55	133	194
	1985	58	149	223
	Phase I Average	56	138	204
Phase II	1986	24	171	225*

* tributary not disturbed in Phase II

sediment loads for (1983-1986) spanning the land use conversion period. Mean annual tributary discharge (l s^{-1}) is indicated in Table 5.2. First, the forested tributary suspended sediment yields are more than double those from the moorland stream. Second, suspended sediment yield appears to reflect mean annual discharge, the higher discharge in 1985 resulting in higher suspended sediment yields. Thirdly, the effect of constructing the stacking area in late 1985 has been to increase the K4 1986 yield and this is discussed in section 5.4.2 later. Thus, over the Phase I period 1983-5 tributary suspended sediment yield has varied by under 15% in the forested tributaries and by around 5% in the moorland tributary even though 1985 was a particularly wet year (see Figure 7.2). The variation appears to be related to the tributary mean annual discharge. Since only one tributary was monitored in the moorland catchment it is not possible to comment on variability between streams, but in the forested catchment K8 yields appear to be far greater than K4 both before and after the stacking area construction. Mean suspended sediment concentrations in four tributaries in the Kirkton glen (K1, K4, K8 and K14) have been published by Ferguson and Stott (1987) and range from 9 to 95 mg l^{-1}. It appears that stream to stream variation in suspended sediment yields can be in the region of an order of magnitude in these type of mountain streams.

5.2.3 Organic content of suspended sediment

Organic content of the suspended sediment was estimated by the loss on ignition method as used by Robinson (1979). In the first instance a sequence of suspended sediment samples taken at 30 minute intervals through typical flood events were analysed for their organic matter content to determine how much short term variation there was with discharge. Figure 5.6 shows how suspended sediment concentration and the organic matter content of the suspended sediment vary with streamflow in each of the three tributaries K4, K8 and M1. It is apparent that percentage organic matter content varies closely with suspended sediment concentration. The maximum organic matter content for all samples in these three flood events was 7.2%. Since the organic proportion of the stream sediment load was so small (of the order of a few percent) it was decided to examine whether or not there was a seasonal variation and to test the hypothesis that fine particulate organic matter (FPOM) in streams varies with season. In order to do this samples from two floods for each season (where winter is January - March, spring is April - mid-May, summer is mid-May - August and autumn is September to December) were combined and the average organic matter content estimated. The results are presented in Table 5.9 and show that the average organic matter content is less than 2% and that there is little seasonal variation, the range being 0.9 to 2.0%. Finally, samples from likely source areas - namely stream banks in all tributaries, a drainage ditch bed in the moorland M1 sub-catchment and the exposed slope (see Plate 5.7) from road repairing in the K4

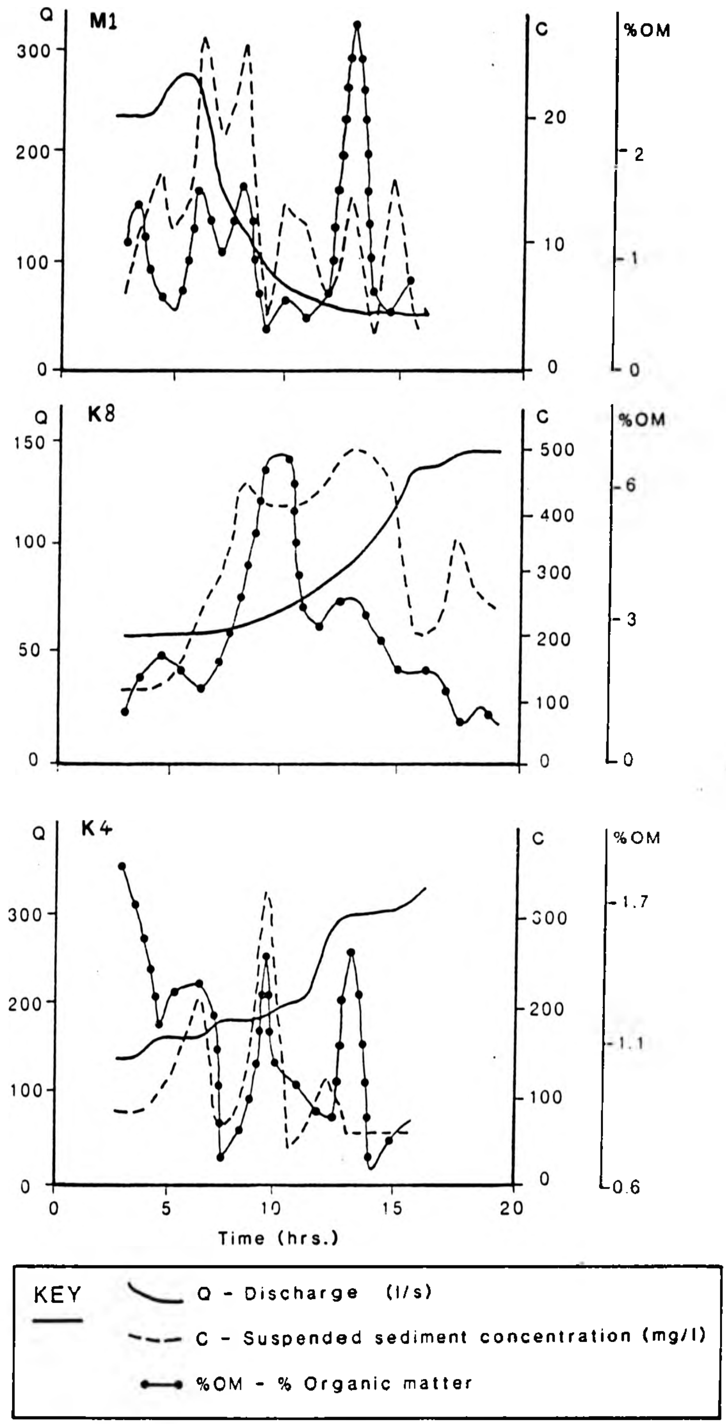


Figure 5.6: Time series plots showing the variations in stream discharge, suspended sediment concentration and organic matter percentage of the suspended sediment sediment. Note the different vertical scales for each graph.

Table 5.9: Percentage organic matter (mean) content of tributary suspended sediment as estimated by loss on ignition of filters.

Stream	Winter		Spring		Summer		Autumn		Annual mean	
	n	%	n	%	n	%	n	%	n	%
M1	23	1.1	46	0.9	39	1.2	40	1.0	148	1.1
K4	*	*	34	1.8	26	1.0	46	1.6	106	1.5
K8	17	1.8	36	1.7	41	2.4	39	2.0	133	2.0

Table 5.10: Percentage organic matter content (%om) of bulk sediment samples from source areas.

Source area	No.samples	%om (mean)	%om (max)	%om (min)
M1 streambank	4	1.5	2.7	0.5
Moorland drainge ditch bed	4	1.8	3.1	1.0
K4 stacking area - exposed slope	4	1.4	1.6	1.3
K8 streambank	4	2.4	4.1	1.4

forested sub-catchment were also analysed for their organic matter content. The results are summarised in Table 5.10. The similarity between the proportion of organic material (by weight) measured in the sampled suspended sediment and that in the selected sources (streambanks, drainage ditch, roadside scar) seems to indicate that these are the right sources for the sediment but the similarity between the alternative sources means that is is not possible to deduce which sources are the most important. For this reason it has not been possible to use organic matter content as a 'signature' to fingerprint exact sediment sources.

5.3 Bedload

'Bedload' is that fraction of the stream's sediment load which is transported either intermittently or continuously in contact with the stream bed, i.e. usually by saltation (leaps and bounces) or rolling along the bed. Bedload is therefore the coarser or heavier particles of the sediment load and is classified in this study as all sediment coarser than 2.8 mm (see Table 3.1).

5.3.1 Bedload dynamics and channel storage

Bedload dynamics were investigated in two ways:

(i) by performing two separate tracer experiments to investigate relative rates of bedload movement in forested and moorland streams in the first instance and then by tracing the routing of individual marked pebbles in the second.

(ii) by attempting to relate amounts of sediment accumulating in bedload traps to streamflow conditions in the preceding time period.

In the first of the tracer experiments which took place from July to October 1985, 150 pebbles were painted yellow and colour coded according to size class (see Table 5.11). These were placed onto the beds of the forest (K8) and moorland streams (M1) but not seeded into it. The average distance moved by each size class was measured on two successive occasions. Table 5.11 presents the data - number in size class, average distance moved for each size class and percentage recovery rates from the date of injection (04 July 1985) to the date of the second measurements (22 October 1985). These data are plotted in Figure 5.7 which also includes error

Table 5.11: Summary data for pebble tracer experiment I showing numbers of painted pebbles injected, percentage recovery and average distances moved.

Size Class (mm)		22-32	32-45	45-64	64-90	90-128	>128	TOTAL	AVERAGE
No.of pebbles injected	(F)	31	30	33	20	30	5	149	
	(M)	39	28	35	21	34	5	163	
% Recovered	(F)	42	63	55	70	100	80		61
	(M)	31	57	77	91	68	100		71
Average distance moved (m)	(F)	8.1	6.2	4.1	0.1	0.4	0		3.3
	(M)	8.6	9.6	10.2	8.5	11.8	5.3		9.0

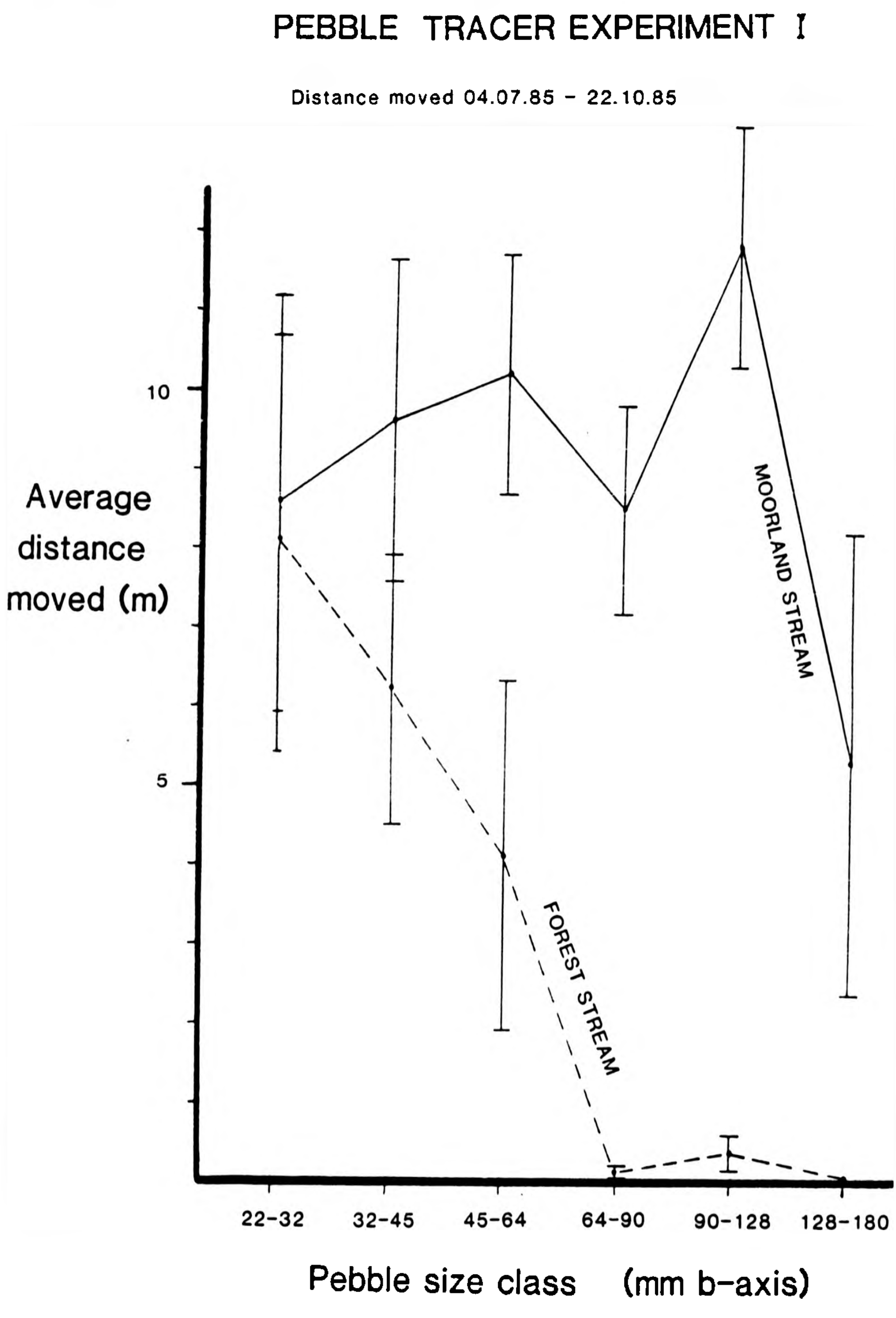


Figure 5.7: Pebble size vs. distance moved plot for tracer experiment I. The 95% error bars are shown.

bars. Even allowing for the measurement errors all but the smallest size class (22-32 mm) moved further in the moorland than in the forest stream. It was provisionally suggested at this stage that the greater average distance moved by all but the smallest pebbles in the moorland stream was due to the organic debris jams which were a feature of the forest tributary (see Plate 3.6).

In the second tracer experiment carried out in tributaries K1 (forest) and M1 (moorland, further upstream than the first experiment to avoid confusion), all 150 yellow painted pebbles were numbered and a note made of their size class. This time the pebbles were carefully seeded into the streambeds by removing a clast of similar size and replacing it with a painted pebble so as to minimise disturbance to the bed. This was done in order to try to simulate natural conditions. The injected pebbles would then lie in realistic locations (unlike in the first experiment in which injected pebbles were not seeded) which would not give them an enhanced chance over other pebbles in the streambed of being moved. The tracers were injected on 5 June 1986 and their distance downstream measured on 3 and 4 occasions in the moorland and forest tributaries respectively during the following ten months. Recovery rates were low, particularly for the smaller clasts which easily became buried, but nevertheless it was possible to trace a few clasts throughout the six month period. The data are summarised in Table 5.12 and plotted in Figure 5.8. The patterns observed show a fall off in distance moved as the size class increases. This has been reported in other studies (e.g. Laronne and Carson 1976, Ashworth 1987) where the D_{50} particle size has the highest

Table 5.12: Summary of results for pebble tracer experiment II.

Forested stream (K1)						Moorland stream (M1)				
Dates: 05.06.86 - 22.09.86										
Size Class	No. Injected	No. moved	Dmean	Dmax	Dmin	No. Injected	No. moved	Dmean	Dmax	Dmin
1	59	31	3.6	15.5	0.3	60	11	4.3	7.4	0.8
2	38	14	3.5	10.7	0.8	42	8	2.4	6.8	0.5
3	21	2	2.6	4.8	0.3	20	1	2.1	2.1	2.1
4	13	3	1.3	1.6	0.8	13	0	0.0	0.0	0.0
5	5	0	0.0	0.0	0.0	12	2	3.8	4.3	3.3
6	4	0	0.0	0.0	0.0	4	0	0.0	0.0	0.0
Dates: 22.09.86 - 28.10.86										
1	,,	22	5.2	11.9	1.3	Not Measured				
2		17	4.9	14.3	0.5					
3		2	0.5	0.5	0.5					
4		4	2.0	3.3	1.3					
5		0	0.0	0.0	0.0					
6		0	0.0	0.0	0.0					
Dates: 28.09.86 - 11.11.86						Date: 22.09.86 - 11.11.86				
1	,,	19	8.4	19.2	1.5		7	9.5	15.3	5.8
2		17	6.5	16.6	0.6		9	8.4	13.2	1.7
3		3	3.3	4.8	1.5		6	3.9	8.3	1.0
4		0	0.0	0.0	0.0		4	5.7	8.9	1.6
5		0	0.0	0.0	0.0		1	5.3	5.3	5.3
6		0	0.0	0.0	0.0		0	0.0	0.0	0.0
Date: 11.11.86 - 14.04.87										
1	,,	11	17.1	46.6	2.9		10	6.8	14.0	0.8
2		13	10.1	28.0	2.2		8	9.1	14.1	3.1
3		8	7.9	14.2	0.5		8	4.1	9.4	0.8
4		7	6.8	16.9	2.6		4	6.4	9.4	1.9
5		0	0.0	0.0	0.0		2	6.0	6.5	5.4
6		0	0.0	0.0	0.0		0	0.0	0.0	0.0

SIZE CLASSES (mm)

1 — 22-32

2 - 32-45

3 — 45-64

4 - 64-90

5 — 90-128

6 — >128

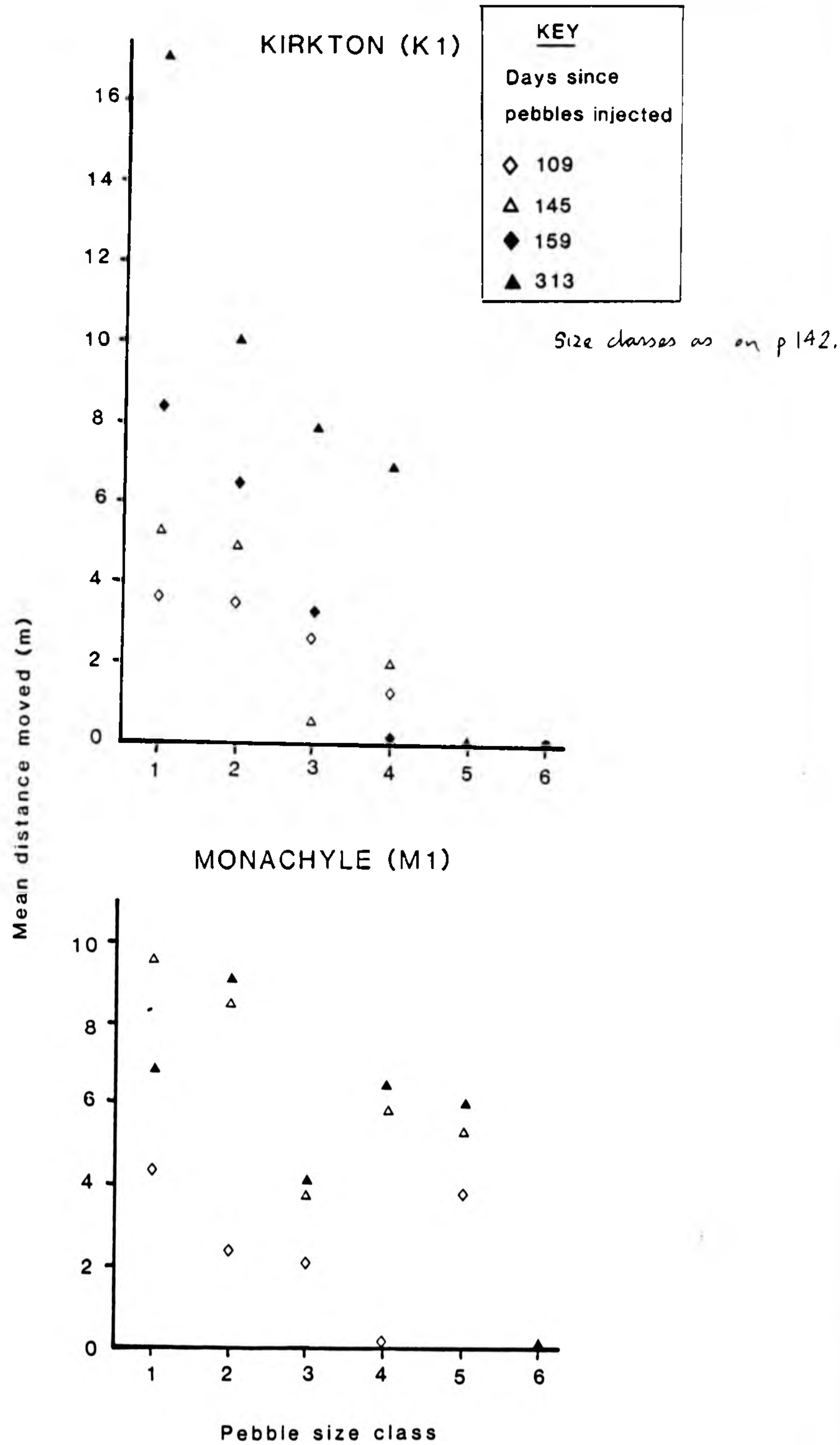


Figure 5.8: Pebble size vs. distance moved plot for tracer experiment II.

movement rate and the rate decreases as the particle size becomes further away from the D_{50} in both the coarser and finer directions. However, because all clasts painted were coarser than the streambed D_{50} of 8 mm (estimated from streambed bulk samples, the grainsize curves for which are presented in Figure 6.4), Figure 5.8 shows that the smaller clasts moved furthest, as was the case in the first experiment with maximum distances of 46.6 m in the forest tributary and 15.3 m in the moorland tributary. However, student's t tests on the mean distance moved showed that with the exception of this smallest size class (22-32 mm) numbered 1 in Figure 5.8, mean distances moved in both tributaries were not significantly different at the 5% level. This differs from the results of the first experiment where average distances moved in the forest stream were much lower than in the moorland stream (significant at the 5% level). However, the rates of movement averaged for all pebbles correspond to 11.0 and 29.9 m yr^{-1} in the in the forest and moorland streams respectively in the first experiment and 8.1 and 6.3 m yr^{-1} in the second experiment. The higher movement rates in the first experiment could be a result of not seeding the pebbles into the bed. It is likely that they would protrude more from the bed into the flow, and since they were not part of the armour layer would be entrained more easily and preferentially transported. A second explanation for the different movement rates could be that local channel gradient, deemed by Laronne and Carson (1976) to "exert an influence on the probability of particle entrainment and on particle mobility", was different in both experiments. Thirdly, although the movement rates have been scaled up to a year, it is conceivable that the streamflow regime was different in both experiments. The unusually wet summer and autumn of 1985 (see Figure 7.2) when the first tracer experiment took place would have produced more floods which could explain the overall higher rates of movement also. Finally, the local channel characteristics and in particular the presence or absence of organic debris jams in the forest and rock obstructions and pools in the moorland must exert an influence over the distance moved by the painted particles. However, it is beyond the scope of this study to attempt to explain or predict bedload transport. Nevertheless, the work has given some idea of the transport processes of coarse sediment in these streams.

The second way in which bedload dynamics were investigated was by means of a correlation analysis using the weight of bedload (sediment coarser than 2.8 mm) trapped (over variable periods within the record) as LOAD (kilograms) with various flow indices and thresholds. Moore and Newson (1986) analysed sediment trap data collected at Plynlimon in a similar way but also using climatic based supply factors. On the basis of their finding that climatic supply parameters were unimportant, only flow parameters as gauged by IH at the catchment outlets are used in this analysis: QMAX is the highest instantaneous discharge in the period, QSUM is the total volume of flow leaving the catchments in the period. In order to attempt to characterise the duration of 'competent discharges', suggested by Werritty (1981) to be a more important control over bedload transport and channel change in the river Nethy than 'flood peak discharge', some flow thresholds were chosen based on the usual discharges at which bedload starts to be collected by Helley-Smith sampling at the catchment outlets (~ 2 $m^3 s^{-1}$ in Kirkton and ~4 $m^3 s^{-1}$ in Monachyle (Johnson pers. comm.)). Therefore, mean discharge over the period, QMEAN, and two other flow thresholds were chosen for each catchment: T > 2 and T > 4 for Kirkton and T > 4 and T > 8 for Monachyle which are times (hours) exceeded by flow thresholds of 2, 4 and 8 $m^3 s^{-1}$ respectively. Table 5.13 shows the correlation matrices (in which all data are logarithmically transformed) for each catchment. Individual bedload traps as well as the total bedload trapped (K_{total} or M_{total} which is the sum of all bedload traps) in each catchment are the column headings, while the flow parameters are the rows. The bedload record is for trap accumulation over 20 variable time periods over the two year study period. There are n - 2 degrees of freedom (18) so that all correlation coefficients higher than 0.444 are significant at the 5% probability level and are underlined.

