National Development Plan 2007 - 2013

Environmental Protection Agency
An Ghníomhaireacht um Chaomhnú Comhshaoil

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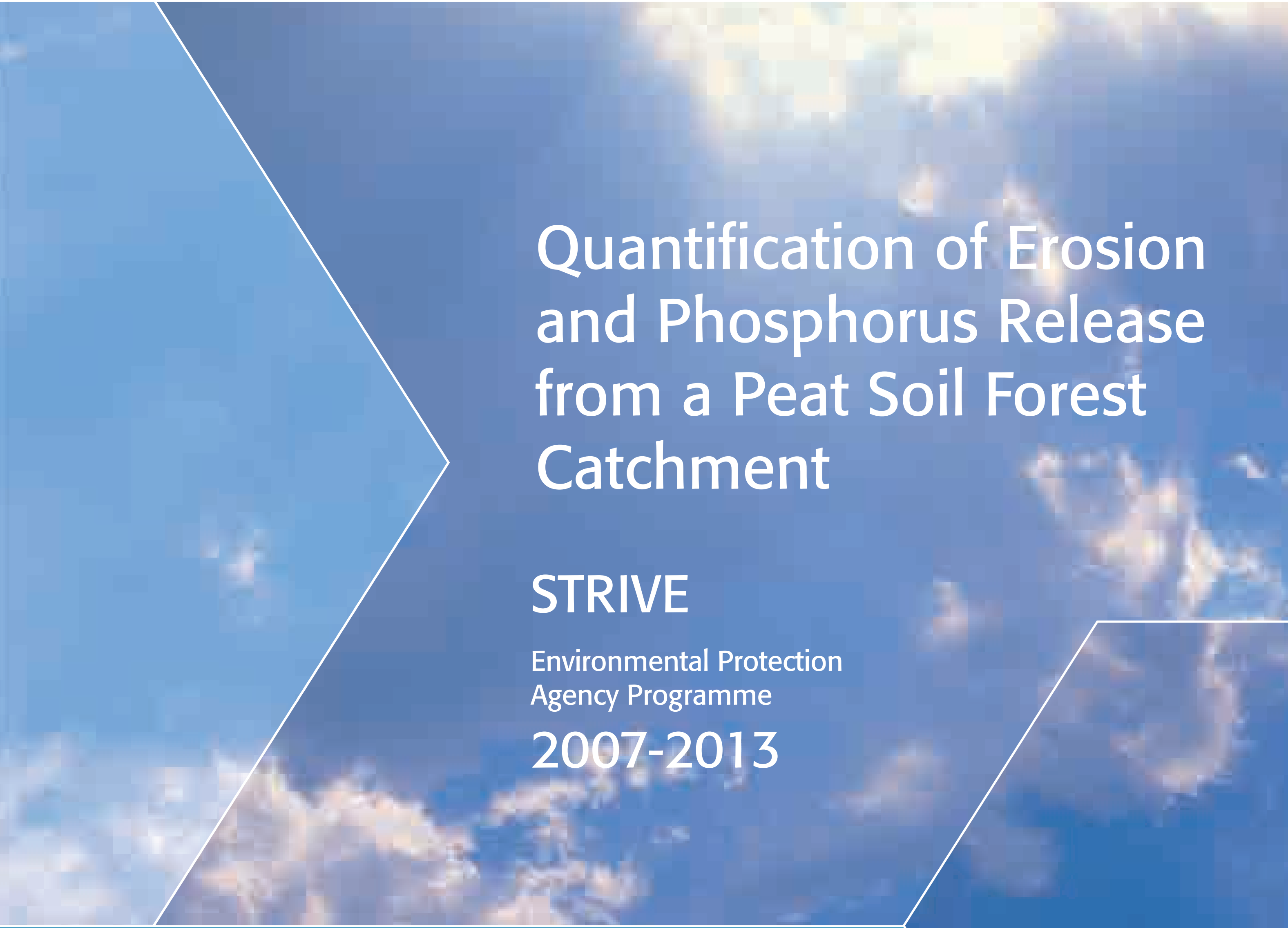

Quantification of Erosion and Phosphorus Release from a Peat Soil Forest Catchment

STRIVE

Environmental Protection
Agency Programme

2007-2013

COFORD
NATIONAL COUNCIL FOR FOREST RESEARCH & DEVELOPMENT
AN CHOMHAIRLE NÁISIÚNTA UM THAIGHDE AGUS FORBAIRT FORAOISE

coillte

Marine Institute
Foras na Mara

SSTI

Comhshaol, Oidhreacht agus Rialtas Áitiúil
Environment, Heritage and Local Government

Environmental Protection Agency

The Environmental Protection Agency (EPA) is a statutory body responsible for protecting the environment in Ireland. We regulate and police activities that might otherwise cause pollution. We ensure there is solid information on environmental trends so that necessary actions are taken. Our priorities are protecting the Irish environment and ensuring that development is sustainable.

The EPA is an independent public body established in July 1993 under the Environmental Protection Agency Act, 1992. Its sponsor in Government is the Department of the Environment, Heritage and Local Government.

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We license the following to ensure that their emissions do not endanger human health or harm the environment:

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The organisation is managed by a full time Board, consisting of a Director General and four Directors.

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- Office of Environmental Enforcement
- Office of Environmental Assessment
- Office of Communications and Corporate Services

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Is í an Gníomhaireacht um Chaomhnú Comhshaoil (EPA) comhlachta reachtúil a chosnaíonn an comhshaol do mhuintir na tíre go léir. Rialaímid agus déanaimid maoirsiú ar ghníomhaíochtaí a d'fhéadfadh truailliú a chruthú murach sin. Cinntímid go bhfuil eolas cruinn ann ar threochtaí comhshaoil ionas go nglactar aon chéim is gá. Is iad na príomh-nithe a bhfuilimid gníomhach leo ná comhshaol na hÉireann a chosaint agus cinntiú go bhfuil forbairt inbhuanaithe.

Is comhlacht poiblí neamhspleách í an Ghníomhaireacht um Chaomhnú Comhshaoil (EPA) a bunaíodh i mí Iúil 1993 faoin Acht fán nGníomhaireacht um Chaomhnú Comhshaoil 1992. Ó thaobh an Rialtais, is í an Roinn Comhshaoil agus Rialtais Áitiúil a dhéanann urraíocht uirthi.

ÁR bhFREAGRACHTAÍ

CEADÚNÚ

Bíonn ceadúnais á n-eisiúint againn i gcomhair na nithe seo a leanas chun a chinntiú nach mbíonn astuithe uathu ag cur sláinte an phobail ná an comhshaol i mbaol:

- áiseanna dramhaíola (m.sh., líonadh talún, loisceoirí, stáisiúin aistrithe dramhaíola);
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- diantalmhaíocht;
- úsáid faoi shrian agus scaoileadh smachtaithe Orgánach Géinathraithe (GMO);
- mór-áiseanna stórais peitreail.

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- Stiúradh os cionn 2,000 iniúchadh agus cigireacht de áiseanna a fuair ceadúnas ón nGníomhaireacht gach bliain.
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- Obair le húdaráis áitiúla agus leis na Gardaí chun stop a chur le gníomhaíocht mhídhleathach dramhaíola trí comhordú a dhéanamh ar líonra forfheidhmithe náisiúnta, díriú isteach ar chiontóirí, stiúradh fiosrúcháin agus maoirsiú leigheas na bhfadhbanna.
- An dlí a chur orthu siúd a bhriseann dlí comhshaoil agus a dhéanann dochar don chomhshaol mar thoradh ar a ngníomhaíochtaí.

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- Cainníochtú astuithe gáis ceaptha teasa na hÉireann i gcomhthéacs ár dtiomantas Kyoto.
- Cur i bhfeidhm na Treorach um Thrádáil Astuithe, a bhfuil baint aige le hos cionn 100 cuideachta atá ina mór-ghineadóirí dé-ocsaíd charbóin in Éirinn.

TAIGHDE AGUS FORBAIRT COMHSHAOIL

- Taighde ar shaincheisteanna comhshaoil a chomhordú (cosúil le caighdéan aeir agus uisce, athrú aeráide, bithéagsúlacht, teicneolaíochtaí comhshaoil).

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- Ag déanamh measúnú ar thionchar phleananna agus chláracha ar chomhshaol na hÉireann (cosúil le pleananna bainistíochta dramhaíola agus forbartha).

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- Eolas níos fearr ar an gcomhshaol a scaipeadh (trí cláracha teilifíse comhshaoil agus pacáistí acmhainne do bhunscoileanna agus do mheánscoileanna).