The results are difficult to interpret but in general most correlations are weak. There does not appear to be any particular trend, tributaries in the same catchment appear to correlate differently with the flow parameters and some have no significant correlations at all. Clearly, either the flow parameters are too crude or local factors of sediment supply and storage must exert a greater control over bedload transport than the crude flow indices chosen. For example, a sudden bank collapse in a particular tributary may supply more sediment to a bedload trap than would be predicted by these simple flow indices. Organic debris jams may interfere in different ways in different streams by either storing

Table 5.13: Pearson correlation coefficient matrix for Balquhidder tributary bedload (excavated from traps) and various flow indices and thresholds. Coefficients higher than 0.444 are underlined and are significant at the 5% level.

Kirkton Bedload

Flow parameter	K1	K4	K7	K8	K9	K12	Ktotal
Qmean	0.302	-0.038	0.356	0.301	0.167	0.027	0.310
Qmax	<u>0.503</u>	0.283	<u>0.580</u>	0.365	0.390	0.368	<u>0.480</u>
Qsum	0.233	-0.078	<u>0.516</u>	0.281	0.069	0.088	0.335
T > Qmean	<u>0.482</u>	0.029	<u>0.449</u>	<u>0.457</u>	0.223	-0.046	<u>0.550</u>
T > 2	<u>0.470</u>	0.155	<u>0.737</u>	0.408	0.341	0.301	<u>0.499</u>
T > 4	0.226	-0.291	<u>0.580</u>	-0.032	0.091	0.398	0.084

Monachyle Bedload

	M1	M2	M3	Mtotal
Qmean	0.009	<u>0.464</u>	-0.123	<u>0.644</u>
Qmax	-0.327	<u>0.697</u>	-0.186	<u>0.882</u>
Qsum	-0.242	<u>0.448</u>	0.043	<u>0.660</u>
T > Qmean	0.014	0.295	0.082	<u>0.583</u>
T > 4	<u>-0.456</u>	<u>0.594</u>	-0.327	<u>0.608</u>
T > 8	<u>-0.451</u>	<u>0.620</u>	-0.078	<u>0.529</u>

sediment and thus reducing the sediment yield or by bursting and releasing a sudden pulse of sediment. However, K_{total}, the sum of all the bedload trap catches seem to average out the local differences and this results in higher and significant correlations with the flow parameters, particularly in the moorland catchment. Here it is QMAX, the peak discharge in the period since the last trap excavation, which has the highest correlation coefficient of 0.882 with the M_{total}. However, in the forested catchment it is the time over which the mean discharge is exceeded which seems to correlate best with K_{total} at 0.550. It must be born in mind that this correlation coefficient is only just significant.

It may well be that the flow indices chosen, particularly the flow thresholds, are too crude. It is possible that the critical threshold for bedload movement at the catchment outlets is different in tributaries. Since no Helley-Smith sampling was carried out in the tributaries it was not possible to select a critical threshold for bedload movement (which may be variable anyway!). It may be that the threshold is lower in the tributaries and that they feed coarse sediment into the mainstream which is removed from tributary fans during a later flood - a two or more stage process? On the other hand the flow threshold for bedload movement in tributaries could be higher in which case bedload movement may only take place in tributaries during the highest flows and QMAX may well be the best predictor. Given the vast amount of work which has been, and is being, dedicated to trying to predict bedload transport it is hardly surprising that a simple analysis such as this has not been more successful in explaining bedload transport in these first and second order streams. It is outside the scope of this study to develop predictive equations for bedload transport, suffice to say that more work to refine the flow parameters and quantify sediment supply and storage factors will be needed if progress is to be made.

5.3.2 Bedload size distribution

At each time of excavating sediment from bedload traps during 1985 and 1986, a 5-10 kg bulk sample of the sediment was taken from the mass of sediment piled up into a cone on the bank. The sample was dried, its volume and weight measured to get an estimate of its bulk density, and then sieved at half phi intervals (coarsest usually < -7 phi (128 mm) through to 4 phi (0.063 mm)). Size distribution histograms and grainsize curves were plotted up for all samples using a FORTRAN graph plotting routine.

In the first instance it was possible to estimate what proportion of the sediment trapped was actually finer than 2.8 mm and therefore already estimated by the suspended sediment sampling programme. The average fine fraction (< 2.8 mm) was found to be 44% in the forest traps but only 12% in the moorland. This fine fraction was deducted from the total weights of bedload trapped for the purpose of estimating bedload yields. Figure 5.9 shows pie chart representations of the average size distribution of sediment trapped with the fine fraction included.

The median particle size (D_{50}) of bedload trapped in tributaries (> 2.8 mm only) is 32 and 8.0 mm in the moorland and forest catchments respectively and at the outlets (estimated from sieving Helley-Smith bedload samples) is 3.5 and 1.0 mm

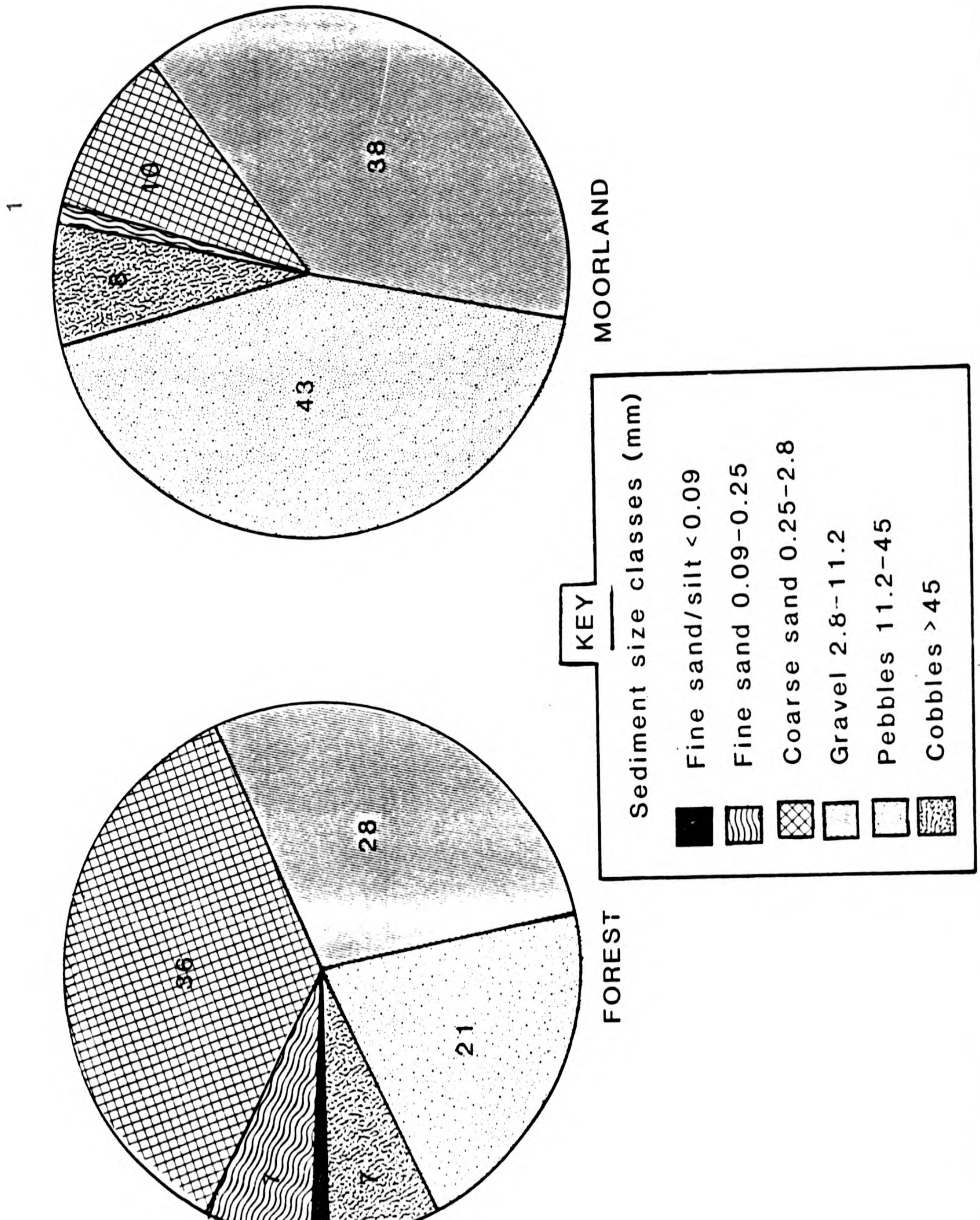


Figure 5.9: Pie chart representations of size distribution of sediment trapped in Monachyle and Kirkton tributary bedload traps.

respectively.

5.3.3 Coarse sediment loads

Bedload is that fraction of the sediment load coarser than 2.8 mm. Amounts trapped in different tributaries in April-December 1985 are expressed as loads (t yr^{-1}) and yields (t $km^{-2}yr^{-1}$) in Table 5.14 under the column headed Phase I and as yields in Figure 5.10. The mean yield from three moorland tributaries draining 26% of the Monachyle sediment contributing area (see unshaded area in Figure 2.7) was 0.3 t $km^{-2}yr^{-1}$, compared to 0.8 t $km^{-2}yr^{-1}$ from six forest tributaries draining 40% of the Kirkton sediment contributing area. These numbers differ slightly from those presented by Stott et al. (1986) as a result of reassessment of the areas drained by some tributaries - not easily judged from contour maps in such rugged terrain. These yields fall within the range reported by Newson (1984) for the British uplands.

5.3.4 In-channel sediment storage and debris jams

Previous work concerned with in-channel sediment storage due to organic debris damming appears to be largely from the western USA (e.g Heede 1972, Swanson et al. 1976, Keller and Swanson 1979, Keller and Tally 1979, Madej 1982 and Megahan 1982) and New Zealand (Mosley 1981). The main findings of this work were summarised in section 3.2.6.

At Balquhidder, tape and clinometer surveys were made on several tributary streams (the results of three are reported here) in an attempt to estimate the frequency of organic debris jams and their importance as sediment stores in a different environment to that in which most previous work had been carried out. Detailed

Table 5.14: Average tributary bedload (sediment > 2.8 mm only) in t yr^{-1} and catchment yields (t $km^{-2} yr^{-1}$) for both phases of the experiment. '-' indicates no data is available in Phase II due to bedload traps not functioning, '*' indicates the sub-catchment was disturbed directly by forestry operations in Phase II.

		Phase I (05.02.85 - 14.10.85)		Phase II (15.10.85 - 25.5.87)	
Stream	Area (km^2)	t yr^{-1}	t km^{-2} yr^{-1}	t yr^{-1}	t km^{-2} yr^{-1}
Kirkton (forest)					
K1	0.42	0.28	0.66	0.51	1.22
K4	1.23	0.05	0.04	0.11	0.09 *
K7	0.42	0.09	0.22	-	-
K8	0.20	1.27	6.34	1.08	5.39
K9	0.16	0.51	3.22	0.53	3.30 *
K12	0.17	0.12	0.70	0.16	0.94 *
Total	2.60	2.32		-	-
Monachyle (Moorland)					
M1	0.24	0.03	0.13	0.08	0.34 *
M2	0.55	0.62	1.13	-	-
M3	0.49	0.03	0.07	0.05	0.10 *
Total	1.28	0.68		-	-

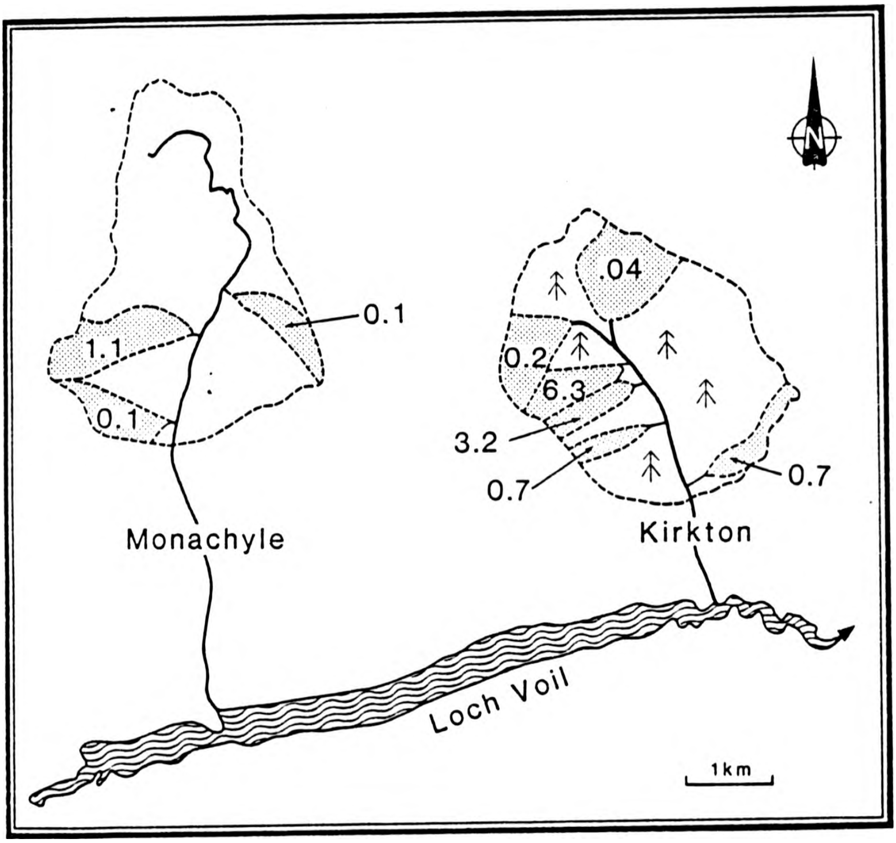


Figure 5.10: Sub-catchment bedload (sediment > 2.8 mm only) yields in t km^{-2} yr^{-1} for Phase I of the experiment.

surveys of two forested tributaries (K4 and K7) and one moorland tributary (M1) were conducted. The stream long profile of K7 (forested) is plotted in Figure 5.10 marking the locations of pools, sediment stores and debris jams. It must be born in mind that for much of their course these mountain streams flow on bedrock, with sediment stores and pools at variable intervals, the spacing of which depends on a number of local factors such as stream gradient, sediment size, channel geometry and supply of organic material to the channel (obviously greater in the forested streams). Both the moorland and forested stream long profiles have the characteristic 'step-pool' appearance reported for example by Heede (1972), Whittaker and Davies (1982) and Whittaker (1987). Natural steps in both moorland and forested streams may occur as a result of a sudden increase in the bedrock gradient. In the moorland stream steps also form as a result of one or a number of larger clasts becoming jammed at a point where the channel narrows. These have been classified as 'rock-steps' by Whittaker (1987). Sediment particles of all sizes then begin to accumulate behind the larger jammed clasts. Streamflow rushes over the 'rock jam' and a small waterfall begins to develop on the downstream side of the jam which increases in size as it erodes downwards creating a plunge pool. The size of the feature seems to be related to the size of the initial rock clasts which were jammed. In the forested stream organic debris jams form in the same way (referred to by Heede (1972) as 'organic stepping'), their size, permanence and frequency depending on the supply of organic material from the forest. This of course can be increased at the time of thinning (about 15 years

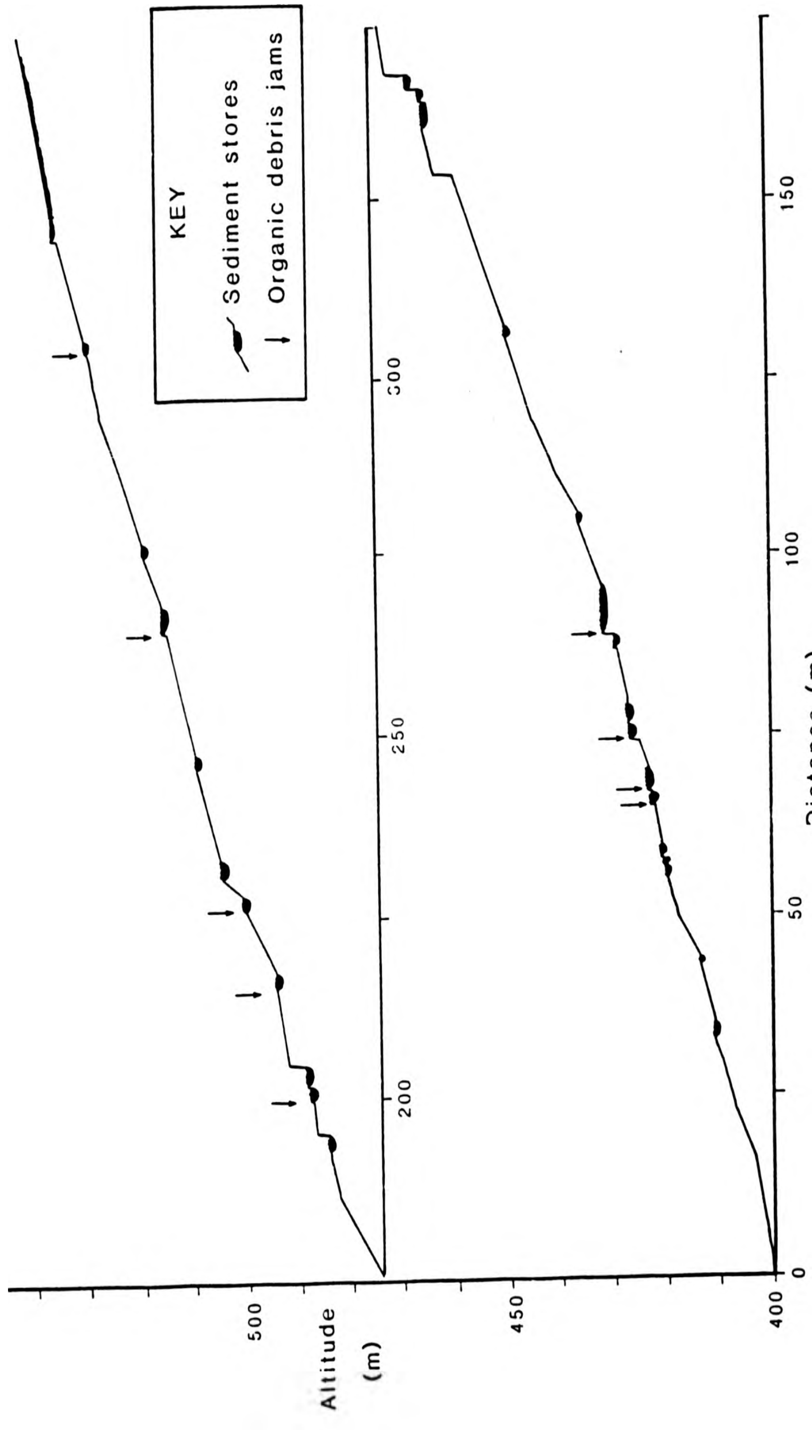


Figure 5.11: Long profile of tributary K7 showing debris jams (location indicated by arrows) and sediment stores.

after planting) and clearfelling unless care is taken to 'clean out' stream courses afterwards. Also, managed plantation forest as at Balquhidder is unlikely to produce nearly as much organic debris as primary or natural forest where all ages of trees are represented. Trees dying naturally of old age are not likely in a Forestry Commission plantation. This should be borne in mind when comparing the results presented here with other studies which are entirely from the western U.S. where the forests are natural.

Tape and clinometer surveys of the long profiles of tributaries were carried out. Notes were made of significant sediment stores (either natural pools or behind obstructions) and the approximate size of the store estimated by measuring its surface area. However, no satisfactory method of estimating sediment store depth was found (driving in of a graduated pointed steel bar proved to be unsatisfactory since where sediment was coarse it was not possible to know whether a large particle had been reached or whether it was bedrock). Nevertheless, it has been possible to make some crude estimates of in-channel sediment storage for typical Balquhidder tributaries (K7), forested in its lower part and moorland in the upper section (see Figure 5.10) and M1, entirely moorland. Considering first the measured surface areas of sediment stores along the forested reach (400 m) of K7 (see Figure 5.11) - there were 34 significant sediment stores with a total surface area of 346 m^2 which represents 865 m^2 km^{-1} of channel. Above the tree line 6 stores were surveyed along 150 m of channel with a total surface area of 26 m^2 which represents 173 m^2 Km^{-1}. In the moorland stream (M1) 19 stores were present in 300 m of channel, the total surface area being 87 m^2 representing 290 m^2km^{-1} of channel. Both above the tree-line in stream K7 and in the moorland stream (M1) the measured surface area of stored sediment appears to be between 20 and 35% of that measured in the forested reach. It therefore appears that in terms of sediment surface area some 3 to 4 times more sediment is stored in the channel in the forested reach and this can only be attributed to organic debris jams which are not present outside the forest.

Clearly, since the average depths of the sediment stores were not measured it is difficult to compute volumes and masses of sediment. However, from occasional measurements of debris jam heights (bearing in mind that sediment stores are likely to be wedge shaped with the thin end upstream), it seems reasonable to assume that average sediment depths would vary between 0.1 and 0.5 m. Using these approximations it is possible to compute maximum and minimum sediment volumes stored, and also sediment mass (t) assuming average bulk density of 1.4 t m^{-3} (as estimated from sediment trap bulk samples):

Total length of stream K7 = 1100 m

Total area of sediment stored = 372 m^2 in 550 m of channel

= 1040 m^2

Minimum volume stored = 1040 m^2 x 0.1 m

= 104 m^3 = 0.1 m^3 m^{-1} of channel

Maximum volume stored = $1040\ m^2 \times 0.5\ m$

= $519\ m^3 = 0.5\ m^3\ m^{-1}$ of channel

K7 in-channel sediment mass (bulk density $1.4\ t\ m^{-3}$)

= 150 (min) to 700 (max) t

= 0.1 to $0.7\ t\ m^{-1}$ of channel

K7 coarse sediment yield > 2.8 mm (1985) = $0.1\ t\ yr^{-1}$

= < 0.1% of min. in-channel storage

Dietrich et al. (1982) in constructing their sediment budgets compute residence times:

Mean residence time in storage = mass of sediment stored / flux

At Balquhidder minimum and maximum residence times of sediment in storage can be estimated using the above formula to be:

= 150 (min.) / 0.1 or 700 (max.) / 0.1

= 1500 to 7000 yrs.