BAINISTÍOCHT DRAMHAÍOLA FHORGHNÍOMHACH

- Cur chun cinn seachaint agus laghdú dramhaíola trí chomhordú An Chláir Náisiúnta um Chosc Dramhaíola, lena n-áirítear cur i bhfeidhm na dTionscnamh Freagrachta Táirgeoirí.
- Cur i bhfeidhm Rialachán ar nós na treoracha maidir le Trealamh Leictreach agus Leictreonach Caite agus le Srianadh Substaintí Guaiseacha agus substaintí a dhéanann ídiú ar an gcrios ózóin.
- Plean Náisiúnta Bainistíochta um Dramhaíl Ghuaiseach a fhorbairt chun dramhaíl ghuaiseach a sheachaint agus a bhainistiú.

STRUCHTÚR NA GNÍOMHAIREACHTA

Bunaíodh an Ghníomhaireacht i 1993 chun comhshaol na hÉireann a chosaint. Tá an eagraíocht á bhainistiú ag Bord lánaimseartha, ar a bhfuil Príomhstiúrthóir agus ceithre Stiúrthóir.

Tá obair na Gníomhaireachta ar siúl trí ceithre Oifig:

- An Oifig Aeráide, Ceadúnaithe agus Úsáide Acmhainní
- An Oifig um Fhorfheidhmiúchán Comhshaoil
- An Oifig um Measúnacht Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáide

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag ball air agus tagann siad le chéile cúpla uair in aghaidh na bliana le plé a dhéanamh ar cheisteanna ar ábhar imní iad agus le comhairle a thabhairt don Bhord.

EPA STRIVE Programme 2007–2013

Quantification of Erosion and Phosphorus Release from a Peat Soil Forest Catchment

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STRIVE Report

Prepared for the Environmental Protection Agency
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by

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DISCLAIMER

The EPA STRIVE Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Executive Summary

The effects of clearfelling and harvesting lodgepole pine trees on the quality of receiving waters in a productive salmonid blanket peat catchment in Burrishoole, Co. Mayo, were investigated in this research study. The blanket peat catchment is representative of a large percentage of areas in the western part of Ireland and of upland areas throughout Ireland. The research was carried out in the context of examining and making recommendations on the Irish Forest Service *Forestry and Water Quality Guidelines*. The trees were planted in 1971 and the annual rainfall in the catchment exceeds 2,000 mm. The site preparation for the original tree planting comprised double mouldboard ploughing at right angles to the contours, and the installation of collector drains.

The study site was contained within a 20-ha area and was drained by a first-order stream that received the flows from the ploughed furrows, mainly via the collector drains. The stream waters discharged directly to the salmonid Srahrevagh River and did not flow through a buffer zone.

The study site was divided into two parts. The downstream part of 10.5 ha was clearfelled from the end of July 2005 for 8 weeks and the upstream part of 7.2 ha was left intact. Two instrumented stations were established – one just upstream and the other just downstream of the area to be clearfelled. The instrumentation at each station included a flume, water-level recorder, automatic water sampler and probes for measuring physico–chemical water variables; two rain gauges were installed at the downstream station. The rainfall, flows and water quality variables at the two stations were examined every 5 min for about 1 year pre-clearfelling, during clearfelling and harvesting, and for 19 months post-clearfelling. During flood events, water samples were taken hourly for suspended sediment (SS) and phosphorus (P) testing at the upstream and downstream stations. Water samples were also taken hourly in base-flow conditions over a 24-h period, once weekly at the two stations. The SS sampling was carried out for 1 year, and the P sampling for 1 month, prior to clearfelling. After clearfelling, both SS and P sampling were carried out for 2 years.

The study site was clearfelled by Coillte Teoranta and its contractors in accordance with the Forest Service guidelines, with no on-site work being carried out during wet weather. The SS concentrations in the stream water were statistically significantly higher than the pre-clearfelling concentrations for less than 1 year after the clearfelling and harvesting operations were complete. One month after the clearfelling and harvesting operations were completed, the mean SS concentrations at the upstream and downstream stations in a flood event on 2 November 2005 were 11 mg/l and 42.2 mg/l, respectively. From August 2005 to April 2006, there were significant differences between the peak upstream and downstream SS concentrations in flood events. From May 2006 to May 2007, the SS concentrations at the upstream and downstream stations were similar, indicating that the effect of the clearfelling and harvesting operations on the SS concentrations in the study stream had ceased. The amount of additional solids (100 kg/ha per year) – above normal losses – that left the harvested area during that first year after harvesting was less than the equivalent of 0.1 mm of peat over the area. The mean daily P concentration at the downstream station increased from about 6 µg total reactive phosphorus (TRP)/l pre-clearfelling to 429 µg TRP/l in August 2006 and had reduced to 100 µg TRP/l by April 2007. More than 80% of the P was in soluble form. These results indicate that the effects of clearfelling and harvesting are longer lasting on the P mass balance in the catchment than on the soil mass balance. However, in this catchment, the dilution available in the Srahrevagh River maintained the average P concentrations in the water downstream of the confluence of the river and study stream at less than 10 µg TRP/l. The dilution ratio in this study was about 24, based on the ratio of the area of the upstream river catchment to the clearfelled area. This indicates that knowledge of areas, flows and nutrient concentrations at strategic locations in a catchment could provide a rational and quantitative basis for sizing felling areas that would have minimal effects on receiving waters.

In summary, the Forest Service guidelines provide good guidance for sustainable forestry. The results demonstrate that the current guidelines and measures implemented in the catchment were effective at protecting water quality. Further detailed studies should be carried out to: (i) provide quantitative data on the removal of solids and nutrients in buffer zones, dilution effects and erodibility indices for Irish soils; (ii) further develop P loss models; (iii) identify the fate of exported material and nutrients; and (iv) identify the concentrations of water physico–chemical parameters that are important for stream organisms.

1 Introduction

1.1 Overview

During forest operations, including clearfelling and harvesting, the forest soil surface can be disturbed, resulting in increases in soil erosion, and suspended sediment (SS) and nutrients in run-off waters. If proper management practices are not exercised, these increases can cause reduced soil fertility and enriched receiving waters, leading to diminished aquatic biodiversity. In Ireland, most forests have been planted in upland areas – many on blanket peats – and, as a result, many Irish watercourses rise in, or receive drainage from, plantation forest areas. This upland planting has led to concerns about the possible impacts that operations in these forests may have on aquatic systems.

In this study, 10.5 ha of a forested peat catchment of about 20 ha at Burrishoole, Co. Mayo, Ireland, which discharges into a productive salmonid river, were clearfelled and harvested. Rainfall, flows and physico–chemical parameters in the receiving waters were monitored pre-clearfelling, during clearfelling and harvesting, and post-harvesting to establish the effects of the forest operations on the local aquatic environment. The parameters were monitored at two instrumented stations on the main catchment stream – one above and the other below the harvested area.

1.2 Objectives

The specific objectives of this study were to:

- Analyse the effects of the forest clearfelling and harvesting operations on the SS and phosphorus (P) concentrations in the catchment drainage stream

- Analyse the effects of the forest clearfelling and harvesting operations on other biological and physico–chemical parameters, e.g. pH and temperature in the catchment drainage stream

- Analyse the effects of the forest clearfelling and harvesting operations on the hydrology of a stream draining a blanket peat catchment

- Assess the *Forestry and Water Quality Guidelines* of the Forest Service with regard to sediment and P releases from the catchment and to suggest amendments where necessary.

2 Literature Review of Forest Activities and Best Management Practices

2.1 Overview

This literature review of forest operations and best management practices (BMPs) covers the following topics:

1. Soil erosion and deposition processes with an emphasis on minimising sediment production and maximising its deposition before reaching aquatic zones

2. Impacts of forest activities on run-off

3. BMPs to minimise erosion and sediment production from forest operations, including ground preparation and drainage, clearfelling and harvesting

4. BMPs in relation to sediment loss controls, including vegetation and buffer strips, and the design, construction and maintenance of silt traps, drains, drop structures and other control measures.