This implies that the residence time of coarse stored sediment is more than 1000 years. It is reasonable to assume that the in-channel sediment storage estimated for K7 is typical of other tributaries in Kirkton glen since all are of a similar gradient (see Table 2.1) and length (see Figures 2.2 and 2.3) and all have been subjected to the same forestry activities (planting and thinning). The mid-point of the range of in-channel sediment storage (400 t) is taken as a typical average for the other tributaries for which bedload yield has been measured. For the 7 tributaries equipped with bedload traps the bedload yield ranges from 0.05 - 1.27 with a mean of $0.38\ t\ yr^{-1}$. Thus, the sediment yield expressed as a percentage of that stored in the channel is (0.38 / 400) x 100 = 0.1% or about 1000 years of sediment yield are held in storage. In other words, by taking the mean bedload yield of all the forest tributaries monitored, rather than just K7, the mean residence time estimated is as about 1000 years. This would imply that the coarse sediment transport movement rates estimated in the second pebble tracer experiment (II) of 8.1 and 6.3 m yr^{-1} in the forest and moorland streams respectively are over estimating the rate of coarse sediment transport down the tributaries. This is logical since the percentage recovered was down to 40% in the smaller size classes. This infers that the remaining 60% which were not recovered must have gone into long term storage. The amount of in-channel sediment storage estimated here differs from that reported by Megahan (1982) working in the Idaho batholith, USA, who estimated that 15 years of sediment yield is stored behind organic debris obstructions. Swanson et al. (1976) also working in the north-western USA calculated that 5-10% of the sediment in storage is yielded annually. From all of these estimates it is clear that small changes in the in-channel storage of sediment could greatly affect sediment yields and likewise, extra sediment entering the channel from the hillside (as could be the case after clearfelling) may be added to this large sediment store and may not show up in the measured sediment yield for some time. The in-channel sediment store thus acts as a buffer.

The much higher residence times estimated for coarse sediment in Balquhidder tributaries compared with Pacific north west U.S findings could be a function of the debris jam spacing. Plate 3.6 shows the nature of some of this in channel organic debris. The debris jam spacing computed from surveys of two forested tributaries, K4 and K7, are 7 jams for 550 m surveyed = 13 jams km^{-1} and 9 jams for 400 m surveyed = 23 jams km^{-1} respectively. In the Pacific NW U.S, Madej (1982) found 2.5 km^{-1} and Megahan (1982) reports 3.6 per 30 m of channel which corresponds to 120 km^{-1}. Thus, the organic debris jam spacing appears to fall within the range found in the north-west US but it must be remembered that the figures for the Pacific NW U.S are for primary undisturbed forest, whereas the figures computed at Balquhidder are for plantation forest only 45-50 years old, but which has undergone thinning at 15-20 years after planting. The sediment stores resulting from organic debris jams in Balquhidder forested tributaries appear to have 3 to 4 times more in-channel sediment storage than moorland tributaries.

5.4 Effect of disturbance

As reported in section 3.5 the land use conversions occurred just over half way through the fieldwork period. Ploughing affected all three of the moorland sub-catchments equipped with bedload traps and ditching affected tributary M1 also (equipped with bedload trap and intensive suspended sediment sampling).

At the outset of the study K4 and K8 were selected as tributaries in which to perform intensive suspended sediment sampling. In the original plan, K4 was to be the control stream to remain undisturbed and K8 was to be felled early in the schedule at the request of the DAFS Freshwater Fisheries Laboratory, Pitlochry who were monitoring the water chemistry in both K4 and K8 throughout clearfelling. However, in practice the northern stacking area construction reported in section 3.5 affected tributary K4 which was equipped with a bedload trap and suspended sediment sampling throughout the period. Apart from the felling of a few trees near the lower road in the K8 sub-catchment this tributary remained more or less unaffected by the end of the field sampling programme in May 1987. Of the other sub-catchments in the forest which were equipped with bedload traps K1 remained completely undisturbed. Felling in the K9 sub-catchment started on the southern boundary in the last week of November 1986 but ceased soon after when only the southern half was felled, this was still the situation at the end of the fieldwork programme in late May 1987. The K12 sub-catchment was completely felled during April and

May 1987 but since clearfelling of K12 was so late in the sampling period, no flood events were experienced in the month of May 1987 and there was no noticeable change in the amount of bedload excavated from the K12 bedload trap on the last excavation on 25 May 1987. The bedload trap in K7 was discontinued after May 1986 when the trap which was located in front of a road culvert was removed by forestry workers (presumably deemed to be a flood hazard?!). This sub-catchment remained undisturbed by the end of the study. Figure 5.10 presented the average bedload yields for all tributaries in Phase I.

5.4.1 Effect of afforestation

Several studies elsewhere have reported dramatic increases in suspended sediment loads during and after forestry ploughing and ditching operations (e.g. Robinson 1978, Burt et al. 1984, Francis 1987). The increase in suspended sediment yield is attributed to increases in fine sediment supply resulting from exposure and erosion of the subsoil. However, in the case of the event sampling in tributary M1 Table 5.4 shows how suspended sediment concentrations in the post-ploughing and drainage ditching period (Phase II) actually decreased. Statistical tests on the Phase I and II concentrations have confirmed that the two populations are significantly different at the 0.1% level. This was a surprising and unusual finding and at first appeared to be inexplicable, but some hand sampling during a flood event on 21 October 1986 (3-4 months after the drainage ditch was dug) taken from water issuing from a plough furrow, from water in the drainage ditch and from the water flowing overland into M1 (upstream of the usual sampling point) had exceptionally low suspended sediment concentrations. Figure 5.12 is a large-scale plan of the lower part of the M1 sub-catchment with the sampled concentrations marked. Plate 5.1 is a view looking north west from the footbridge in Figure 5.12 up the sub-catchment. The only explanation which can be offered for the lower suspended sediment concentrations sampled in M1 in the post-ploughing and ditching period is that water collected from the plough furrows by the cross-drain (which flows overland and into M1 upstream of the sampling point) carried significantly less suspended sediment than the background concentrations sampled in M1.

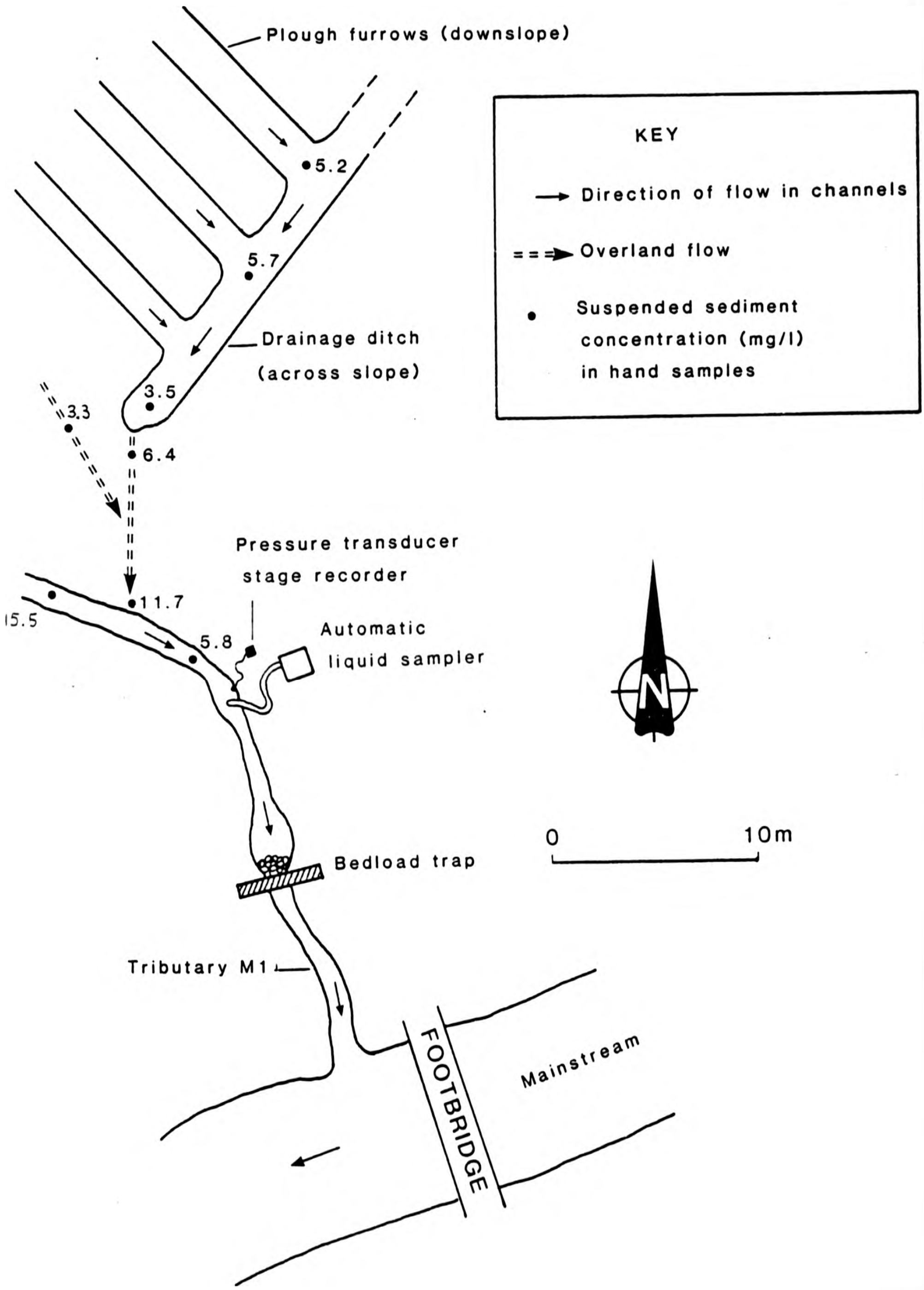


Figure 5.12: Plan of sampling area in M1 sub-catchment showing location of drainage ditch, hand sampling points and suspended sediment concentration in the samples expressed in mg l^{-1}. Sampling carried out on 5 October 1986.

Plate 5.1 View of Monachyle sub-catchment M1 after ploughing and ditching. The arrow 'A' indicates the downslope end of the drainage ditch, 'B' is the overland flow track from the ditch to the M1 stream, 'C' indicates the flow direction of the M1 tributary, 'D' is the automatic sampling point and 'E' is the bedload trap.

Sampling of three flood events at Upper M1 during the summer of 1986 (data are summarised at the bottom of Table 5.4) confirms that the background concentrations upstream of the point at which the drainwater enters M1 has concentrations not significantly different from in Phase I and significantly higher than the Phase II mean concentrations sampled downstream of where the drainwater enters the tributary. In this particular example the effect of installing the cross-drain which delivers water into M1 appears to have been to dilute the suspended sediment load in M1 with water carrying an even lower suspended load collected from the plough furrows. This can be explained in terms of Walling and Webb's (1982b) mixing model for explaining suspended sediment concentrations wherein it is proposed that suspended sediment concentrations reflect the mixing of sediment-laden storm runoff with the prevailing sediment free baseflow (or in this case baseflow and drainwater). Just why the water draining from the plough furrows should have such low suspended sediment concentrations is not clear. It seems that within the M1 sub-catchment the majority of the ploughing was in peat and did not disturb the underlying mineral soil except in a few places at the upslope end of the furrows. Ploughing of the mineral soil appears to have been kept to a minimum which may well have helped to keep suspended sediment concentrations low. However, in cases where the mineral soil was disturbed fans of fine sediment accumulated at the downslope end of the furrows seen in Plate 5.2. It appears that the coarse nature of this sediment has resulted in it being deposited in the riparian buffer zone. Plate 5.3 shows the nature

Plate 5.2 Fine sediment issuing from the downslope end of plough furrows in M1 sub-catchment in September 1986 four months after ploughing. Note where the ploughing has disturbed the mineral soil which underlies the peat at the top of the photograph. (taken by R.I. Ferguson).

Plate 5.3 Sediment deposits in the riparian buffer zone, Monachyle, after drainage ditching. The rucsac marks the end of a drainage ditch. Note the relatively coarse nature of some of the sediment in front of the shovel. Photograph taken in May 1987 twelve months after ditching.

of this sediment which has been delivered to the riparian buffer zone from a cross-drain further up the catchment.

Figure 5.13 presents cumulative tributary bedload yields for the study period for all bedload traps. The three moorland bedload traps are M1, M2 and M3 and the timing of the ploughing and draining operations are indicated on the curves. The ditching operations do appear to have caused a four-fold increase in bedload trapped in M1 and M3. In the case of M1 it seems that it was the termination of the cross-drain some 10 m upslope to the north of the stream (indicated in Plate 5.1) which appears to have caused the observed increases in bedload trapped. As mentioned earlier the cross-drain collected water and sediment from a number of plough furrows, and by the late summer sediment (mostly finer than approximately 8 mm) had accumulated in the downslope end of the ditch. It seems that this became flushed out with the drain's discharge overland as bedload into tributary M1 during successive flood events. Particles of up to 8 mm were observed on the flow track (see Plate 5.3).

Tributary M3 however, was crossed by the ploughing and ditching machines every day during the two month period when the upper part of the catchment north of tributary M3 was being ploughed and ditched. This caused damage to the bed and banks of the stream some 50 m upstream of the bedload trap and resulted in the increase in bedload trapped over the late summer and autumn of 1986. Some recovery to the pre-disturbance yield appears to have taken place by May 1987. Though this may not be obvious from the cumulative curves, it was borne out by time-series plots of the

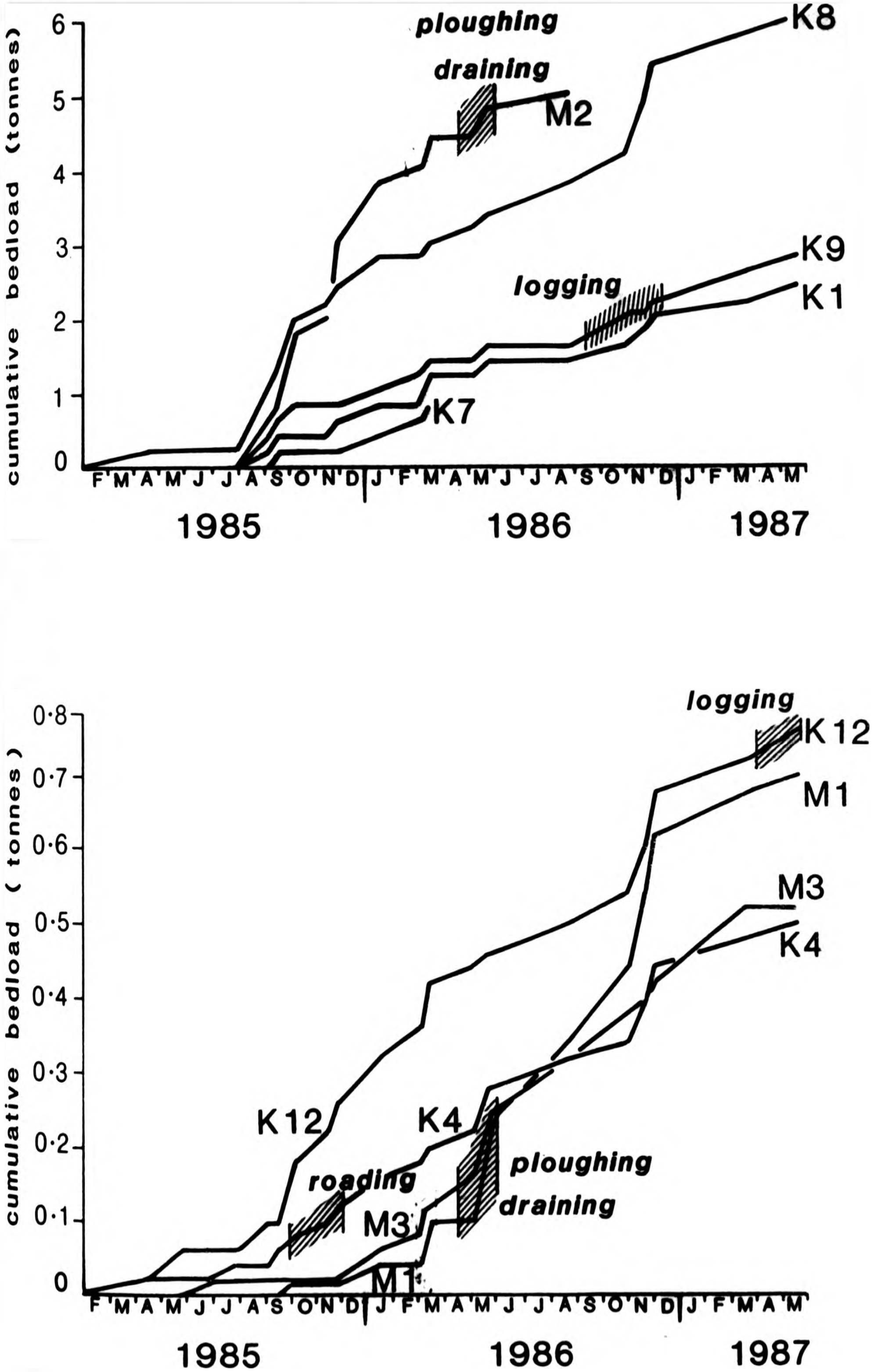


Figure 5.13: Cumulative tributary bedload yields (in tonnes) for the study period 1985-7. Approximate timing of forestry activities are marked. Note the different vertical scales for the two plots.

data.

M2 is a larger tributary than either M1 or M3 and until November 1986 had much higher bedload yields (note the different vertical scale in Figure 5.13). This is represented by the steeper slope of its cumulative curve. However, there was a sudden termination of bedload accumulating in the trap after autumn 1986 and this was due to a bank collapse which occurred some 5 m upstream of the trap and completely blocked the channel. Plate 5.4 taken on May 25 1987 shows the bedload which was deposited behind this turf obstruction thereby causing no bedload to reach the trap. The cumulative curve would therefore flatten out and is not plotted beyond the time of the bank collapse.

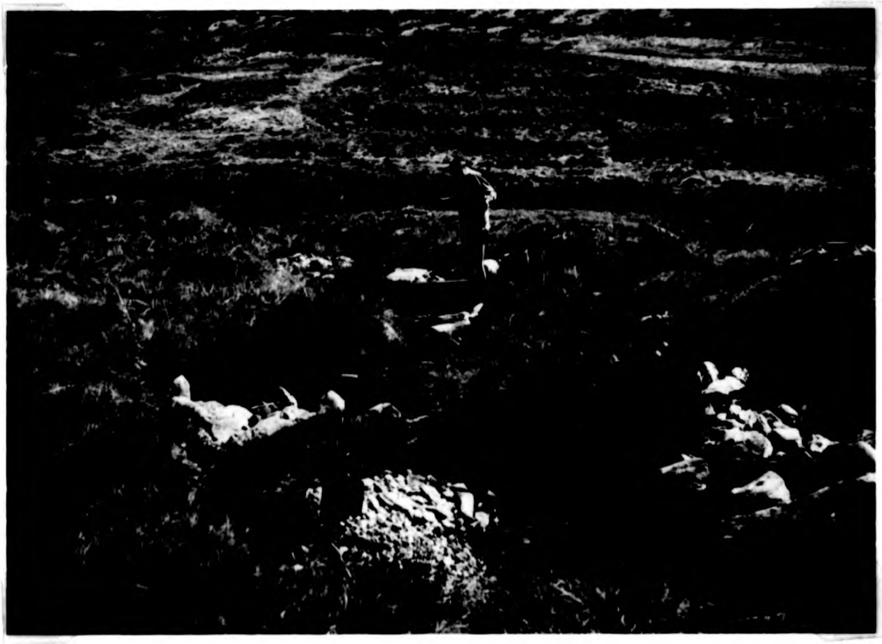


Plate 5.4 Bank collapse and channel blockage in M2 at the end of the study period in May 1987. The shovel marks the accumulation of sediment behind the turf obstruction, no sediment therefore accumulated in the bedload trap downstream where the field worker is standing.

5.4.2 Effects of clearfelling

Three of the six sub-catchments equipped with bedload traps were directly affected by deforestation activities. They were K4 (in which the northern stacking area was constructed), K9 (half of which was clearfelled by December 1986, and K12. The K12 sub-catchment was clearfelled during late April and May 1987 right at the end of the study period. No flood events were experienced during May 1987 and since the last bedload trap excavation. There was no apparent change in the sediment yield estimated from the last K12 bedload trap excavation on 25 May 1987. This tributary is therefore not discussed any further in this section.

Tributaries K4 and K8 were sampled for suspended sediment throughout the period. K8 remained unaffected by the deforestation programme during the fieldwork period and so a single rating curve is applied to estimate the total suspended sediment load (see Figure 5.5). K4 however was affected by the construction of a timber stacking area just upstream of the suspended sediment sampling point during November and December 1985 in the middle of the study period. Plate 5.5 shows the work in progress and the extent of the cleared area in early December 1985. On the morning of 20 May 1986 some opportunistic suspended sediment hand sampling was carried out around the K4 (northern) stacking area during a sudden rainstorm. Hand samples were taken from runoff from the stacking area which was flowing for some 200 m down the road gully seen in Plate 5.6 (a) (taken a week later) and entering tributary K4. The brown runoff seen in Plate 5.6 (b) was heavily laden with fine

Plate 5.5 Preparing the northern Kirkton stacking area in K4 sub-catchment, December 1985.

(a)

(b)

Plate 5.6 (a) Road gully and runoff at K4 sampling site.

(b) Sediment laden road runoff entering tributary K4, May 1986. 'A' indicates the upstream or background samples (marked Δ in Figure 5.14), 'B' indicates sampling point of the road runoff (marked O in Figure 5.14) and 'C' indicates the downstream sampling points (marked X in Figure 5.14).

sediment and the peak suspended sediment concentration in the road runoff was close to 50 000 mg l^{-1} and was by far the highest ever recorded during the study. Further samples were collected from tributary K4 (as indicated on Plate 5.6 (b)) both upstream (typical background concentrations were around 10 mg l^{-1}) and downstream (concentrations of the order of 100 mg l^{-1} were measured) of where the road runoff entered the tributary. Clearly, although the sediment laden road runoff is diluted considerably on entering tributary K4, it still has the effect of raising the background suspended sediment concentration by an order of magnitude during this storm event. Further hand samples were collected from other tributary streams draining from the stacking area into the mainstream, and from the mainstream itself both upstream and downstream of the stacking area. All the measured suspended concentrations as well as the duration of the storm rainfall are summarised in Figure 5.14 from which it appears that suspended sediment concentration was higher while it was actually raining. From the field observations it seemed likely that rainfall impacting on the bare stacking area surface was detaching sediment particles which are then carried in surface runoff (e.g. the road gully seen in Plate 5.6 (a)) to the streams. This type of sediment production from forest road surfaces was studied by Reid (1981) and Reid and Dunne (1984) in the north-west USA and more recently by Fukushima (1987) in Japan.