This review examined current *Forest Harvesting and Environment Guidelines* (Forest Service, 2000a), *Forestry and Water Quality Guidelines* (Forest Service, 2000b), *Forest Protection Guidelines* (Forest Service, 2000c), *The Irish National Forest Standard* (Forest Service, 2000d), *Forest Harvesting and the Environment Guidelines* (Forest Service, 2002), the *Forestry Schemes Manual* (Forest Service, 2004), the *National Report to the Fourth Session of the United Nations Forum on Forests* (Forest Service, 2003), and publications from the Forestry Commission Great Britain and the Centre for Ecology and Hydrology, Wallingford (Robinson and Dupeyrat, 2005). Coillte Teoranta reports (ECOWOOD project) and Forest Service publications dealing with BMPs are also reviewed along with Irish, UK and US studies that monitored erosion, sediment yields and hydrology during the phases of forest establishment, mature forest growth and timber harvesting.

2.2 Introduction

Forest activities, including afforestation, thinning, clearfelling, reforestation and forest road construction, can radically alter the forest soil characteristics (Cunningham *et al*., 1999) and impact on receiving waters (Cummins and Farrell, 2003a,b). Clearfelling can cause changes in the soil water content and increase the surface run-off, leading to diminished soil fertility and biodiversity (Cunningham *et al*., 1999). Although the land now becoming available for forestry is of better quality than in the past and located at lower altitudes, the majority of Irish forests have been planted in upland areas and, as a result, many Irish watercourses rise in, or receive drainage water from, plantation forests. This has led to concerns about the possible impacts that operations in these forests may have on aquatic systems. During planting, road construction, thinning and harvesting operations, sediment from soils may be released and washed into streams, causing increased SS and nutrient loads in the receiving waters. Where certain soil types (e.g. sandstone-derived soils) and steep slopes occur together, there is a high risk of soil erosion and subsequent sedimentation (Forest Service, 2000a,b). Additionally, drainage and clearfelling operations can have a major influence on catchment hydrology, particularly on water and bedload yields. Within the Irish forest industry there is an increasing awareness of the need for the minimisation of forest soil damage.

2.3 Forestry Erosion and Best Management Practices

2.3.1 Erosion processes

Soil erosion by water results in a depletion of soil *in situ* and the export of sediment to downslope and downstream areas. It is caused by the processes of rainfall detachment, entrainment of soil by overland flow and transport in sheet and rill flow (Rose, 1993). When sufficient energy is no longer available to transport soil particles in suspension, deposition occurs. Detachment refers to the removal of soil from the original soil matrix by raindrop-induced shear stresses in the absence of any flow (Torri and Borselli, 2000). Some of this soil sediment settles back close by where it came from and some may be splashed into the air to be captured by a thin covering water layer, if there is one. Re-detachment refers to detachment of already detached and deposited soil sediment. Virgin soil always has some cohesion, while the deposited sediment is loose and much more easily erodible, as it does not have time to build up cohesive links with neighbouring particles (Rose, 1993). A similar reasoning applies to entrainment of original soil and its re-entrainment by overland flow following on deposition.

Soil erosion is commonly differentiated into sheet and rill erosion. Sheet erosion is due to rainfall detachment/re-detachment and/or run-off entrainment/re-entrainment on a land surface. Detachment and re-detachment are dominant where the thickness of the water layer on the soil is less than three raindrop diameters (Rose, 1993). The stream power of the run-off increases with land slope and velocity of flow leading to greater erosive power. The magnitude of the erosive effects of rainfall and run-off depend on the soil, primarily its cohesion. In erodible soils, the combination of intensive rainfall and run-off produce the greatest soil loss (Proffitt and Rose, 1991). Also, in these soils, e.g. sandy soils, a vegetation cover or canopy near the soil surface can be very important in limiting erosion. Where soil strength is dominant, due to reinforcement by a dense mesh of strong roots, e.g. peats, the effects of a surface cover or canopy of low-growing vegetation in reducing soil loss is secondary (Rose, 1993). Likewise, a surface contact cover, such as a brash mat, is effective against detachment and entrainment by intercepting rainfall and slowing down run-off rate. Rills are small streams eroded out by water flow, fed by run-off from sheet flow, e.g. ruts in drains and roads. Erosion from rills is due to entrainment and re-entrainment by running water aided by mass movements of soil into the rill due to sidewall sloughing and slips, undercutting of sidewalls and head cutting of rills. Generally, the erosive power of flowing water in rills is greater than in sheet flow. An empirical erodibility index (Mulqueen *et al.*, 2007), which quantifies the susceptibility of soils to erosion, can be defined as:

$$\beta = \frac{\ln c}{\ln c_t} \qquad \text{Eqn 2.1}$$

where c is the flux-weighted concentration (mg/l), determined from run-off plots or soil flumes and c_t is the maximum or transport-limiting sediment concentration (mg/l) for given flow conditions.

Laboratory flumes, packed with soil and subjected to simulated rainfall or overland flow, allow control of erosion variables such as rainfall intensity, streamflow, slope and soil type. Flume experiments have been widely used for determining the susceptibility of soils to erosion (Sharpley *et al.*, 2001a,b; Kleinman *et al.*, 2004; Penn *et al.*, 2006; Mulqueen *et al.*, 2007). Typically in these soil flume studies, 50 mm deep intact or reconstituted soil slabs are placed in a 2 m long by 0.225 m wide box and are subjected to overland flow or simulated rainfall. The SS concentrations are then measured in the surface run-off and the erodibility index value determined. The erodibility index experiments can also be carried out in the field on run-off plots.

2.3.2 Cultivation and drainage – erosion and best management practices

2.3.2.1 Cultivation, drainage and erosion

In afforestation operations, poor management practices such as unsuitable ground preparation and drainage can result in soil disturbances leading to erosion, sedimentation and nutrient delivery in riparian and aquatic zones. Until the late 1970s, the traditional site cultivation method for plantation establishment in Ireland and the UK was ploughing (Carling *et al.*, 2001). Ploughing operations using furrows and cross-drains without the use of buffer zones can pose considerable environmental risk (Carling *et al.*, 2001). Mateos and Giráldez (2005) examined flow velocity, SS and sediment bedload concentrations in a 132 m long by 18 m wide loamy alluvial soil containing a series of furrows, spaced at 0.75 m centres at a slope of 0.3% in the direction of the furrows. Under incremental influent water loading rates up to 2.3 l/s, the SS concentration increased from 1.9 g/l at the top of the furrow to 4.6 g/l at a distance of approximately

100 m from the top of the furrow. Correspondingly, the bed sediments had concentrations ranging from 5.5 g/l at the top of the furrow to 5.4 g/l at 100 m from the top of the furrow (Mateos and Giráldez, 2005).

Today, ploughing has virtually ceased as a cultivation method. Excavator mounding is now by far the predominant method of cultivation for both afforestation and reforestation. Worrell (1996) states that mechanical methods, such as mounding, disturb up to 30% of a site, ripping and moling disturb up to 25%, whereas ploughing accounts for the most site disturbance at up to 70%.

2.3.2.2 Best management practices for cultivation and drainage

To avoid erosion caused by cultivation and drainage, BMPs for ground preparation, buffer zones, silt traps and drainage must be well planned, correctly designed, properly executed and managed, e.g. mounding, moling, ripping and subsoiling cause less soil disturbance than ploughing and can lead to more stable forests (Mulqueen *et al*., 1999). The Forestry Commission Great Britain (2003) advised that cross-drains should discharge into vegetated areas with a gradient less than 2% and spacing on cross-drains on erosion-susceptible soils should be reduced. In Ireland, the Forest Service guidelines (2000a,b,c,d, 2002) and the *Code of Best Forest Practice* (Forest Service, 2000e) recommend a number of options on the proper design and installation for drainage, cultivation and sediment traps.

Monitoring showed that BMPs can significantly reduce sediment loss caused by cultivation and drainage. Nisbet *et al*. (2002) found that a combination of restricting the depth (30–45 cm) and length (50–70 m) of plough furrows and retaining relatively wide (30–50 m) buffer strips was successful in preventing significant sediment loss and protecting the freshwater environment (Nisbet, 2001; Nisbet *et al*., 2002).

2.3.3 Harvesting – erosion and best management practices

2.3.3.1 Harvesting and erosion

Erosion from timber harvesting and reforesting operations is generally less per unit area than erosion from roads, but can still be significant in the absence of BMPs, since harvested areas are much larger than the roaded areas (Elliot *et al*., 1999). Skidder logging systems – a process where the logs are dragged along the forest floor – cause much disturbance through soil compaction, remoulding, puddling of soil, removal of litter cover and loosening of mineral subsoil. These are rarely practised in Ireland, where the predominant system is based on precut shortwood extracted by forwarder. Wallbrink and Croke (2002) found that highly disturbed and compacted surfaces, such as skid tracks, are a major source of soil loss during low to medium rainfall events.