In order to investigate the possibility that stream sediment concentrations in K4 downstream of the stacking area were more closely related to rainfall intensity than to stream discharge

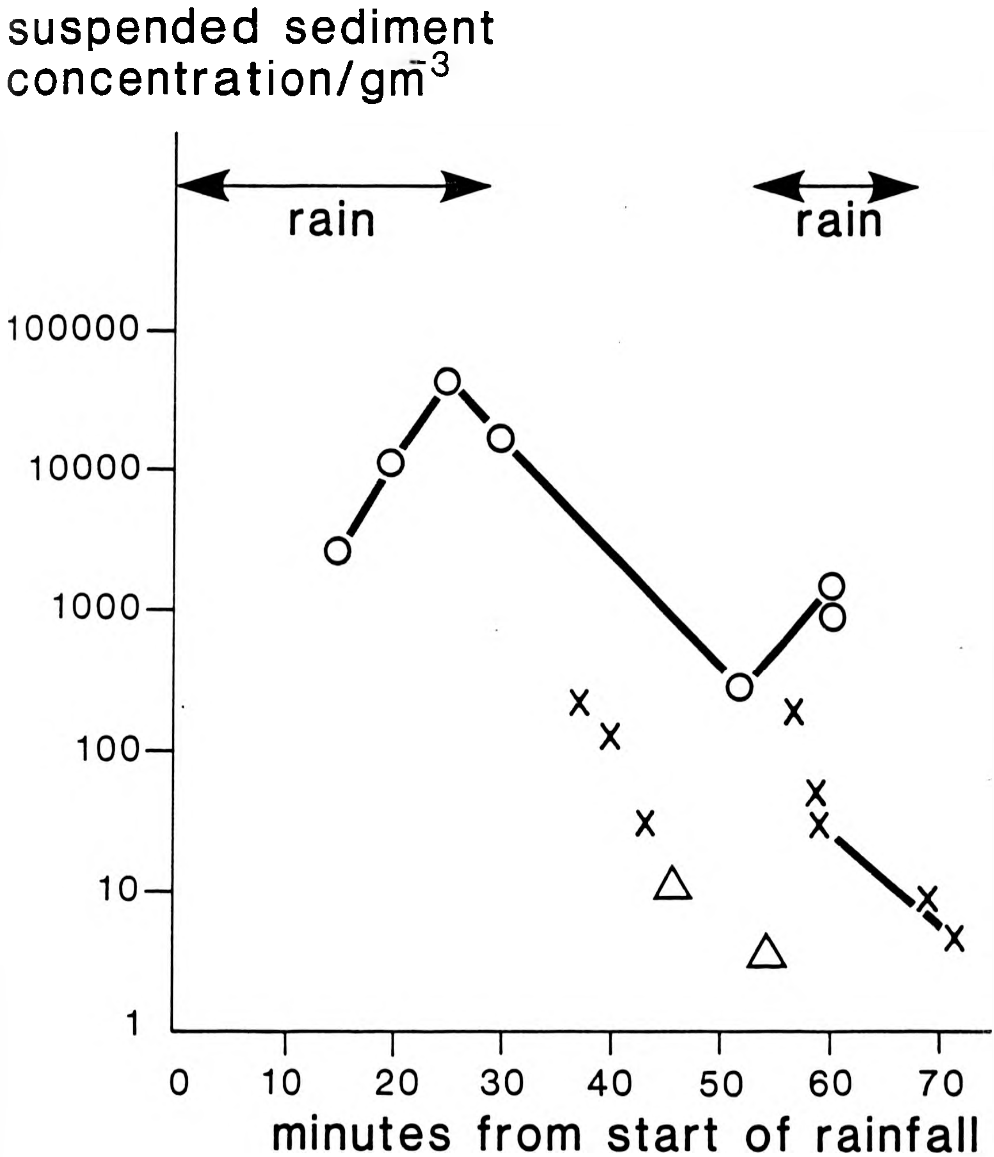


Figure 5.14: Suspended sediment concentrations (g m⁻³) in manual samples of runoff from the unsurfaced road and timber stacking area in the K4 sub-catchment (O), and in streams above (Δ) and below (X) the road, during a minor rainfall event on 20 May 1986. See plate 5.6 (b) for photograph of sampling points.

two automatic samplers were sited on stream K4, one upstream (upper K4 or UK4 hereafter) and one downstream (lower K4 or LK4) of where the sediment laden road runoff flowed into the K4 tributary. Several flood events were sampled during autumn 1986. Hourly rainfall intensity data for two storm events on 28 October and 5 November 1986, during which suspended sediment was sampled at 30 minute intervals in K4, were obtained from an IH Rimco tipping bucket raingauge located in the centre of the catchment some 1.5 km from the K4 sampling site (see Figure 2.2). In most cases two suspended sediment samples were taken per hour by each sampler. In order to compare these data with the rainfall intensity data the two samples and the corresponding instantaneous stream discharges were averaged to give compatible hourly data. The summary concentration (C) in mg l^{-1}, discharge (Q) in l s^{-1} and rainfall intensity in mm hr^{-1} (I) data are presented in Table 5.15.

The 28 October storm had a higher maximum rainfall intensity but lower mean than the 05 November storm. On 5 November the flood mean discharge was 2 to 3 times higher than on 28 October but mean sediment concentrations at both sampling points (UK4 and LK4) were about half. It must be borne in mind that the 28 October storm was one of the first following a dry September and October during which time it is suggested that supply of loose sediment on the stacking area was large whereas the supply for the 05 November storm which was soon after had been exhausted. This might help to explain the considerably lower concentrations sampled on 05 November even though the flood event was much larger. A second possible explanation is that the more intense storm of the 28

Table 5.15: Suspended sediment concentration (C) mg.l⁻¹, discharge (Q) l.s⁻¹ and rainfall intensity (I) mm.hr⁻¹ data for stream K4 during two sampled events in autumn 1986

		Mean over whole storm	Storm Maximum
28 October 1986			
Upper K4	C (mg.l⁻¹)	72	176
Lower K4	C (")	58	221
	Q (l s⁻¹)	176	202
	I (mm.hr⁻¹)	2.0	6
05 November 1986			
Upper K4	C	39	71
Lower K4	C	25	34
	Q	453	673
	I	2.5	4

October might have eroded more sediment from the bare stacking area surface by rainsplash detachment processes.

A correlation analysis was carried out on the data in Table 5.15 to see whether stream discharge or rainfall intensity had more effect on suspended sediment concentrations sampled at two points in the stream. Table 5.16 presents the results of this analysis.

Table 5.16: Pearson correlation coefficients for suspended sediment concentration (C), stream discharge (Q) and rainfall intensity (I) at two sampling points downstream of the northern stacking area on tributary K4. All data ~~is~~ are logarithmically transformed.

	$\log_{10}$ UK4 C	$\log_{10}$ LK4 C
Flood of 28 October		
$\log_{10}$ Q	0.185	0.281
$\log_{10}$ I	0.114	0.576*
Flood of 5 November		
$\log_{10}$ Q	0.081	-0.072
$\log_{10}$ I	0.798*	0.417

* indicates correlation coefficients significant at the 5% level.

During both flood events suspended sediment concentrations (C) are correlated more highly with rainfall intensity (I) than with streamflow (Q) and it is only the correlations of rainfall intensity with concentration (*) which are significant. However, in the first storm it is the downstream (LK4) sampling point at which concentration correlates best with intensity whereas in the second storm it is the upstream (UK4) sampling point at which concentration correlates more highly. One explanation for this could be that as explained earlier, the 28 October storm followed a long dry period in September and October. Flood mean concentration is higher at both sampling points and it is the lower sampling point (LK4) downstream of the road gully entry point which correlates best with rainfall intensity. Runoff from this road gully is much more controlled by rainfall intensity (see Figure 5.14 and Plate 5.6). It is therefore likely that this sediment laden road runoff, generated during heavy rainfall, is dominating the suspended sediment concentrations at LK4. However, in the second storm, owing to the large sediment supply from the road and stacking area (transported to stream K4 in the road runoff) being depleted in the first storm, the concentrations in the road runoff must have been lower than the concentrations from upstream (sampled at UK4). The contribution of the road runoff as a sediment source must have been less in the 05 November storm. A second possibility is that the different mean and maximum rainfall intensities of the two storms summarised in Table 5.15 might account for the differences in the observed stream suspended sediment concentrations with the more intense shorter duration 28 October storm generating higher mean and maximum concentrations at both sampling points than the lower intensity longer duration 05 November storm. In conclusion, both the road runoff sampling exercise summarised in Figure 5.14 and the results of the correlation analysis suggest that most sediment reaches the streams during rainfall when overland flow from the stacking area and roads can carry exceptionally high sediment loads to streams.

In terms of the sediment load of tributary K4 the overall effect of constructing the stacking area was to increase the slope of the suspended sediment rating curve at UK4 as shown in Figure 5.5 which resulted in an increase in the total suspended sediment yield from an average of 133 t km^{-2} yr^{-1} in the 1983-85 period to 170 t km^{-2} yr^{-1} in 1986 (see Table 5.8). In terms of the actual suspended sediment load this represents an additional 30 t in 1986 even though the mean annual discharge for 1986 is lower than for 1985. This means that there was a real increase in the suspended sediment yield which must have been due to an increase in the supply of fine sediment (from the stacking area) and not due to a different streamflow regime. Section 5.2.2 discusses the likely year to year variation in suspended sediment yield which can be expected in these streams.

In order to find out if erosion (surface lowering) of the stacking area could account for the increased sediment load measured in K4 a newly exposed slope resulting from the construction of the stacking area was instrumented with 50 erosion pins (see Plate 5.7) as used elsewhere to measure slope erosion (e.g. Bridges and Harding 1974, Haigh 1977). The pins were 1 cm diameter x 30 cm and were installed in a grid pattern and resurveyed on two successive occasions. Average slope retreat values of 10.7 $\pm$ 2.8 mm (over 115 days) and 9.7 $\pm$ 2.5 mm (over the following 112 days) were estimated for the periods 10 October 1986 to 02 February 1987 and 02 February 1987 to 25 May 1987

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Plate 5.7 Erosion pins installed in the newly exposed roadbank on the northern Kirkton stacking area. Fifty pins were installed in this slope and average slope retreat measured over six months. (taken by R.I. Ferguson).

respectively. Over the whole period 10 October 1986 to 25 May 1987 (227 days) the average slope retreat was 17.4 mm with a standard error of 3.6 mm or 21%. The total area exposed by constructing the stacking area (including sloping area) was measured and estimated to be 2050 m^2 and the bulk density of the surface soil/sediment estimated at 1.2 t m^{-3}. These were only measured on one occasion and so it is not possible to attach measurement errors to these numbers but it is reasonable to assume that the errors are much smaller than for the erosion pin measurements (probably not more than a few percent). Since these errors are outweighed by the erosion pin measurement error they are ignored in estimating the total error. The total sediment removed from the stacking area is then estimated as the product of average slope retreat (m), exposed area (m^2) and surface sediment bulk density (t m^{-3}) and the estimated error is calculated as +/- 21% of the total mass of sediment removed.

The estimated sediment loss is 69 t yr^{-1} and the standard error of the estimate at the 5% confidence level is +/- 28 t yr^{-1}. Since all the extra sediment passing the sampling point downstream in 1986 must have come from surface erosion of the stacking area, the sediment that would be produced using the minimum estimated measurement error is 69 - 28 = 41 t yr^{-1}. This is more than enough to explain the increased sediment yield of stream K4 (30 t yr^{-1}). It must be born in mind that the slope retreat rate estimated from erosion pin measurements and used in this calculation is for a steep cut bank and therefore it is likely that the erosion rate is higher than for much of the rest of the stacking area draining into tributary K4. This might help to explain why the estimated amount of sediment eroded from the stacking area (69 ± 14 t yr^{-1}) exceeds the increased suspended sediment yield (30 t yr^{-1}) measured downstream in tributary K4.

In K4 the total amounts of bedload excavated from the bedload trap are exceptionally low compared to other tributaries but appear to have doubled from 0.04 to 0.09 t $km^{-2}yr^{-1}$ after the construction of the stacking area (see Table 5.14). Figure 5.15 illustrates how the grainsize distribution of sediment excavated from trap K4 becomes finer over the winter of 1985/86 after which fine sediment presumably washed off the newly exposed stacking area became deposited in the K4 trap. After the winter the D_{50} of the sediment trapped becomes finer than the netlon mesh lining the trap. In the pre-stacking area period only 5% on average of the sediment trapped was finer than 2.8 mm. However, in the post-disturbance period an average of 64% was finer than 2.8 mm. For comparison the average proportion of fine (< 2.8 mm) sediment in 44 sieved bulk samples taken from all forest bedload traps over the study period was 44%.

The southern stacking area (see Figure 2.2) was constructed in March 1984 before the start of this investigation. Figure 5.16 is a plan of this southern stacking area showing its location in the catchment in relation to the main IH weir, its main drainage pattern and stores of fine sediment (S1 and S2) identified during a survey made on 14 June 1985. Bulk samples were taken from the two stores and sieved at half phi intervals. Median grainsizes were 0.125 and 0.032 mm from stores S1 and S2 respectively. These lie

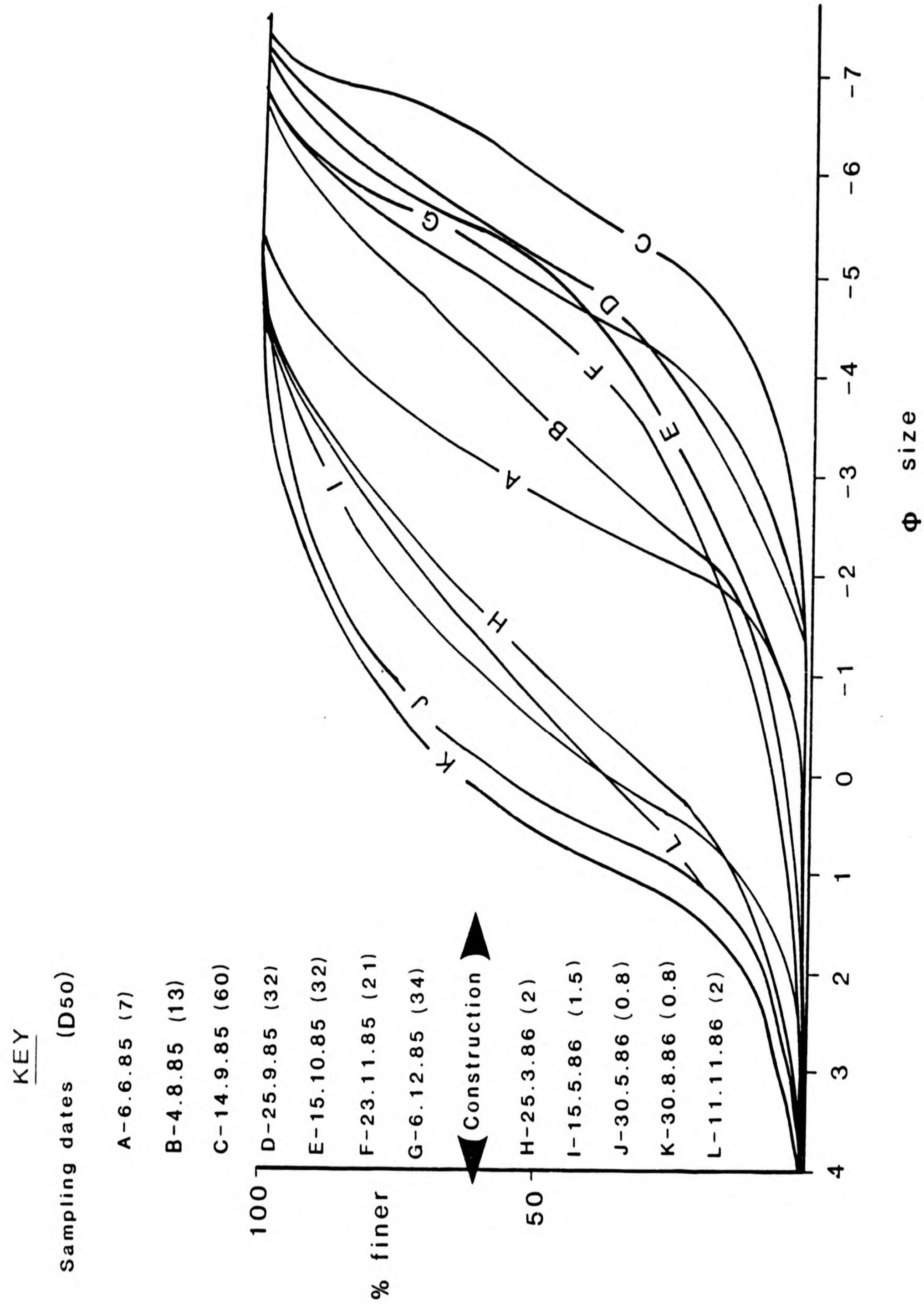

Figure 5.15: Grainsize curves for sediment trapped in K4 bedload trap downstream of timber stacking area (June 1985 - November 1986). Curves A - G are samples taken before construction of the stacking area, H - J after.

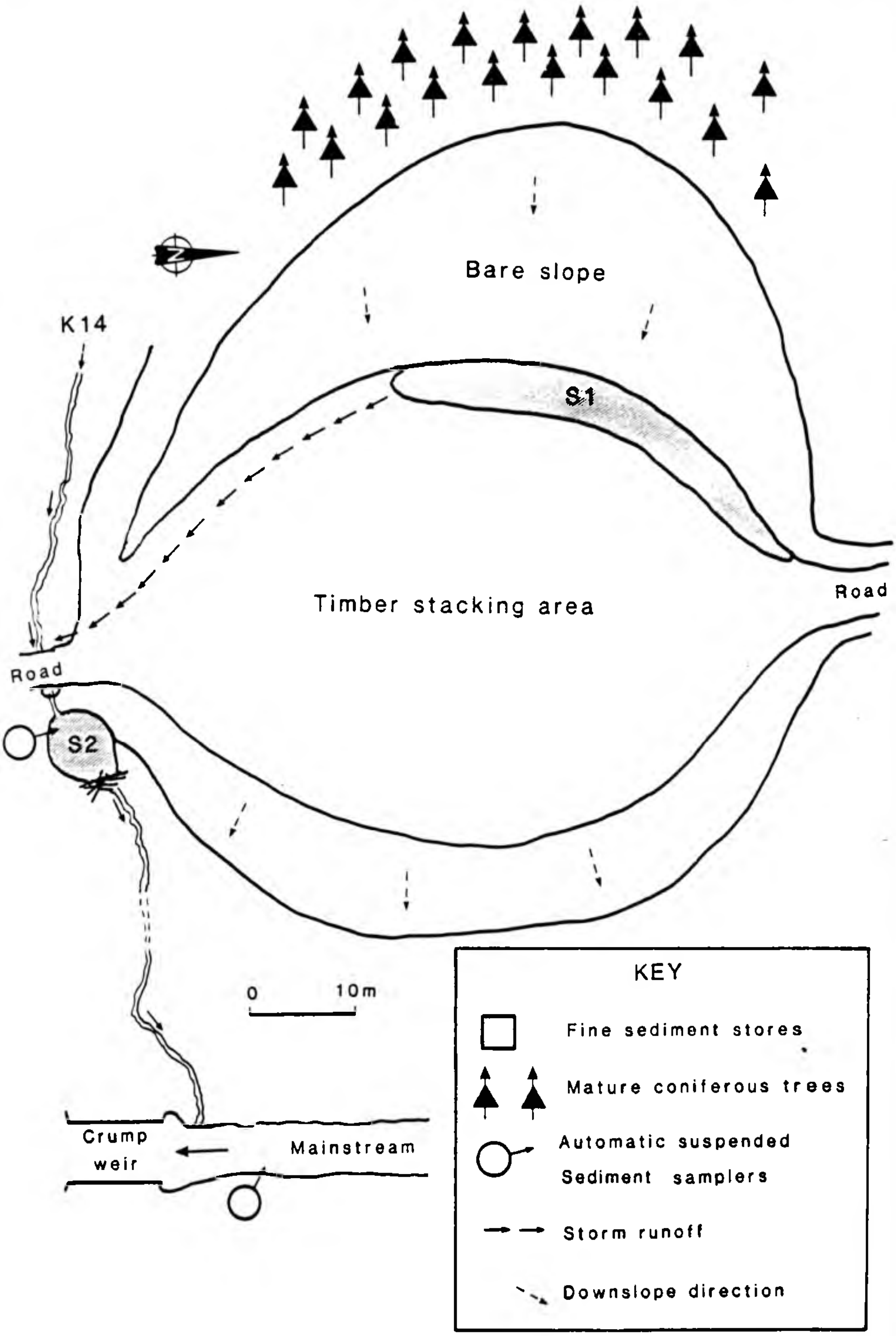

Figure 5.16: Plan of the southern timber stacking area showing sampling sites (the mainstream ALS is IH sampling point) and fine sediment stores S1 (at the foot of the bare slope) and S2 caused by an organic debris jam in stream K14.

in the Fine sand and silt categories in Table 3.1. Sediment in store S1 must have been washed from the exposed slope. The volumes of these two stores were estimated using a depth probe (pointed half-inch mild steel bar graduated in cm) and the results are summarised in Table 5.17.

Table 5.17: Volume estimation data for fine sediment stores on the southern stacking area.

Store	No. depth readings	Mean depth (m)	S.E mean	Volume (m^3)	t* +/- S.E
S1	20	0.096	0.007	2.88	3.50 +/- 0.26
S2	27	0.207	0.031	0.83	0.98 +/- 0.15

* = estimated assuming bulk density of 1.4 t m^{-3}

$$\text{Total sediment stored} = 3.50 + 0.98 \pm \sqrt{(0.26^2 + 0.15^2)}$$
$$\approx \underline{4.5 \pm 0.3 \text{ t}}$$

This is the amount of sediment eroded from the stacking area in the 15 months and corresponds to 3.6 t yr^{-1} which has come to be stored in S1 at the foot of the slope and in an organic debris jam just downstream of the road culvert on stream K14 (S2) since construction in March 1984.

During the period 11 April to 2 May 1985 some 55 water samples were taken automatically at 8 hour intervals from stream K14 at the point indicated 'ALS' on Figure 5.16. These were analysed for their suspended sediment content and the mean concentration was 116 mg l^{-1}. In the absence of any streamflow records or dilution gauging an estimate for the mean annual discharge of tributary K14 can be made by assuming that this sub-catchment delivers runoff to the main catchment outlet in proportion to its 0.15 km^2 area, which implies a mean discharge of 8 l s^{-1} in 1984. A crude estimate of the annual suspended sediment load of K14 can be made as the product of the mean suspended sediment concentration (C) and mean discharge (Q) grossed up to one year (La in section 5.2.):

Estimating total annual sediment load by the $\bar{Q}.\bar{C}$ method:

Instantaneous sediment load = 116 x 8 mg s^{-1}

When scaled up to one year the load is found to be 3 t.. This however is a lower bound since this method of estimating sediment load has an inherent statistical underestimation. However, from this simple calculation it appears that something like half of the sediment eroded from this stacking area remains stored at the foot of the slope (S1) and behind an organic debris jam (S2) in the outflow tributary stream K14. This example illustrates the dangers of a 'black-box' approach to assessing changes in sediment yields ensuing from land use change activities such as forestry operations. The sediment in storage may not be released to the catchment outlet for several years or more, depending on future storm magnitude and frequency. All sediment in storage could be flushed out to the catchment outlet during one storm event of high magnitude and low frequency or it could be released gradually over a number of years.

The implications which these individual studies of bare areas have for the catchment sediment budget and in particular the catchment sediment yield can be estimated provided the approximate total 'bare area' (roads and stacking areas) within the catchment is known. This task was kindly undertaken by Geography students of UCW Aberystwyth during a field day in Kirkton glen at Easter 1985. Small groups of students simply walked along the roads measuring the width at approximately 50 m intervals. The average road width was computed and multiplied by the total road length (estimated from the 1: 10 000 O.S map to obtain the total road area.

(i) Total road area estimated as above = 30 000 m^2

(ii) Three newly created stacking areas have total area = 6000 m^2

Total 'bare area' = (i) + (ii) = 36 000 m2

= 0.036 km^2

or 0.5% of the total catchment area.

From the slope recession study (autumn/winter 1986/7) using erosion pins mentioned above an average surface lowering of 0.017 +/- 0.004 m was estimated for a bare slope over a period of 227 days. This corresponds to an annual lowering of 0.027 +/- 0.006 m. If we assume that the measured rate of surface lowering applies over the whole of the 'bare area' it is then possible to estimate a total volume and mass of sediment (assuming average bulk density of 1.4 t m^{-3}) eroded from the bare area:

Mass of sediment eroded from new stacking areas only = 6000 x 0.027 x 1.4

$= 227 +/- 50\ t\ yr^{-1}$

Mass of sediment eroded from total road area $= 30\ 000 \times 0.027 \times 1.4$

$= 1134 +/- 250\ t\ yr^{-1}$

Total mass of sediment from stacking areas and roads $= 227 +/- 50 + 1134 +/- 250$

$= 227 + 1134 + \sqrt{(50^2 + 250^2)}$

$= \underline{1400 +/- 250}\ t\ yr^{-1}$

N.B. The error is estimated from the measurement error calculated from the erosion pin surveys where the error is 21% of the average slope retreat. Errors in estimating the total bare area and the bulk density are assumed to be negligible in comparison and are ignored.

However, it must be remembered that extrapolating the erosion rate estimated from the study of one bare newly exposed area to the total estimated bare area is clearly dubious since the monitored area may not necessarily be representative of the rest of the bare areas. The computed numbers must therefore be treated with caution and only used to give an indication of the order of magnitude of sediment yield from the bare areas. All roads were graded between October and December 1985 preceding the start of felling, some have been repaired and all have received extra usage (frequently by heavy logging lorries) since the start of felling in January 1986. Also, large stretches of existing road were laid with brashings and used by forwarders for removing felled timber from the lower slopes. Sediment production from roads has most certainly increased drastically in Phase II. If it is assumed that sediment production from roads in Phase II is the same as from the stacking areas (see calculation above) then it can be seen that the bare areas alone are capable of producing a very significant portion of the total catchment sediment yield increase reported in section 4.3.2.

CHAPTER 6. RESULTS - NON-TRIBUTARY SOURCES

6.1 Hillslopes

6.1.1 Slope Failures

The initial assumption that direct sediment contributions from hillslopes to channels are negligible in the Balquhidder catchments was reviewed when a slope failure occurred in the moorland catchment during heavy rain on 17 September 1985. An estimated 36 m^3 or 65 t of sediment was removed from the scar which was presented earlier in Plate 3.9 (a). This travelled some 500 m down a minor tributary gully to the main channel where the sediment cone in Plate 3.9 (b) containing an estimated 14 t of coarse sediment (D_{50} = 32 mm; 10% finer than 2.8 mm) was deposited. Some of this fresh sediment was visible on the bed of the main channel for up to 100 m downstream but much of the discrepancy between the headcut and cone volumes is due to deposition in or alongside the slide track before reaching the main channel. Grainsize analysis of mainstream bank material showed that between 70 and 90% of the material is finer than 2.8 mm (i.e. would be classified as 'suspended sediment' when undergoing fluvial transport). If we assume that a similar proportion of the material removed from the slope failure is 'fine' sediment, then we can estimate that somewhere between 30 and 38 t of fine sediment entered the channel as a consequence of this slope failure and probably left the catchment in suspension during the same storm event. Unfortunately no sediment output monitoring was being carried out during the storm and so it is not possible to quote typical concentrations.

However, the dispersion of the slug of coarse sediment was apparent in aggradation of the first two levelled cross sections downstream over the fourth survey period (08 August 1985 to 27 September 1985) when the two cross-sections F1 and F2 (located in Figure 3.4) which were 3 and 6 m downstream showed mean bed height increases of 60 +/- 12 and 35 +/- 12 mm respectively (see Table 6.6). This accumulation appears to be scoured out over the fifth survey period (27 September 1985 to 02 April 1986) when the mean bed height of sections F1 and F2 decreased by 69 +/- 12 and 70 +/- 12 mm respectively. Sections G1 and G2 some 180 m downstream showed no significant change in mean bed height until the sixth survey period (02 April 1986 to 03 April 1987) when increases of 65 +/- 12 and 48 +/- 12 mm were detected. No significant increase in bedload transport was detected at the catchment outlet some 400 m downstream by IH Helley-Smith sampling in subsequent floods (Johnson pers. comm). It seems that some of the coarse material was stored in the sediment cone in the main channel at the mouth of the tributary and some on the channel bed some metres downstream. The remainder must have left the catchment as suspended sediment and some bedload during the same and subsequent flood events as suggested earlier. The cone of sediment seen at the tributary mouth in Plate 3.9 (b) was gradually removed over the following eighteen months.

6.1.2 Rainfall/slope failure return period

An attempt was made to estimate the return period of this type of slope failure in order to assess their importance as a source of sediment in this type of terrain. Both daily and hourly rainfall totals were obtained for the periods in September and December 1985 when the two slope failures occurred. Both failures took place during rainfall intensity-duration conditions which were well below Caine's threshold for shallow landslides (Caine 1980) both in terms of duration and intensity implying that some other factor(s) such as lithology or soil saturation were contributing. This was also found by Jenkins et al. (in press) for similar slope failures in November 1984 in the Ochil hills some 50 km south of Balquhidder. Further landslides occurred in central Scotland at Loch Lomond (Ferguson pers. comm) during the summer of 1985. A glance at the Parkhead (Stirling) quarterly rainfall data in Figure 7.2 shows how exceptionally wet 1984 and 1985 were and it could well be that wet years, or at least wet seasons, are required to totally saturate the ground before such slope figures are triggered by fairly moderate rainfall intensity-durations well below those proposed by Caine (1980). Past rainfall intensity figures were not available since autographic rain gauges were only installed in the area since the catchments were instrumented in 1982. Nevertheless, in order to get some idea of the return period of the daily rainfall totals for the days on which the slope failures occurred daily totals for a nearby gauge at Strathyre (Grid ref. E2501/N7167, only 10 km to the E.S.E of Monachyle glen and at a similar altitude of 130 m) were available on microfiche from 1961. These data were consulted in the Meteorological Office, Edinburgh, and all rain days of greater than 40 mm were noted. Unfortunately the Strathyre gauge was read monthly for several years and so only 16 complete years of data were obtained. The top ten highest daily totals for the period were ranked and plotted on a Gumbel EV1 probability scale (Figure 6.1) from which the return period of a 45 mm daily total was estimated to be 1.2 years. Clearly it is not possible to equate slope failures with daily rainfall totals in excess of some threshold (e.g. 45 mm), but nevertheless, this does give an idea of an upper limit to the number of such failures which could occur naturally in such a steep sided once glaciated glen such as Monachyle.

If we assume that a maximum of one such slope failure does occur every year (two occurred in 1985 and a further small one in September 1986, but none from 1982-5), and if the material removed from the hillside directly enters the main channel as in the case of the September 1985 failure where upwards of 14 t of coarse sediment and an unknown quantity (< ~ 40 t) of suspended sediment entered the system, then this corresponds to an average yield of around 9 t km^{-2} yr^{-1} which features as a significant sediment source in the catchment sediment budget. However, this is a maximum possible contribution and it is doubtful whether slope failures in these regions are as significant as this estimate suggests. The occurrence of three slope failures during the 30 month study period in Monachyle glen (one within the gauged catchment) is, I would suggest, exceptional. If we assume more realistically that such an event would be likely to occur only once

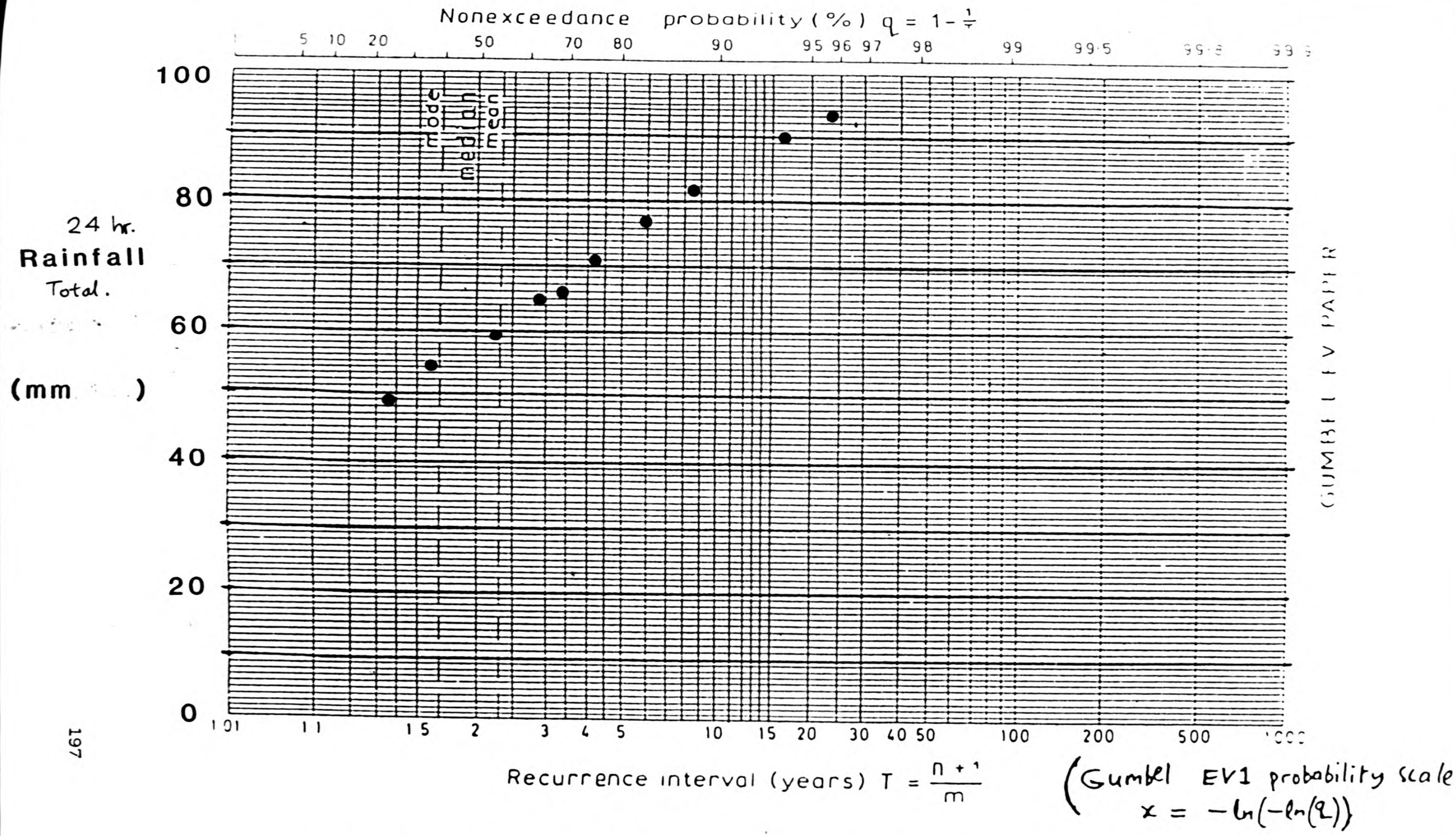

Figure 6.1: Gumbel EV1 probability plot of rainfall return period at Strathyre gauge for 1960-1982.

every three years, then the contribution to the sediment budget would become 3 t $km^2 yr^{-1}$. This example highlights one of the major problems in attempting to construct sediment budgets in the short timescale within which a project such as this must operate. In this case I would suggest perhaps, that slope failures would appear to be more important than they really are?

6.2 Mainstream channel banks

6.2.1 Bank erosion dynamics

The erosion pin surveys indicated mean bank retreat rates of 4 to 19 mm per 3 months (Figure 6.2), with standard errors varying from 1 to 3 mm. Average annual retreat rates were 42 and 63 mm on the forested and moorland mainstreams respectively. This is comparable with average rates measures by Cummins and Potter (1972) on the Bradgate brook, Cropston reservoir, Leicestershire who report erosion rates of 30 mm yr^{-1} and by Hill (1973) for bank erosion rates in glacial till in Northern Ireland who reports 30-60 mm yr^{-1}. At Balquhidder a clear seasonal cycle is apparent with maximum bank erosion in the January-March period in both catchments in both years.

In order to investigate the relative importance of various factors affecting bank erosion which might help to explain the observed variations over the year mean daily erosion rate over the three monthly periods (ERRATE) was correlated with various frost and streamflow predictors. The predictors selected were: FROST which is simply the number of days on which the grass minimum temperature at the nearby IH Tulloch Farm weather station went below 0°C, FROST<-1 ,FROST<-3 and FROST<-5 are the number of frosts which recorded temperatures below -1 and -3°C respectively (these are presented in Table 6.2 later). A number of streamflow indices were used. QMEAN is the mean discharge over the period, QMAX is the maximum instantaneous discharge over the period and QSUM is the total discharge which passed the gauging stations within the period. Also, various flow thresholds as used in the bedload

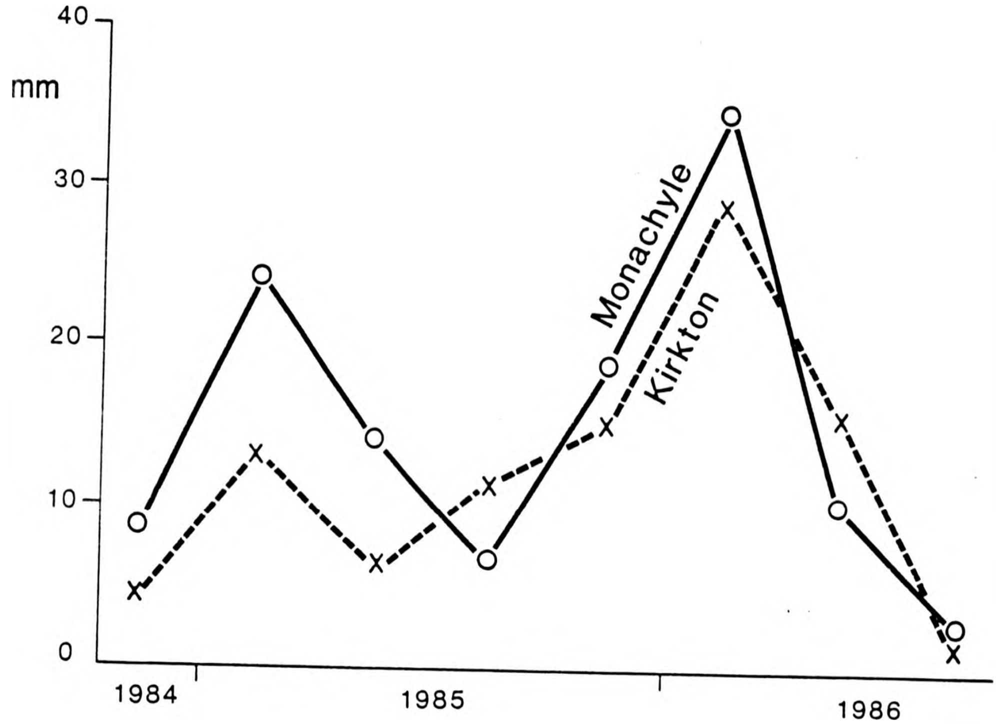

Figure 6.2: Mean rates of mainstream bank erosion for three-monthly periods from September 1984 - September 1986.

transport analysis in section 5.3.1 were used. On both streams T > QMEAN was the time in hours when the stream discharge exceeded the mean annual discharge, T > 2 and T > 4 (in Kirkton) and T > 4 and T > 8 (in Monachyle) are times (hours) when streamflow exceeded discharge thresholds of 2, 4 and 8 m^3s^{-1}. The streamflow parameters were estimated from IH streamflow records. Table 6.1 presents the Pearson correlation coefficients for erosion rate with the various predictors for both streams. The stars indicate the level at which the coefficients are significant and it is clear that the frost indices correlate better with erosion rate than any of the streamflow indices. Only coefficients higher than 0.666 are significant at the 5% level, and so it is only the frost indices for the moorland stream which are significant at the 5% level (FROST < -3 is significant at the 1% level). That frost is an important factor affecting bank erosion was suggested back in the 1950's by Wolman (1954) and more recently has been supported by the work of Lawler (1986) in south Wales. At Balquhidder, it may well be the influence of the trees on the forested Kirkton stream which results in the frost indices correlating less well with bank erosion rate. Nevertheless, the frost indices are still much better predictors than any of the streamflow indices.

In autumn 1984, at the start of the project, some 14 maximum/minimum thermometers were located on streambanks, 9 in the forested catchment (3 of these above the tree line) and 5 in the moorland catchment, and the minimum temperatures read on 13 occasions between October 1984 and March 1985. On averaging all the data, minimum temperatures for thermometers located on

Table 6.1: Pearson correlation coefficients for mean daily bank erosion rate (ERRATE in mm) over eight three monthly periods with various frost and streamflow indices for Monachyle and Kirkton mainstreams (1984-1986).

Index	Kirkton (KERRATE)	Monachyle (MERRATE)
FROST	0.504	0.785**
FROST>1	0.499	0.761**
FROST>3	0.602	0.801**
FROST>5	0.591	0.760**
QMEAN	0.140	0.166
QMAX	0.363	0.033
T > QMEAN	-0.094	0.029
T > 2	0.090	*
T > 4	0.329	0.099
T > 8	-	0.341

- no flows exceeded this threshold
* not estimated

Coefficients greater tham 0.666 are significant at the 5% level, ** indicates significance at the 1% level.

QMEAN, QMAX and all thresholds are in $m^3 s^{-1}$.

streambanks under the forest canopy were 2.5 °C higher which is why FROST<-3 is the best frost index. Smith (1970) working in a small upland plantation in County Durham and Hurst (1965) working in the forest of Thetford chase both also found higher minimum air temperatures under forest.

The frost data for the two year period are presented in Table 6.2 and show that only 49% of all frosts exceed the FROST<-3 threshold which would effectively cause a frost on streambanks under the forest canopy:

Table 6.2: Sub-zero grass minimum temperature data (frosts) from the IH Tulloch Farm weather station for the bank erosion study period.

PERIOD	No.FROSTS	No.FROSTS<-1	No.FROSTS<-3	No.FROSTS<-5
1 (Sept-Dec 84)	23	13	3	3
2 (Dec-Mar 85)	64	61	43	37
3 (Mar-Jun 85)	30	20	8	2
4 (Jun-Sept 85)	3	2	1	1
5 (Sept-Dec 85)	41	35	19	12
6 (Dec-Mar 86)	58	51	42	33
7 (Mar-Jun 86)	31	20	9	8
8 (Jun-Sept 86)	25	21	12	8
Totals	277	223	137	104
%	100	81	49	38

Trees can have a protective influence on river banks in various ways. First, through mechanical strengthening and binding of the banks by roots. Second, through intercepting rainfall and thereby regulating the moisture regime of a bank which in turn would affect frost effectiveness and thirdly by shading the banks against drying out and frosts (e.g Maddock 1972, Charlton, Benson and Brown 1978, Keller and Swanson 1979, Stott 1984). However, these studies referred to open banks vegetated by undergrowth as well as mature trees and in contrast to the findings here, Murgatroyd and Ternan (1983) for example, working on a coniferous forested reach of the Narrator Brook in Dartmoor found that more active bank erosion was taking place in the forested reach and that the channel capacity was double that predicted from the basin area. This they attributed largely to the suppression by the forest of a thick grass turf and its associated dense network of fine roots. Zimmerman, Goodlett and Comer (1967) working in small catchments in the US observed that different reaches on the same stream varied in width depending upon whether the banks were lined with trees or sod (a thick grass mat). They found that the mean width of stream reaches with forested banks was significantly greater than that of reaches with sod banks.

Since the erosion pins used at Balquhidder were installed in verticals in the banks with a 0.1 m spacing it has been possible to analyse vertical differences in erosion rate on the banks. Table 6.3 presents mean erosion rates for the first two survey periods (October to December 1984 and December to March 1985) on both mainstreams averaged according to the height on the bank. In both mainstreams maximum erosion rate was between 30 and 50 cm from the bank top and the vertical profiles are plotted in Figure 6.3. From observations of the streambanks over the study period this undercutting process appears to be followed by collapse of the upper part of the bank, often as a turf (see Plate 6.1), either

Table 6.3: Mean bank erosion rates at different heights on mainstream banks for two three-monthly periods on Monachyle and Kirkton mainstreams.

	Height from top of bank (cm)	Mean erosion (mm) Oct.-Dec. 1984 mm	n	Dec.-Mar. 1985 mm	n
Monachyle	10	4.1	55	6.0	34
	20	11.3	65	17.3	38
	30	11.5	61	36.1	35
	40	14.8	49	43.5	31
	50	11.0	28	46.5	22
	60	16.1	16	27.5	8
	70	3.2	9	5.0	2
	80	1.3	4	*	
Kirkton	10	4.3	13	4.8	15
	20	4.8	18	7.1	13
	30	6.2	16	20.2	13
	40	5.1	14	17.6	10
	50	5.6	8	30.4	8
	60	5.5	4	18.0	4

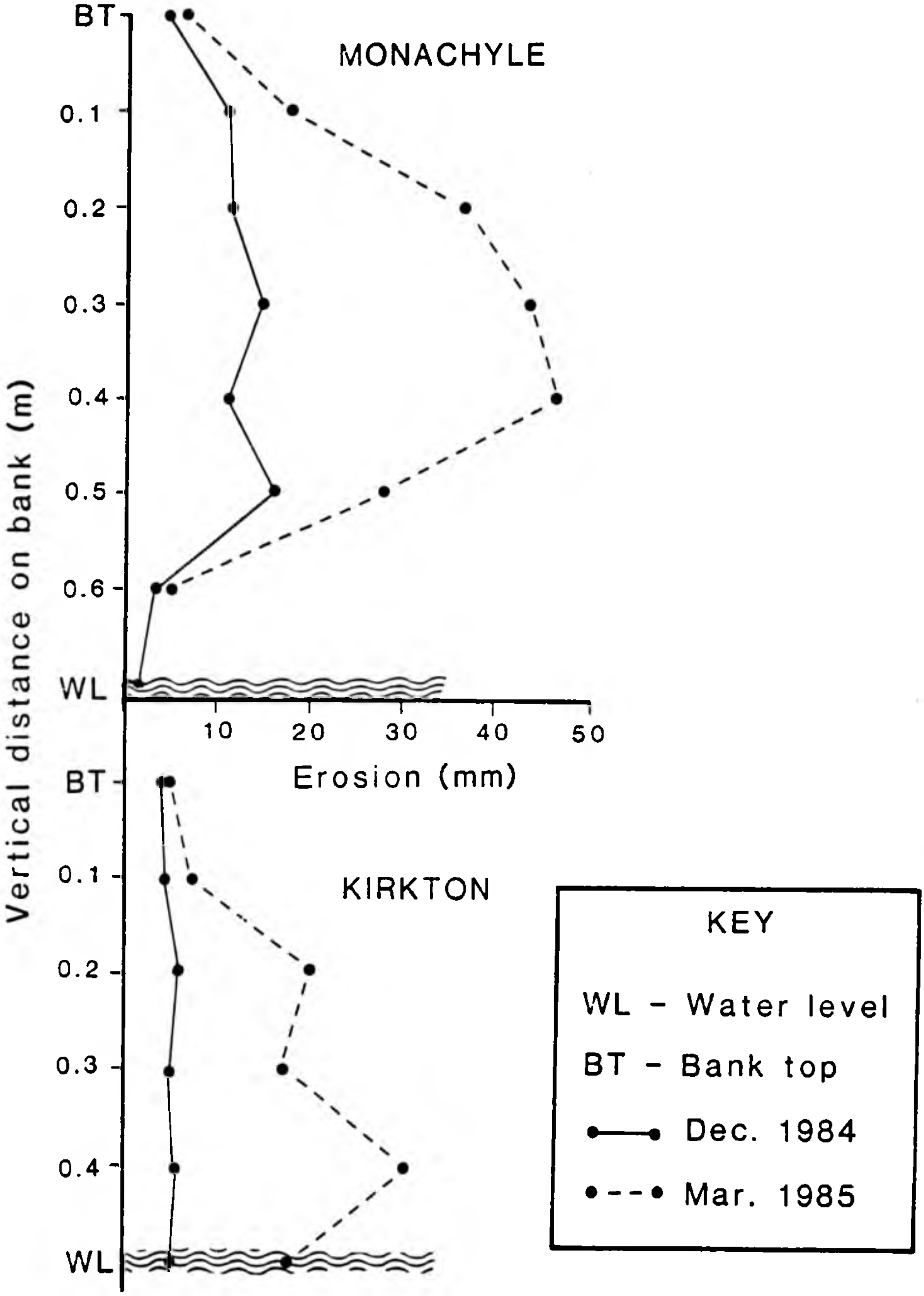

Figure 6.3: Vertical profiles of mean bank erosion for 3-monthly survey periods for Monachyle and Kirkton mainstreams. The horizontal scale is exaggerated, the number of erosion pin measurements averaged to give these plots are presented in Table 6.3.

Plate 6.1 Mainstream bank collapse in Monachyle. This reach is in the middle section of the Monachyle mainstream. The mechanism postulated for bank erosion is a continuous cycle of undercutting followed by collapse of turfs as seen here.

directly into the channel or onto the foot of the bank to be removed by the next flood. Murgatroyd and Ternan (1983) in their study on the Narrator brook reported crescentic bank slumps and slumping and collapse has been reported on several other studies (e.g. Hooke 1979).

6.2.2 Bank erosion inputs

In order to estimate the contribution of sediment to the system from the channel banks it was necessary to extrapolate the average measured forest and moorland erosion rates of 62 and 43 mm yr^{-1} to the estimated area (240 and 250 m^2) of actively eroding banks. This gave volumes of sediment equivalent to 10.3 and 15.8 m^3 for the forest and moorland catchments respectively. This volume was converted to a mass of sediment by estimating the average bulk density of bank material from samples taken from typical banks. Average bulk densities were estimated to be 1.16 and 1.04 which gave total sediment inputs of 12 and 16 t yr^{-1} for the forest and moorland catchments respectively. This corresponds to total catchment yields of 1.6 and 2.2 t km^2 yr^{-1} over the two year survey period.

Samples of bank material analysed for their grain size distribution showed that the material was predominantly fine grained with 72 and 93% finer than 2.8 mm in the forest and moorland catchments respectively showing that most of the sediment coming from bank erosion is finer than 2.8 mm and would therefore be sampled as suspended sediment in this study. Figure 6.4 shows typical grainsize curves for the channel banks (including forest drainage ditches) as well as some other likely sediment sources such as roadside banks. Grainsize curves for bulk sediment samples taken from the tributary bed and side bars are plotted for comparison. The curves show how material sampled from the banks contains more fines, presumably because the fines have been transported out from the bed material.

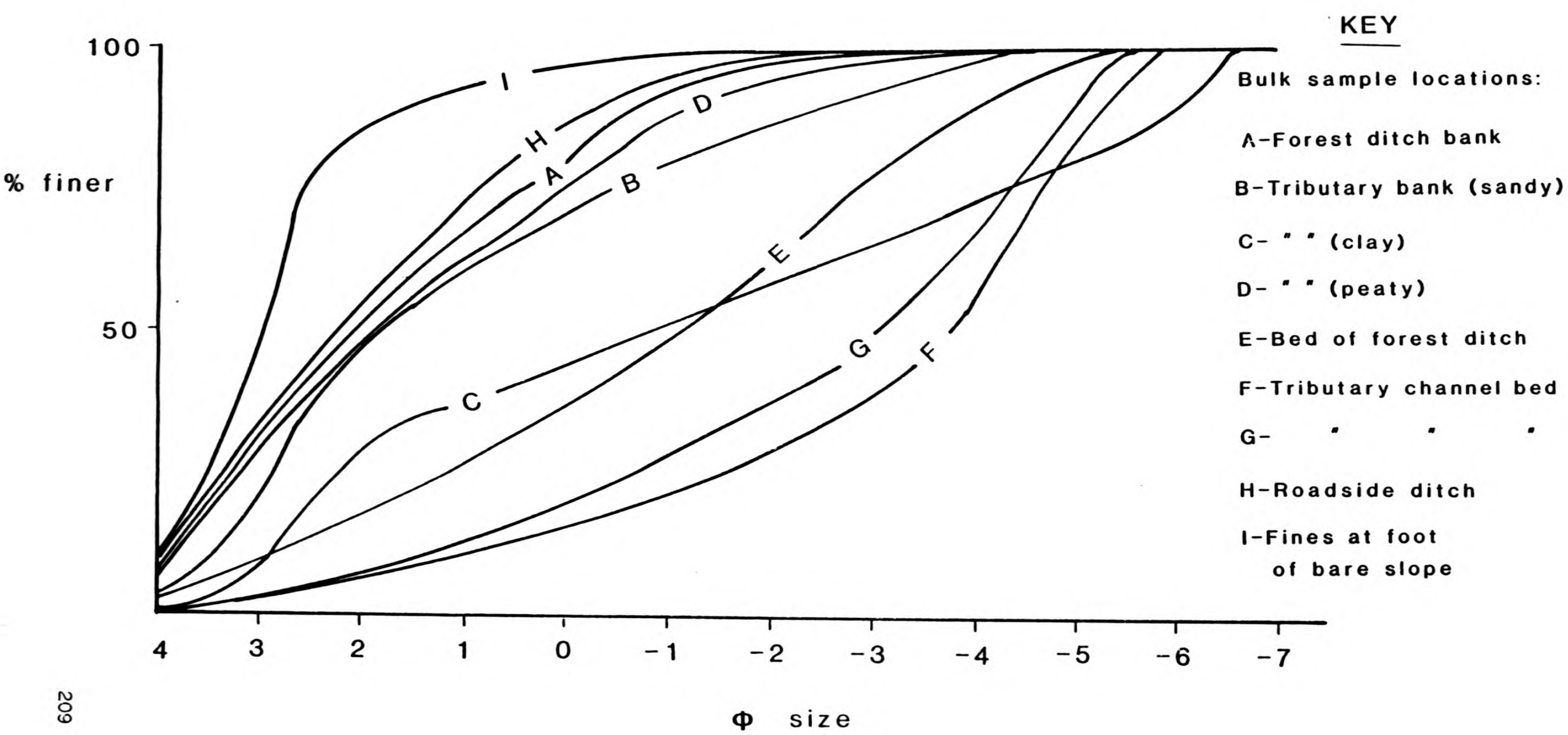

Figure 6.4: Grainsize curves for source area bulk samples. Samples A - D from streambanks, E - G streambeds, H - I are fine sediment stores.

6.3 Mainstream bed scour and fill

The technique employed to assess changes on the stream bed attributable to scour and fill of coarse sediment was to relevel cross sections as done in previous studies (e.g. Werritty and Ferguson 1980, Mosley 1981, Murgatroyd and Ternan 1983). Twenty seven channel cross sections were levelled in all (23 in Monachyle, as located in Figure 3.4), and 4 on a short accessible reach in Kirkton forest) and these were resurveyed on six occasions over the 30 month period October 1984 - April 1987. From the results of the cross-section levelling replication exercise detailed in section 3.3.2 any changes in mean bed height within the error limit of 12 mm should be viewed with caution since they may not be real, but rather may be due to surveying error.

Table 6.4 summarises the net changes in mean bed height of all the sections surveyed and so deals with net changes in mean bed height (and therefore total amount of sediment flux in the last two columns) over the total length of channel over which the cross sections were relevelled. In the case of the Monachyle the length of channel from the first to the last section is 830 m and the mean width of the gravel levelled for 23 sections is 8.8 m. The Kirkton reach was 50 m long and the mean width of gravel for the 4 sections was 14 m. If we assume that the cross sections are representative of the whole reach, and that the bulk density of the sediment is 1.4 t m^{-3} (as estimated from bulk samples taken from sediment traps), then it is possible to estimate the total mass of sediment (t) which has been deposited or removed from the channel reach as the product of the change in mean bed height (m), reach length (m),

Table 6.4: Summary of changes in mean bed elevation, corresponding estimated quantities of sediment (see text for calculations) and the estimated errors. All mean bed height changes are in mm, all changes in amounts of sediment in tonnes.

Survey Period	Dates	No. Sections Levelled	Total Scour (-)	Total Fill (+)	Net Change	Mean Change/ Section	t over whole reach	s.e of t sedt. (+/-)
Monachyle								
1	05.10.84 25.03.85	12	079	462	+383	+32	33	34
2	25.03.85 30.05.85	23	161	344	+183	+8	8	24
3	30.05.85 05.08.85	12	210	089	-121	-10	-10	34
4	05.08.85 27.09.85	23	179	427	+248	+11	11	24
5	27.09.85 02.04.86	23	312	467	+155	+7	7	24
6	02.04.86 03.04.87	16	383	349	-34	-2	2	29
Kirkton								
1	03.04.85 23.11.85	4	62	58	-4	-1	1	6
2	23.11.85 02.04.86	4	41	76	35	9	8.8	6
3	02.04.86 03.04.87	4	15	46	31	8	7.8	6

mean gravel bed width (m) and estimated sediment bulk density (t m^{-3}). Also, from the levelling replication exercise it is possible to represent the error in estimating mean bed height in terms of tonnes of sediment in the same way and these estimates are presented in the last two columns of Table 6.4.

In all cases in the Monachyle the estimated levelling error, represented in terms of tonnes of sediment, exceeds the measured changes. Only in the first period over winter 1984-5 does the measured change in channel sediment storage even come close to the estimated error. However, even though it has not been possible to compute these channel sediment storage changes with any certainty, Table 6.5 is a summary of changes in mean bed height for individual cross sections in each of the resurvey periods throughout the study and this certainly does show local changes in mean bed height which are well in excess of the estimated measurement error (12 mm) and can therefore be assumed to be real. Groups of sections marked B, E and F are on meander bends (see Figure 3.4), and meander bend B shows consistent deposition in excess of the error in all four sections in periods 1 and 5 whereas meander E shows scour in period 2 and deposition later in periods 4 and 5. A slug of sediment was delivered to the channel just upstream of sections F1 and F2 by the slope failure on 17 September 1985. Section 6.1.1 discussed the effect that this seemed to have on mean bed height changes.

In the Kirkton reach, however, the estimated sediment accumulation over the reach is only exceeded by the measurement error in the first survey period, the second and third periods showing net sediment accumulations which appear to be real.

Table 6.5: Changes in mean bed height (mm) detected by cross section levelling. Note that the estimated measurement error is +/- 12 mm so any changes not exceeding this limit should be viewed with caution. See Figure 3.4 for cross section locations, numbering increases downstream.

	Survey dates					
Section number	05.10.84 to 25.03.85	25.03.85 to 30.05.85	30.05.85 to 05.08.85	05.08.85 to 27.09.85	27.09.85 to 02.04.85	02.04.86 to 03.04.87
A1	0	0	-33	+23	-17	-39
A2	+35	+13	-54	+43	+48	*
B1	*	-11	+9	-1	+21	*
B2	+100	-21	+1	-9	+17	+5
B3	+83	0	+8	+10	+48	+9
B4	+71	+12	+5	+1	+23	+52
B5	+73	+3	+25	-32	-21	*
C1	0	+10	-1	-4	+57	-26
C2	0	+30	-93	+60	+59	-173
D1	*	+10	+30	-23	+23	*
D2	*	+8	-30	+30	+31	-29
D3	*	+63	+12	-61	+38	-19
E1	*	-29	*	+1	-22	+92
E2	+17	-33	*	+48	+25	*
E3	+83	-38	*	+25	+38	*
E4	*	-21	*	-14	+16	*
F1	-59	-2	*	+60	-69	+31
F2	-20	-6	*	+37	-70	+47
G1	*	+118	*	-9	-105	+65
G2	*	+10	*	+9	+10	+48
H1	*	+31	*	-16	+13	-43
H2	*	+21	*	-11	-4	-36
H3	*	+15	*	+82	-4	-18

N.B '*' indicates that the survey was not carried out and so no change of mean bed height is reported

6.4 Effect of disturbance

The effect of the forestry operations in 1986 on hillslope and bank erosion sediment sources does not appear to be significant at this early stage, any changes will probably only become apparent in the longer term. It is therefore not possible to present results in this section but merely to speculate on the possible longer term effects based on the findings of the study so far.

6.4.1 Afforestation

On the basis that slope failures appear to be a feature of the moorland catchment only, no such failures having been noted in the afforested Kirkton glen, it might be reasonable to assume that afforestation in the Monachyle glen would help to stabilise at least the lower slopes in the longer term. However, it must be noted that of the three slope failures which occurred in the glen within the study period, two were at a low level which had been planted with young saplings in one case, and was about to be planted in the second case. The third landslide furthest up the glen and within the experimental catchment (reported in section 6.1) actually had its source area well above the proposed tree-line where the slope angle is steeper. A large slope failure which occurred at Loch Lomond in the summer of 1985 (Ferguson pers. comm) had its source upslope of a forestry plantation, but flowed downslope through the forest uprooting trees and a fence on its way to the loch. It is therefore unlikely that afforestation would prevent future slope failures of this kind but tree roots in landslide source areas may help to stabilise the material and prevent large masses of soil becoming mobile. However, once the source material of a slope failure is in motion afforestation is unlikely to stop it as evidenced by the Loch Lomond slide mentioned above. Further effects which may occur at the time of canopy closure will be to block out light and thereby inhibit undergrowth (currently a grass/heather/bracken complex). It is this dense vegetation cover which is inferred as preventing any significant fine sediment (slope wash) coming from the hillslopes (section 3.4).

Moving on to look at the effect which afforestation may have on streambank erosion, it may well be that the new policy of leaving wide riparian buffer zones alongside streams (unplanted with coniferous trees, but left either to regenerate naturally or possibly planted with some broadleaf species such as alder, willow or hazel) will prevent canopy closure over the streams and benefit stream ecology in general (Smith 1980, Mills 1985). In the early stages then, there should be little or no effect on bank erosion since frost, which has been diagnosed earlier as the most important factor affecting bank erosion in these catchments, will be able to attack the banks until the bankside vegetation matures. Even later when the broadleaf riparian zone has matured, it will not have such a good insulating effect against frost as the coniferous trees since the leaves are shed in winter when frost activity and bank erosion are highest (see Figure 6.1). This may be compensated by mechanical strengthening of the banks by the broadleaf tree roots in combination with the rooting of undergrowth which would not be inhibited under broadleaf trees. However, this is only the case for the mainstream channel banks which contribute less that 5% to the total catchment sediment yield. There is not as yet a policy to leave riparian buffer zones alongside tributary streams or drainage ditches. A simple calculation in section 7.1 shows that if only 5-10% of the catchment sediment yield is coming from erosion of the mainstream banks, then most of the remainder must be provided by erosion of tributary banks and drainage ditches. It appears that the suppression of undergrowth (grass/heather/mosses) caused by the canopy closure of coniferous afforestation and seen in Plate 6.2 leads to unvegetated banks which are vulnerable to erosion as is the case with the old drainage ditch seen in Plate 6.2. It has been suggested that it is the presence of undergrowth on the banks which helps to protect streambanks from erosion (Zimmerman, Goodlett and Comer 1967, Stott 1984). Thus, perhaps major tributaries, at least, should also be allowed a riparian buffer zone also?

6.4.2 Deforestation

Again, no results for the effects of felling activities on these sediment sources are available in the short time since clearfelling began. Longer term effects can only be speculated. Logging of primary natural forests in the Pacific North West, U.S, has been associated with severe erosion and increased sediment yields from road construction, landsliding and increased streambank erosion (Brown and Krygier 1971, Roberts and Church 1986). Findings from the H.J. Andrews Experimental Forest (see section 1.2) attributed the landsliding and increased sediment yields to road building at the time of logging. However, in the British case in general, and at Balquhidder in particular, the roads are already

Plate 6.2 Old drainage ditch in Kirkton forest. Note how the forest supresses undergrowth which in turn leaves channel banks vulnerable to erosion.

established from the time of planting and since they have had at least 40 years to stabilise, decreases in slope stability and subsequent failures are not likely to be as dramatic as in the Pacific north-west U.S. However, less spectacular effects may ensue as a consequence of the sudden removal of a canopy which can intercept (and even re-evaporate or transpire) anything up to one quarter of the incoming precipitation (Newson 1979). First, more water in total will reach the streams and this will most likely be in a shorter time after rain starts. Bigger floods and faster times to peak may result (see Hewlett and Helvey 1979). Secondly, since rain will be falling on newly exposed ground, especially in the first few years after clearfelling, intense rainfall could remove hillslope sediment by splash detachment and overland flow processes. Sediment removed may either be temporarily stored in hillside hollows or enter stream courses directly. Much will depend on the magnitude and frequency of rainstorm events between the time of clearfelling and canopy closure of the second crop (10-20 years).

Forest removal from alongside streams could have a two-fold effect on streambank erosion. First, large trees felled on streambanks can fall into, across, or away from streams. This can damage and loosen the structure of the banks unless care is taken to fell trees away from streams. Secondly, the removal of the tree canopy would allow frosts to act on the unvegetated banks with no established undergrowth, the results of which could be large increases in bank erosion in the early years after felling. This type of effect has been reported after recent clearfelling of parts of the Beddgelert forest in north Wales (Wong pers. comm). Once a bankside vegetation becomes established streambank erosion should stabilise.

CHAPTER 7: DISCUSSION

7.1 Pre-disturbance sediment budgets (Phase I)

This study has been an attempt to integrate a range of erosion and sediment monitoring techniques in sediment source areas and combine them with IH catchment sediment output measurements to construct sediment budgets. Four land use types were encompassed in the experiment: moorland and mature forest in Phase I and ploughed/ditched moorland and clearfelled forest in Phase II. One of the major problems in any geomorphological study, and this study is no exception, is that of timescale and magnitude and frequency of events (Cullingford et al. 1980). Walling (1978) has suggested that at least ten years of data collection is required to characterise the sediment regime of a particular stream or river. Clearly, the very short calibration period permissible in a Ph.D study of this type, and even the 3 - 4 years of IH monitoring must leave doubts as to the representativeness of such short-term monitoring. A second problem lies in the use of different monitoring techniques to calibrate different parts of the budget (e.g. for bedload - trapping in the tributaries and Helley-Smith sampling at the outlets). Nevertheless, in most cases the sediment monitoring techniques in the source areas and at the outlets were either standard (e.g. automatic liquid samplers, Helley-Smith bedload sampler) or had been used successfully elsewhere (e.g. bedload trapping,

trapping, erosion pins, cross section relevelling) but even so all these techniques are prone to errors. Many types of error are inherent in this type of study right from the initial field sampling stage through laboratory analysis to statistical and computational error. Some of these errors are simply not possible to estimate and therefore have to be considered negligible or to cancel each other out. For others, it is possible to make a statistical estimate of the likely error and therefore to define limits between which, with a certain probability, the true value lies.

Considering first the measurement errors at the field sampling stage it is the duty of the observer or field worker to try to minimise bias and to be as objective as possible at all times. Nevertheless, situations arise where subjective decisions have to be taken - an erosion pin in a streambank appears to have moved or has been bent, a bedload trap appears to have overflowed or the intake nozzle of an automatic liquid sampler has been buried by gravel. How does the fieldworker ensure objectivity in these situations? Obviously, a certain unmeasureable amount of human error has to be accepted. Measurement errors have been estimated and discussed in the respective methods or results sections for erosion pins (6.2.2), cross-section levelling (3.3.2 and 6.3) and suspended sediment analysis (3.1.2) and load estimations (5.2.2). Measurement technique and the associated errors, if large enough, can present difficulties when trying to compare findings with other studies in similar environments (Newson 1981). However, when comparing before and after treatment results as is also done in this study (see section 7.2), the problems of measurement technique and error should remain constant throughout and any changes detected should be real.

Figure 7.1 (a) is a schematic sediment budget for the Balquhidder catchments based on 1982-1985 output data and 1985 source data for the Phase I pre-disturbance period. There may be large margins of error in the calculations of both inputs and outputs of sediment. Tables produced by Ferguson (1987) based on scatter about the rating curves, sample size and rating curve slope suggest that the estimated errors are of the order of +/- 20% for the suspended sediment load estimations. Taking first the Monachyle (moorland) catchment, there seems to be a good agreement between the 'inputs' measured in the source areas and the 'outputs' measured at the whole catchment scale for both suspended sediment and bedload i.e. a high delivery ratio from source areas to outlet. When the measured tributary suspended load is added to the mainstream bank erosion input and the estimated slope failure contribution there is almost an exact match. However, it must be borne in mind that the slope failure which occurred in the moorland catchment in autumn 1985 (see Figure 7.1 (a)) may well be an over representation of this sediment source. As years go by without further failures (or contributions of such large slugs of sediment directly to the channel) then the average contribution of this one slope failure would become less and less significant as time went on.

The tributary bedload input also agrees reasonably well with the outputs but it must be remembered that tributary bedload

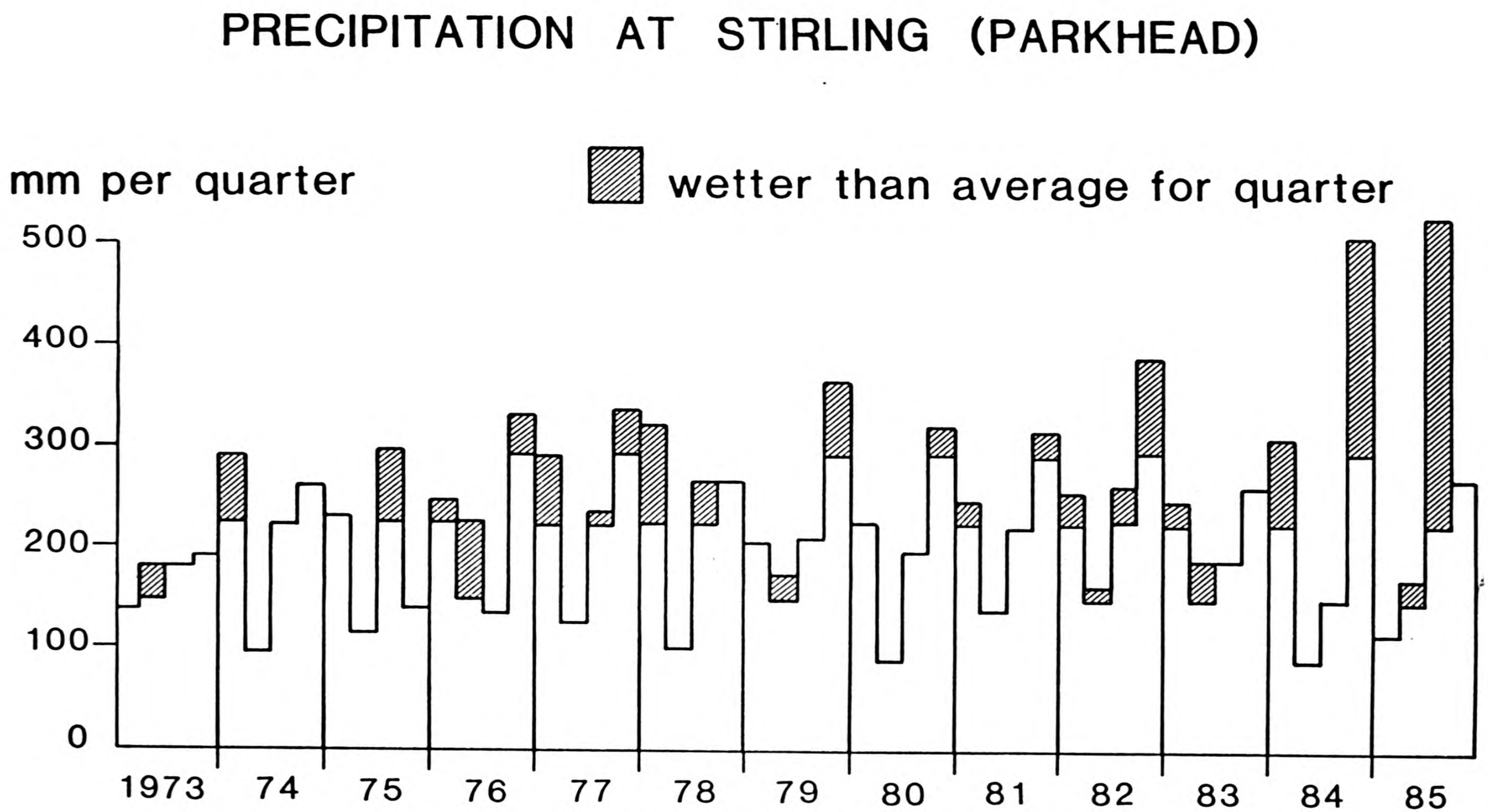

Figure 7.2: Quarterly precipitation (mm) for Parkhead rain gauge (Stirling) for the period 1975-1985. Totals wetter than average are shaded (data from S.J. Harrison, compiled by R.I. Ferguson, both Dept. of Environmental Science, University of Stirling).

is sediment coarser than 2.8 mm only (with the finer proportion which is trapped deducted) whereas the outputs are for sediment trapped by the Helley-Smith bedload sampler, i.e coarser that 0.125 mm (the mesh size of Helley-Smith bags). Bearing this in mind there may not be such a good agreement as the budget diagram in Figure 7.1 (a) implies. For example, the median particle size (D_{50}) for bedload reaching the catchment outlets is 3.5 mm (Johnson, pers. comm) which is finer than the D_{50} of 32 mm for bedload sampled in the tributary bedload traps (estimated from 17 sub-samples). Even taking into account that the D_{50}'s are for all sediment coarser than 2.8 mm (tributaries) and 0.125 mm (outlets) the tributary D_{50} must still be coarser. The indication is that coarse sediment supplied by the tributaries is not the same sediment as that passing the outlets - there seems to be an exchange somewhere in the main channel. One likely possibility is that bedload from tributaries accumulates at their mouths in fans or bars at the side of the mainstream (on a smaller and longer timescale to the cone of sediment delivered by the slope failure), which is subsequently removed over a long period, the length of which may depend on flood magnitude and frequency ? Flood deposits measured by IH in both catchments have a D_{50} of about 64 mm. It could be that the extreme events in which the coarser bedload is transported has not been sampled by Helley-Smith sampling at the outlets, but it has accumulated in the bedload traps? One is left with the conclusion that channel storage of the coarser sediment (as trapped in the tributaries) must be an important process until a low frequency event might remove some of this coarser material. Unfortunately the cross section survey work reported in section 6.3, did not have sufficient sensitivity to be able to confirm this. There is undoubtedly a small coarse sediment contribution from channel banks, but grainsize analysis of bank material suggests that more than 70% is finer than 2.8 mm. In the sediment size classification used in this study (Table 3.1) this would be classified as suspended load. However, some of the coarser fractions could still be sampled by the outlet Helley-Smith sampling and therefore be counted as bedload. It seems that only a very small proportion of the total coarse sediment stored in the mainstream channel passes out of the catchment annually. A crude estimate of the order of magnitude of the mainstream bed sediment store volume could be made as follows: length (2000 m) x mean width (5 m) x mean depth (0.1 m) = 1000 m^3 of coarse sediment or about 1500 t which represents something like 600 years worth of bedload yield at the present rate. It does seem feasible that input from the tributaries is capable of balancing the sediment lost as bedload yield. Coarse sediment stored on the bed of the main channel therefore acts as a sink or buffer and consequently, small changes in this reservoir of sediment could have large effects on yields of coarse (and possibly fine) sediments. This study has not been able to deal adequately with this component of the sediment budget. Future sediment budget work should bear this in mind (see section 7.6). It must be also be noted that the calibration year for the sediment sources (1985) reported in these Phase I sediment budgets was wetter than usual with the mean annual catchment discharge being 0.4 - 0.5 m^3s^{-1} higher than the average for 1983 and 1984 (see Table 4.1). Figure 7.2 shows the quarterly precipitation totals for Parkhead weather station (Stirling) for the period 1973-85. The increasing precipitation trend and exceptional nature of the winter 1984 total (a number of slope failures were reported in the Ochil hills at this time by Jenkins et al. (in press)) and again the autumn 1985 totals (even higher) are clear. It was in autumn 1985 when two slope failures in Monachyle glen occurred. Extrapolation of sediment rating curves backwards to the 1983 and 1984 flow duration records gave load estimates 10-20% lower which were probably more representative than the estimates based on 1985. Even so, data collection during 1985 (the calibration year for both suspended and bedload in tributaries) may have led to overestimates of yields.

Comparing now the Kirkton (mature forest) Phase I sediment budget (Figure 7.1 (a)) with the moorland budget, there is not the same good agreement between supply from the sources and outputs. The estimated tributary suspended sediment yield appears to be more than double the catchment output of suspended sediment. Even taking into account the possible errors in estimating the loads (estimated from Ferguson (1987) to be of the order of +/- 20%) at the opposite extremes, there is definitely still a considerable mis-match. How can this be explained?

The first idea which must be considered is that the tributaries chosen as typical for the purpose of estimating tributary suspended sediment yield were in fact atypical and produced inflated estimates. Detailed suspended sediment monitoring was only undertaken in two (K4 and K8) of many

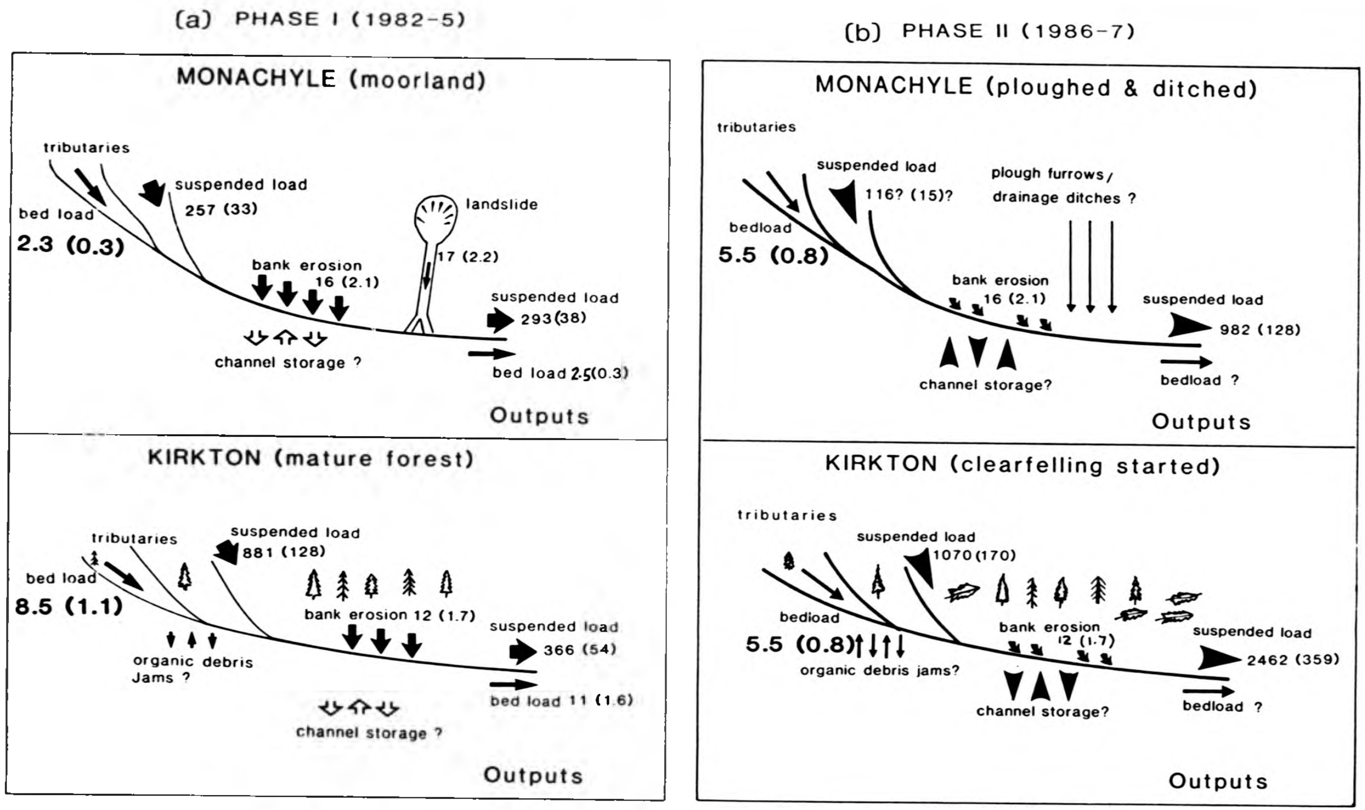

Figure 7.1 (a): Schematic sediment budgets for Balquhidder catchments before disturbance by forestry operations (Phase I - 1982-5).

(b): Preliminary schematic sediment budgets for Balquhidder catchments for the first eighteen months after forestry activity disturbance (Phase II - 1986-7). All loads are in t yr^{-1} and equivalent catchment yields (shown in brackets) are in t km^{-2} yr^{-1}.

tributaries (at least 14 major and numerous minor ones) in the Kirkton catchment. The area drained by the two monitored tributaries corresponds to about 25% of the total catchment area considered to be contributing sediment to the system (see unshaded areas in Figure 2.7). The actual 1985 suspended sediment inputs to the system from tributaries K4 and K8 were 172 and 41 t yr^{-1} and the other source measured (mainstream bank erosion) contributed 12 t yr^{-1}. This totals 225 t yr^{-1} from about 25% (1.6 km^2) of the total catchment area believed to be contributing sediment (or around 900 t yr^{-1} as suggested in the budget). In order for tributary 'inputs' (225 t so far from 25% of catchment) to balance 'outputs' (366 t), the imbalance of 141 t (366 - 225) must come from the remaining 75% (4.8 km^2) of the catchment. Is this realistic? If this is the case it would mean that the average suspended sediment yield from the rest of the catchment would need to be about 30 t km^{-2} yr^{-1}. This is comparable with the moorland tributary suspended yields. It might therefore be possible that the monitored tributaries K4 and K8 were unrepresentative of the sediment yield of the catchment as a whole and that the figure reported for Kirkton tributary suspended sediment yield in the Phase I budget is inflated. The bedload yields reported in Figure 5.10 and Table 5.14 show that K8 has an unusually high bedload yield also.

A second possible explanation for the high tributary suspended yield was referred to earlier in this section. The exceptionally wet nature of 1985 (see Figure 7.2) as a calibration year for the tributary yields might have resulted in data collection which was unrepresentative. Thus, when unrepresentative rating curves are applied to the 1983 and 1984 flow duration records this may still result in over-estimates of yields. In contrast, IH data at the outlets was collected over three years (1982-5) and may not be as susceptible to this over-estimation resulting from the exceptionally wet 1985?

Lastly, if the measured tributary suspended sediment yield really is in excess of the yield measured at the outlet there is always the possibility that some proportion of the excess sediment becomes stored. The most likely explanation would be overbank sedimentation during floods and storage in the floodplain. However, the Kirkton mainstream within the catchment has only a few areas that could be termed 'floodplain' unlike in the Monachyle catchment where the mainstream tends to meander far more (see Figures 2.3 and 2.4). The only other possible 'sink' for this excess fine sediment is the channel bed itself. However, a simple calculation would suggest that if the excess quantity of sediment were all to be stored in the 2 km by 5 m wide Kirkton mainstream then the mean depth of sediment would be of the order of 5 cm ! Clearly this is highly unlikely and would be clearly noticeable. In conclusion, there would be scope for <u>some</u> fine sediment storage between the tributaries and catchment outlet either on the channel bed or over banks, but excess from the tributaries is too large to be accommodated in either or even both of these stores combined.

Turning to the Phase I Kirkton bedload yields which are averaged in the budget diagram, on a catchment scale considerably more bedload leaves the outlet than is contributed by the tributaries. Again this could be a result of the different measurement techniques and the fact that only sediment coarser than 2.8 mm is reported for the tributaries whereas all sediment coarser 0.125 mm is caught in the Helley-Smith sampler. Again the D_{50} of Helley-Smith bedload samples is 1.0 mm (Johnson, pers. comm) and considerably finer than the average of 44 sub-samples taken from the tributary bedload traps which had a D_{50} of 8.0 mm. From this it would appear that different sediment is leaving the catchment to that supplied by the tributaries as discussed for the moorland catchment earlier. If the apparent imbalance is real then the in-channel coarse sediment store must be depleted on this short timescale (only one year of tributary bedload monitoring in Phase I compared to three years at the outlet). In both the tributaries and at the outlets, the forested Kirkton catchment bedload yields are much higher - more than double those of the moorland in the tributaries and five times higher at the outlet.

Comparing the suspended sediment yields (in brackets on Figure 7.1 (a)) of the forested with the moorland, catchment outputs seem to be about one and a half times higher from Kirkton. This is explained in Chapter 4 where the rating curves (Figure 4.1) show a more sensitive link between concentration and streamflow from the forest indicating that there is a greater supply of sediment available for transport out of the catchment at a given discharge. Conversely, the suspended sediment yield of the moorland can be said to be more supply limited. The difference in the catchment yields reported here is not as great as reported previously by

Stott et al. (1986) and Ferguson and Stott (in press) owing to extra data being incorporated into the rating relationships and recalculation of loads.

The sediment input from mainstream bank erosion is of the order of 5 and 3% of total catchment yield (12 and 16 t yr^{-1} over the two year survey period) in the Kirkton and Monachyle catchments respectively. However, it must be remembered that though this contribution seems small, it is an estimate for the mainstream channel banks only. Tributary streambank erosion was not directly measured in this study owing to the difficulties in placing and monitoring erosion pins in the frequently undercut and overhanging banks. However, a very crude and simple idea of the tributary streambank contribution could be obtained by extrapolating the average erosion rates measured on the mainstreams to an estimated area of tributary streambanks. The O.S 1:10 000 topographical maps of the catchments mark only the larger tributary streams and since the forested catchment contains a network of drainage ditches (as does the moorland in Phase II of the experiment) as well, it is very difficult to estimate even the total length of tributary streams, and even more difficult to estimate the total area undergoing erosion and therefore contributing sediment. However, considering only the streams marked on the O.S map (the larger ones) total stream lengths measured were 14 500 and 15 400 m in Monachyle and Kirkton respectively. If the mean tributary bank height is assumed to be of the order of 0.25 m, then using the erosion rates and bulk densities measured from the mainstream banks, the total tributary streambank yields would be in the region of 60 and 55 t km^2 yr^{-1} for Monachyle and Kirkton respectively. Clearly, this type of estimate is extremely crude and prone to large errors. Nevertheless it does serve to give an idea of the order of magnitude of the total bank erosion contribution.

Comparison of these streambank yields with the Phase I total suspended sediment yields (Figure 7.1 (a)) shows that channel bank erosion, at the rates measured in this study, is capable of contributing enough suspended sediment to account for the total catchment suspended sediment yield. This is logical since the only other possible sources for suspended sediment are channel bedrock weathering, in-channel pebble attrition and possibly some sediment carried as washload in hillslope surface runoff. All these sources are considered to be small or even negligible (certainly not large enough to account for anything like the total catchment suspended sediment yields). Thus, even though the budget diagrams portray the major suspended sediment sources as 'tributaries' it must be appreciated that the source of the vast majority of the suspended sediment yield of tributaries (and associated drainage ditches) probably comes from bank erosion.

Finally, other methodological problems peculiar to this study are:

(a) Although bedload trapping is the most suitable technique for channel source areas and Helley-Smith sampling is most suitable for larger catchment outlets, there are obvious problems in reconciling the two types of data with complete certainty. In this study the existence of ad hoc traps in the gauging weir pools has supported the estimates made from Helley-Smith sampling. Clearly, recording traps offer an attractive alternative (Raemy and Jaeggi 1981, Reid et al. 1985).

(b) It is clearly desirable to improve the seasonal rating curves for suspended sediment loads in both the tributaries and at the catchment outlets. The corrections applied probably make the estimated loads more accurate but rising and falling subdivision, for example, should be an aim for all seasons, backed by continuous records through floods to detect exhaustion effects. Phase II suspended sediment data collection and analysis in particular clearly needs some form of sub-division into smaller timescales in order to improve the estimates as discussed in section 4.2.

(c) The harsh and unusual climate of Balquhidder invalidates the use of standard seasons in sediment studies. There are particular problems of successful data collection in winter and these unfortunately impair the utility of automatic samplers and turbidity meters. The turbulent high energy nature of these mountain streams means that relatively coarse sediment becomes entrained and transported in suspension during storm periods at any time of the year. In the author's experience, this makes the calibration and performance of turbidity meters (used successfully elsewhere in lowland rivers, e.g. HRS 1977, Truhlar 1978, Walling 1977, 1978, 1982, Brabben 1981, Grobler and Weaver 1981, Carling and Douglas 1984, Finlayson 1985, Gilvear and Petts 1985) both difficult and unreliable during flood events when most sediment is transported.

(d) The relatively small fluxes of coarse material make direct assessments of storage changes difficult and this is clearly a weakness in this study. Further progress might involve routing sediments by size class over common time bases (e.g. Arkell et al. 1983) and determination of storage volumes from which changes can be assessed.

Newson (1986) suggests that yields of bedload from mountainous or disturbed upland catchments are anomalously high in relation to their area. Both Kirkton and Monachyle bedload yields are, however, unexpectedly low. Walling and Webb (1981a), in their survey of British suspended sediment yields estimated at river gauging sites, found suspended sediment yields ranging from 0.8 to 488 t km^2 yr^{-1}. The Phase I yields at Balquhidder fall well within this range. The Monachyle Phase I yield also falls within the range of upland (moorland) catchment sediment yields estimated from reservoir surveys in east central Scotland by McManus and Duck (in press). The Kirkton Phase I yield, however, is comparable with their highest estimates. The suspended sediment proportion of the yields are, however, anomalously high. At Plynlimon the suspended load contributed 49 and 24% of total load in the grassland and forest sub-catchments respectively (Newson pers. comm) whereas at Balquhidder suspended load contributes more than 97% of the total load in both catchments. Duck (1985) has pointed to the major impact of disturbance on suspended loads in a nearby stream in Glen Ogle and it may well be that bedrock, drift and soil factors in this part of the Highlands explain the relative proportions of the two forms of sediment transport.

7.2 **Post-disturbance sediment budgets (Phase II)**

7.2.1 Effects of afforestation on the sediment budget

Figure 7.1 (b) shows schematic representations of the catchment sediment budgets for the first eighteen months since ploughing and draining in Monachyle and clearfelling in Kirkton started. Clearly the most drastic effect from the ploughing and draining operations in the Monachyle catchment has been to increase the catchment suspended sediment yield three-fold. However, this was not detected in the one tributary source area studied where it seems that the Phase I suspended sediment yield of tributary M1 may have been diluted by sediment free water issuing from a cross-drain installed upslope (see section 5.4.1). Clearly it would have been desirable to have conducted the same type of intensive suspended sediment sampling in at least one other moorland tributary stream. During Phase I some suspended sediment sampling was carried out in two other tributaries for short periods but the termination of the road at the bottom of the catchment near tributary M1 meant that retrieval of bottle crates on foot from further up the catchment was too time consuming to fit into the existing monitoring programme in the post-disturbance period and it was decided to concentrate efforts on M1. In retrospect, perhaps this was a mistake and weakness in the monitoring design, since it has largely left unanswered the question of where the apparent trebling in the catchment suspended sediment yield has come from. It is only possible to suggest explanations with hindsight based on the experience of visiting the catchment weekly and photographing the ploughing and drainage operations. The hand sampling during a moderate flood event described in section 5.4.1 (Figure 5.12) showed that the water draining from the drainage ditch cut into peat in the M1 sub-catchment had very low suspended sediment concentrations indeed. Based on this piece of evidence alone it is not possible to pin point the plough furrows or ditches in this particular sub-catchment at that particular time. However, in other parts of the catchment coarse and fine sediment has been observed issuing from the downslope end of plough furrows and ditches onto the unploughed buffer zone as seen in Plates 5.2 and 5.3. It can only be assumed that during storm events considerably more fine sediment has found its way through the buffer strip and into the mainstream than had previously been assumed. Previous studies have pointed to plough furrow and drainage ditch erosion in particular as the source of the extra suspended sediment leaving the catchment following forestry ground preparation (Robinson 1978, Newson 1980b, Burt et al. 1982).

Even though tributary suspended sediment monitoring showed no increase, coarse sediment trapped as bedload in two of the three tributaries equipped with sediment traps did show three and four-fold increases immediately following the ditching operations (see Figure 5.13 and Table 5.14). Since output data for bedload in Phase II are not yet available it is not possible to comment on whether or not this has increased also. One further possible source might have been created during the ploughing and ditching work when the ploughs and ditching machines had to cross streams on their way up the catchment. The streambanks and streambed are disturbed periodically releasing fine sediment. Over the whole catchment this source has undoubtedly made a contribution to the large increases at the catchment outlet. Only an examination of the dates and times of suspended sediment sample collection at the outlet compared with the ploughing and ditching work schedule could reveal whether or not many of the highest concentrations coincide with the timing of the work or whether the highest concentrations were taken during subsequent flood events. This kind of approach to future estimates of catchment sediment yields could well refine the current provisional estimates based on one single rating relationship.

Clearly, it has not been possible to adequately identify and monitor the new sources of sediment which have obviously been created by the ploughing and ditching of the catchment. The tendency is to suggest that the plough furrows and ditches in particular, especially where they are deep enough to expose the erodible mineral soil beneath the peat as seen in Plate 5.2, must be the major new sediment sources. Streambank erosion of both mainstream and tributaries will remain as the other major source as it was in Phase I.

7.2.2 Effects of clearfelling on the sediment budget

As in the moorland catchment the striking change in the sediment budget is that suspended sediment outputs have undergone what appears to be a seven-fold increase. Again it must be emphasised for the reasons given earlier, that this is a provisional estimate in need of refinement. Results from the monitoring in the source areas seem to point to roads and stacking areas in particular (section 5.4.2) as the main new sources of sediment contributing to the increased catchment yield. The calculations at the end of section 5.4.2, bearing in mind that erosion rate (for the purposes of this calculation) was measured on a road cut-bank and not on road surfaces (which therefore may invalidate its use to a certain extent), neverhteless, crudely indicate that erosion of the bare areas alone can account to a large extent for the measured increases in catchment sediment yield. However, as the study of the southern stacking area concluded (section 5.4.2), as much as half of the sediment eroded from these bare surfaces can be temporarily stored (in roadside gullies, hollows or trapped in vegetation for example) and flushed out at a later stage.

Further contributions to the catchment sediment yield might be expected from streambank erosion in the future as discussed in section 6.4.2, but up until the end of the field study period (May 1987), very little tree felling alongside the mainstream had been carried out. However, a considerable amount of felling had been carried out on the banks of tributaries on the west side of the catchment (unfortunately those not monitored for suspended sediment yield) and it is likely that this will have caused localised damage to banks and thereby released new supplies of fine sediment.

The sediment yield increases resulting from ploughing and drainage ditching in Monachyle are comparable with those reported at both Coalburn (Robinson 1980) and in north Yorkshire (Burt et al. (1982). To date there is no other published British data reporting the effects of clearfelling on sediment yields.

7.3 Problems and management implications

The catchment areas of the upper Monachyle and Kirkton glens have been selected for the Balquhidder experimental study because they are typical of the many glens in upland Scotland which are scheduled for afforestation (and some deforestation) in the next few decades. It is in these areas that many of our salmon and trout rivers begin, arising from the extensive network of small, fast-flowing first and second order tributaries (like those studied in this project) which serve as the spawning and nursery grounds of these economically important fish species. It is the fish life of these mountain streams which is held in delicate balance and is probably the best indicator of a 'healthy stream'. If the physical properties of these streams remain suitable and are not threatened by human induced changes such as afforestation, then fish life should continue to thrive. However, an increasing number of research studies are beginning to detect adverse changes in both the physical properties and water quality of these streams. This means that characteristics such as channel geometry, flow regime, sunlight (including shade and cover), temperature, acidity and chemical balance (including toxic herbicides and fertilisers), dissolved oxygen content and suspended solids and silt content must be preserved in, or as close to, their natural state as is reasonably possible. This study has been concerned with just two aspects of the aforementioned stream properties - the stream channel geometry and the suspended solids and silt content of these mountain streams. Clearly, since such a delicate balance exists between fish life and each and every one of these stream properties on the one hand, and since UK Government policy advocates the need for extensive new afforestation (and of course harvesting of existing plantations) in these sensitive environments on the other, then only by exercising the most stringent and thoroughly tested management practices can this threatened British mountain stream environment and its breeding fish populations be protected. Brown (1980) reviews the interaction between forestry on the one hand and water quality on the other.

The Forestry Commission, responsible for only about half of the proposed afforestation in upland Britain in the next 50 years, has its own management guidelines and policies which have been considerably updated in the recent past in the light of both Forestry Commission's own and independent research findings. The Forestry Commission publishes literature ranging from Policy and Procedure papers on Forestry Commission Objectives, Recreation, Landscape Design and Conservation in general to very specific booklets, leaflets and records concerned with such aspects as ploughing practice, road planning and drainage schemes referred to earlier (section 2.5). A particularly useful one of these leaflets is 'The Management of Forest Streams' (Mills 1980) which deals with all aspects of stream ecology and puts forward forest management guidelines which are aimed at preserving and improving forest stream ecology.

However, drawing on the conclusions from this study, the large increases in sediment yield resulting both from ground preparation for planting in Monachyle and clearfelling and associated roading activities in Kirkton indicate that a problem exists in this environment although similar effects have been reported elsewhere (Robinson 1978, Burt et al. 1982, Francis 1987). It is beyond the scope of this thesis to attempt to assess the extent to which aquatic life in the system can tolerate such increases in fine sediment and silt. However, it is well documented (Mills 1980, Ottaway et al. 1981, Milner et al. 1981, Carling 1984) that high turbidities and suspended sediment can reduce sunlight penetration (which has direct effects on vegetation and algal existence on which fish can feed) as well as settle out on the gravel bed both suffocating developing eggs or alevins and smothering insect larvae living between the stones (again on which fish may feed). Further downstream other problems may arise concerned with drinking water supplies (Greene 1987); increased transport of nutrients, pollutants and contaminants (Ongley 1982, Lewin et. al 1983, Macklin and Rose 1986); increasing infill rates of reservoirs (McManus and Duck 1985) causing operational problems (Oldman pers. comm.); and channel instability (Newson and Leeks 1987) but again only further research and specific case studies will enlighten us to the extent of the problem.

The increased sediment outputs have occurred for one or a combination of several reasons. Either the management practices are inadequate, the execution of the work has been careless and has not adhered to the guidelines or given the combination of terrain, soil type and climate it has simply not been possible to carry out the ground preparation and felling operations without causing the observed release of sediment. Many have claimed that because the effect of the forestry operations have been closely monitored in this experiment, that extra care would have been taken to ensure good practices were carried out. In the author's experience this has not been the case and work in these catchments has been carried out in a 'typical' manner. Also, in the case of the clearfelling, not all has been done by the Forestry Commission - some timber was sold as standing sales and therefore has been extracted by contractors. What lessons can be learned?

On 4 November 1986, at the request of the Forestry Commission, both catchments were visited to review planting and felling progress in Monachyle and Kirkton glens with respect to their effects on sedimentation of watercourses. The party consisted of Dr. Graham Pyatt (Head of Site Studies, Forestry Commission Northern Research Branch), two staff of the Aberfoyle Forestry Division concerned with planning forestry operations within the catchments, Dr. Rob Ferguson and the author. The main conclusions of the visit are worthy of note here and were summarised in Dr. Pyatt's report following the visit. In Kirkton glen the northern stacking area was visited first, Dr. Pyatt's report notes that "recent road regrading had increased the sources of mobile material" but that remedial draining could be carried out by local staff. Next a 10 ha area being extracted by a contracted forwarder was visited where "in spite of elaborate thatching of the forest road there was evidence of sediment being washed off the road and from off-road tracks into minor tributaries. It seems clear that if forwarding had been possible and used over much of the 200 ha (sold to contract) there would have been a very significant increase in sediment reaching the mainstream." Also in

Kirkton glen we visited a site where cable crane extraction was taking place and concluded that this was relatively harmless as far as releasing sediment was concerned. Plate 7.4 shows the cablecrane or skyline extractor in operation. In Monachyle glen Dr. Pyatt was "surprised by the extent to which erosion had taken place in plough furrows before cross-draining was done." He added that "the ditches which have been put in mainly run down-valley and in places have gradients that are steeper than ideal. A few of them are producing significant amounts of sediment, the coarser part of which is presently being collected by the vegetation of the wide riparian buffer zone. The ditches will need to be watched during this critical first winter. Appreciable erosion may necessitate either re-routing or the digging of additional relief ditches." The digging of remedial drains and ditches seems to feature as a method of countering erosion problems in both catchments by Dr. Pyatt. By the end of the fieldwork period in May 1987 there was no sign of this having been done in either catchment. Perhaps if it had been done then the increased catchment sediment output might not have been as significant.

7.3.1 Minimising sedimentation from ploughing and drainage

Mills (1980) suggests that in order to catch silt where drains are leading to streams they should either be tapered in depth and stopped 15-20 m short so that the water discharging from the drain has to filter through the ground vegetation, or, in areas of high rainfall, a sump should be taken out just before the drain opens into the watercourse. On very steep slopes he suggests that a large V-type sump drain should be cut along the bottom of the slope to trap debris which is carried down the plough furrows. Either of these suggestions might prove useful in Monachyle glen and in other steeper than ideal sites. Robinson (1979) reported similar increased sediment yields but noted a recovery to a new equilibrium level within 5 years which was higher than the pre-disturbance yield. This is largely explained by revegetation of the drainage ditches and plough furrows which began in the Monachyle plough furrows very soon after the work was completed (see Plate 7.1) but there was little sign of vegetation in the drainage ditches by the end of the study period in May 1987. The recently evolved practice of leaving an unploughed and unplanted buffer strip alongside the mainstream was carried out in the catchment (see Plate 7.2) which is a good improvement on the planting practice of about 5 years ago in the lower part of Monachyle glen (see Plate 7.3) when young trees were planted right up to the mainstream. By May 1987 no broadleaf planting had been carried out in this zone, but this is the intention (M.J. Stewart, Forestry Commission site planner, pers. comm.). Mills (1986) suggests small deciduous planting such as birch (*Betula* spp.), willow (*Salix* spp.), rowan (*Sorbus aucuparia* L.) or alder (*Alnus* spp.). Alder grows vigorously and to prevent excessive shading and to allow access for recreation and stream management, it should be used in well scattered groups, especially along streams less than 12 m wide. If willows are used they require regular basal pruning but their root systems are effective in strengthening banks against erosion (Graham 1973, Stott 1984). A variety of other species

Plate 7.1 Revegetation of plough furrows in Monachyle only four months after ploughing. The peat seen in this photograph appears to quite resistant to erosion (see Figure 5.12), the underlying mineral soil seemingly contributing more sediment.

Plate 7.2 View of ploughed area in Monachyle showing unploughed riparian buffer zone, July 1986.

Plate 7.3 Mainstream in lower part of Monachyle glen showing forestry planting right up to the channel edge before the 'riparian buffer zone' policy.

Plate 7.4 Cablecrane or 'skyline' timber extraction in Kirkton glen appears to do little damage to the soil surface thereby minimising erosion problems.

suitable for water margins has also been suggested (Greer 1979), including common ash (*Fraxinus excelsior* L.) and aspen (*Populus tremula* L.). Finally, the Forestry Commission research division is experimenting with methods of planting which would not require ploughing at all. Instead, various mulches are applied around the young sapling to supress weed competition. This they feel would reduce the problem of windthrow which frequently occurs alongside drainage ditches where trees develop one sided root systems because they are unable to cross the drainage ditches. If planting without ploughing, and minimal drainage, could be achieved in the future then problems of sedimentation such as reported would undoubtedly be reduced.

7.3.2 Minimising sedimentation from roads, thinning, felling and extraction

Most research concerned with the effects of felling operations on stream sedimentation is from North America where studies such as that at the H.J. Andrews experimental catchments (see section 1.2) have pointed to road construction at the time of logging as the major cause of increased sediment yields. Studies of remedial methods to reduce the impact have also come from the US (e.g. Haupt and Kidd 1965, Ponce 1986, Sharpe and De Walle 1980). However, the forestry practices in upland Britain are somewhat different from north America where logging is of primary natural forests into which roads have to be made for felling and extraction purposes. In Britain, the primary forests were clearfelled a few centuries ago so modern day clearfelling is concerned with forestry plantations. One major difference is that in general roads were constructed at the time of planting and so only need to be improved and regraded at the time of felling. However, road construction within a catchment can considerably increase both erosion risks and the catchment sediment output as shown for nearby Glen Ogle (Duck 1985) which is some 10 km NW of Kirkton glen with the same underlying geology and soils (see section 2.4). Here, the construction of an unmetalled road for agricultural purposes in the glen which crossed several left bank tributaries of the Ogle burn, one of the main influents of Loch Earn, resulted in a deposit of 1824 t of sediment on the loch bed in 2 months which would have taken 20-25 years to accumulate had the road not been constructed. Current Forestry Commission policy is not to construct roads at the time of planting, no road being made into the Monachyle glen catchment, the reason being that felling and extraction technology is changing so rapidly at present that roading requirements for 40-50 years time are simply not known - extraction could be done from the air! (M.J. Stewart, pers. comm.). Private forestry companies however, do still construct roads at the time of planting for reasons concerned with tax evasion. However, although no new road construction was carried out in Kirkton glen, considerable road regrading was required as well as the construction of stacking areas, which combined with the increased road usage frequently by heavy logging lorries as section 5.4.2 explains, has mobilised a vast new source of sediment.

From the management point of view it is clearly important proper drainage be incorporated into the road design and construction to minimise erosion on the road surface, on the roadside banks and in roadside ditches. Water from roadside ditches should be discharged into natural watercourses at frequent intervals through culverts where necessary, a sump to trap silt and debris being put in where water is directly entering stream courses. Special erosion-control techniques may be required on roadside banks including such measures as intercepting trenches or terracing. Bare earth embankments and cuttings should, where possible, be left at a low angle of repose to encourage revegetation. Where the slope angle is steep, or erosion is severe, erosion-control netting manufactured by companies such as 'Netlon', 'Landguard' and 'Wyretex' for example should be pinned to the slope and possibly even seeded with a grass seed mixture to encourage rapid re-vegetation. Road culverts should be carefully placed at the design and construction stage, both inflow and outflow ends (especially for hanging culverts) being provided with rock or concrete aprons as stilling areas to reduce water velocity and prevent downcutting and erosion. Wherever possible culverts should be installed with a view to allowing the passage of fish on all watercourses frequented by them. In all cases the size of culverts used should be based on an assessment of the catchment area draining to it and local rainfall/runoff characteristics.

As far as the effects of thinning, felling and extraction on sedimentation stream ecology and fish are concerned again most research has been carried out in North America (e.g. Gibbons and Salo 1973, Meehan 1974, Meehan et al. 1969, Megahan 1972, Ramberg 1977). The major effects of these activities can be changes in streamflow regime, increased stream temperatures, sedimentation, loss of nutrients, damage to spawning grounds, blockage of streams, prevention of the movement of migratory fish, and bacterial decomposition of any bark, wood debris or pine needles smothering the stream bed. Preventing the fall of lop and top (branches stripped from trees after they are felled) into streams is the best way to control the last three effects. Trees should be felled away from streams where possible and if tree tops, branches or logs do enter a stream they should be removed as soon as possible and not left to clog up the stream as seen in Plate 7.5. Before felling teams move away streams should be checked to see that they are clear of this organic debris which will otherwise create organic debris jams which retain sediment (see section 5.3.4) and prevent the passage of migratory fish. This is in fact one of the conditions laid down by the Forestry Commission to felling contractors, but judging by the amounts of organic debris in the channels in Kirkton glen and by the number of organic debris jams reported in section 5.3.4 (see Plate 3.6) it seems that these conditions are not adhered to or followed up. Perhaps these practices should be regulated and checked more stringently? When logs are to be moved care should be taken to avoid breaking the ground surface if possible which would release sediment. This can be done by avoiding the use of long skid-roads (especially on steep slopes), stacking logs well away from stream courses and not operating heavy equipment in or near streams. From observations of the small area of timber extracted by forwarder in Kirkton glen it seems that this machine is capable of causing considerable damage to the ground and road surfaces which result in increased erosion

Plate 7.5 Recently felled timber allowed to clog up a small tributary (K12) in Kirkton glen, May 1987.

and sedimentation. Considerably more thought and control should be exercised when selecting which areas are suitable for extraction by this method, particularly when extraction by the comparatively harmless cable crane method is being carried out on the adjacent steeper slopes.

Unfortunately at present the Forestry Commission has no control over how timber sold as standing sale is felled and extracted by private contractors. Perhaps more stringent policies and controls should be exercised over all forestry operations in Britain, including the increasing number of private groups now operating, rather than leaving the Forestry Commission with its improved policies to lead the way in the hope that all other foresters will follow suit. After all, around half of all forestry in Britain today is under the control of the private forestry groups. It seems time to tighten up regulations and check that good forestry management practices are being carried out particularly since a predicted 1.8 million hectares of Britain's uplands are scheduled for afforestation in the next 50 years.

CHAPTER 8: CONCLUSION

8.1 Summary of findings

The research reported in this thesis was designed to supplement the Institute of Hydrology 'black-box' approach to monitoring sediment outputs from two paired catchments at the major disturbance phases of forestry operations. This was achieved by identifying and monitoring sediment sources (see section 2.2, p.19) within the catchments and adopting a sediment budget approach to combine the findings. During Phase I,

a. sediment sources were identified as:

(i) mainstream channel banks - both catchment mainstreams were instrumented with erosion pins, average bank erosion on the moorland mainstream being slightly higher than in the forest.

(ii) tributary sub-catchments - in the forested catchment sediment traps were installed on six tributaries, two of which were monitored intensively for suspended sediment. In the moorland catchment sediment traps were installed on three tributaries, one of which was intensively sampled for suspended sediment.

(iii) mainstream channel beds - this large sediment store was identified as both a source and a sink for sediment. Cross-section relevelling was carried out in order to attempt to assess changes in mean bed height and therefore sediment supply or storage. Unfortunately the estimated changes were usually within the estimated measurement error of the technique and could therefore not be claimed to be real.

b. erosion rates or sediment supply in these source areas was compared with sediment yields at the catchment outlets. In the moorland catchment there is very good agreement between the estimated supply of both suspended sediment and bedload from the sources and the yields at the outlet which implies a high delivery ratio of near to 100%. However, in the forested catchment the estimated supply of suspended sediment from the tributaries is well in excess of that measured at the outlet and this can only be explained by the selected tributaries being unrepresentative of the rest of the catchment. This is demonstrated to be feasible if other sub-catchments within the forest have lower yields. Bedload supply from the tributaries is only slightly lower than that measured at the outlet. This could be a reflection of the different measurement techniques or a real effect of storage of coarse sediment on the mainstream bed. The delivery ratio is still in excess of 70%.

c. sediment budgets were constructed which compared the moorland and forested catchment. The major conclusions were that in both catchments more than 97% of the sediment was yielded as suspended load. The total sediment yield from the forest was one and a half times higher than from the moorland and this was attributed to earlier disturbance in the form of roading and ditching at the time of planting.

In Phase II,

a. the major new sediment sources identified in the forested catchment at the time of preparation for clearfelling were the newly created timber stacking areas and roads (used by forwarder timber harvesting machines and large timber removal lorries). Erosion and sediment yield from one of these timber stacking areas was monitored. In the moorland new sediment sources were identified in the drainage ditches but direct monitoring of this source was not undertaken and is regrettable.

b. monitoring in the original source areas identified in Phase I was continued in exactly the same way in Phase II until May 1987.

c. Preliminary sediment budgets for the first eighteen months of Phase II were constructed. The estimates are provisional but suggest that catchment outputs have increased three and six-fold in the moorland and forest catchments respectively as a result of ploughing/ditching and clearfelling and associated roading/stacking area activities. In the forested catchment supply from the one tributary affected by the stacking area construction increased but not as much as the catchment output increases suggest. The delivery ratio is higher than 1.0. In the moorland, the one monitored tributary showed a decreased suspended sediment yield after the sub-catchment was ploughed and ditched. This result was surprising and can only be explained by sediment free water issuing from the drainage ditch diluting the original tributary suspended sediment load. The bedload yield of the moorland tributaries, however, showed a four-fold increase. No bedload data for the catchment outputs was available for Phase II at the time of writing.

8.2 Further research

A research investigation of this type attempts to find the answers to certain questions. Some questions are answered but inevitably as knowledge is advanced a whole new set of questions arise as a result of the findings. Thus, some questions have remain unanswered and some new questions have arisen - these are the lines on which further research must be based.

Clearly, a weakness in the part of the study on the effects of the ploughing and ditching (Phase II) has been the inability to match the supply of sediment from the most likely sources (plough furrows and ditches) with the large measured increases in sediment yield measured at the catchment outlet. This certainly needs further research at the plot scale as well as the sub-catchment scale. The author is aware of one such study which is a Forestry Commission contract awarded to Dr. Paul Carling (pers. comm) of the Freshwater Biological Association which is to be conducted in Scotland and will examine in detail soil erosion of plough furrows. A further weakness has been the inability to detect changes in channel storage of coarse sediment which has been shown to play such a significant role in the system (e.g. Trimble 1981). The moorland tributary bedload yields appear to be significantly higher than catchment outputs and yet no systematic deposition of coarse material on the main channel bed could be detected. This was due to the large errors in the survey technique (see section 6.3) compared with relatively small fluxes of material. Perhaps detailed surveys of the channel bed using electronic survey techniques (e.g. Leeks 1981), scour chains (Carling 1982) or netting pinned to the bed to detect deposition (Ashworth pers. comm) supplemented by larger scale sediment routing and tracer experiments which might use magnetic techniques (e.g. Arkell et al. 1983) could be a way forward with this problem. From the pebble tracer experiments carried out in the tributaries in this study the approximate rates of coarse sediment transport are now known and this will be useful in designing further sediment tracing studies.

In Kirkton it would seem prudent to concentrate future research efforts on the 'bare areas' (roads, cuttings and stacking areas) as sediment sources and to relate sediment production to road usage as done on the US (Megahan and Kidd 1972, Reid and Dunne 1984), to model recovery rates (e.g. Fukushima 1987) and re-vegetation and to assess the effectiveness of the remedial practices proposed in section 7.4.2. Also, due to the initial uncertainties in the felling programme the tributary selected for detailed sediment monitoring (K8) was not clearfelled during the study period and so the actual effects of clearfelling only (excluding roading etc.) on stream sedimentation could not be assessed. A detailed study of this, possibly at the plot scale (as done by the Forestry Commission on much flatter sites in the Kershope forest, Cumbria) should be a future aim for these steeper and wetter regions.

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APPENDIX I: TRIBUTARY DISCHARGE ESTIMATION BY SALT DILUTION GAUGING

This simplified method of gauging the discharge of small streams utilises the principle that when a mass M (g) of salt is added to a stream of unknown discharge Q ($m^3\ s^{-1}$), it will become fully mixed in the flow and at a point downstream its concentration C ($g\ m^{-3}$) starts to rise, peaks, then returns to its natural background level C_b. Mass balance requires that

$$M = Q(C-C_b)\ dt = Q(C-C_b)t \qquad (1)$$

where C is mean concentration over duration t of salt wave.

Concentration is monitored via electrical conductivity E($mS\ m^{-1}$) of stream, which is related to C and water temperature T (°C) by

$$E = k(0.5 + 0.02T)C \qquad (2)$$

where k is a constant for the particular combination of salt and conductivity meter used (k = 0.214 for pure salt and accurate meter). From (1) to (2), Z

$$Q = M\ k(0.5 + 0.02T)/(E-E_b)t$$

where E_b is background conductivity and E is average over salt wave.

Laboratory calibration

A strong primary solution of salt in deionised water is prepared and successive increments added to beakers of deionised water to give salt concentrations of 0, 5, 10,....50 g m^{-3} (or mg l^{-1}). Each beaker is stirred well and temperature and conductivity measured:

Salt concentration(C)	Electrical conductivity(E)
0	04
5	09
10	24
15	32
20	35
30	44
40	61
50	92

$E/(0.5 + 0.02T)$ is plotted against C to determine k for this particular combination of salt and conductivity meter. In this case k was calculated to be 0.146.

Field procedure

A channel reach of about 20 channel widths, preferably including narrows, rapids and falls to help mixing is selected and the conductivity meter set up at the downstream end and checked to be reading consistently. The background conductivity and stream temperature is recorded and a rough estimate if the stream Q made from the product of width, depth, velocity (time a floating object over a paced distance). About 500 g of salt per $m^3 s^{-1}$ is allowed, this being tipped into the centre of the channel at the upstream end of the chosen reach. Meanwhile, the conductvity reading is noted every 5 seconds until it returns to background.

Computation of Q

A BASIC computer routine was developed and run on an Apple microcomputer. The program used salt weight (g), background conductivity, seconds between readings, stream temperature (°T) and the conductivity readings as input. Stream discharge (Q) is printed in $l\ s^{-1}$.