In a study of the impacts of woody debris in streams Giller *et al*. (2002) reported that at one of the clearfell sites, mechanical removal of woody debris from the stream channel caused bank collapse and a substantial input of soil. At another clearfell site in the same study, effects of inadequate sediment trap size and its overflow were recorded 2.4 km downstream of the clearfelled area and, on one occasion, sediment was observed to travel 4–5 km downstream from the clearfell area (Giller *et al*., 2002).

In the south-west of Ireland, Johnson *et al*. (2000) monitored 16 clearfell sites and found that, of all the physico–chemical parameters investigated, SS was the most affected by clearfelling operations. Results showed increases in SS at 10 of the 16 clearfell sites. Some increases were short term and clearly centred around the duration of clearfelling operations. Where long-term increases were found, they were generally associated with flood events post-felling, whereby soil was washed from the clearfell area into streams. Increases in sediment and soil on the stream bed, originating from the clearfelling operation, were found at 7 out of 16 sites. Again, most of the increases were short term, but it is not known to what extent sediment became trapped within the gravel of the stream bed.

The intensity of harvest, depending on the felling method, may increase concentrations and loadings of sediment during storms. In catchment studies conducted in Arkansas and Oklahoma, Scoles *et al*. (1996) found statistically significant increases in annual soil loss in the first year after clearfelling, compared with selectively harvested and control sites. Annual soil losses averaged 237 kg/ha and 261 kg/ha on the clearfelled catchments in Arkansas and Oklahoma, respectively.

Crossing points for machinery, particularly during harvesting and forwarding operations, have also been identified as major sources of soil loss into watercourses. A range of parameters can influence the impact of crossing points on streams, including type of crossing point, the intensity and duration of use of the crossing points, the gradient of the track, weather conditions and the character of soil in the stream bank (Giller *et al*., 2002).

2.3.3.2 Best management practices for harvesting

In Ireland, the BMPs to minimise soil erosion and nutrient enrichment during harvesting operations are described in the *Forest Harvesting and the Environment Guidelines* and the *Code of Best Forest Practice* under the headings: Harvest Planning and Harvesting. These BMPs include:

- strategic location for landings and turntables
- short extraction routes
- suitable extraction equipment
- good weather conditions, and
- the proper use of effective brash mats (Hutchings *et al*., 2002), sediment traps and buffer zones.

It is important to implement BMPs over the entire harvest area, since run-off is regulated by natural processes throughout the catchment. Also, it is necessary to select harvesting methods and equipment to minimise soil disturbance, including proper layout of roads and skid trails. Furthermore, heavy equipment should not be allowed in or across drainage ditches.

Buffer zones or strips can reduce the effects of soil erosion. In south-west Ireland, Johnson *et al.* (2000) found that the presence of a buffer strip, even as narrow as 5 m, appeared to be effective in preventing an input of SS into the aquatic zone at a number of sites. At a study site in Mallow Forest, Ballyhoura Mountains in north Co. Cork, a small experimental site on Old Red Sandstone was established to monitor the effects of felling and reforesting operations (windrowing, drainage and mounding) on two streams with and without buffer zones (O'Halloran *et al*., 2002). Suspended sediment concentrations in the stream without buffer strips increased tenfold immediately following ground preparation before re-planting and the value decreased immediately following completion of operations, while the SS concentrations in the stream with a buffer strip was the same as that at a control station (O'Halloran *et al*., 2002).

The effects of operating with and without brash mats during harvesting have been investigated by Coillte Teoranta at a number of field tests in the EU ECOWOOD-Project. The observations of the field tests suggest that in clearfell situations, where sufficient quantities of brash mat material are available, ground disturbance can be minimised with adequate maintenance of the brash mat (Tiernan, 2001). Hutchings *et al.* (2002) examined the effectiveness of various thicknesses of brash mats to reduce the compaction of soil from forest harvesting machinery and concluded that brash mats were successful in reducing the degree of soil disturbance. Tiernan and Lyons (2000) investigated the progression of ground disturbance on a peat site during forwarder extraction on a brash mat, and found that when maintenance of the brash mat was conducted on an ongoing basis, the deterioration of weak areas in the brash mat was prevented and, as a consequence, deep disturbance and rutting were minimised. In summary, the protection of the aquatic zone during harvesting operations can only be achieved if sufficient on-site care is taken, particularly with regard to the use of brash mats, matching of machinery to site conditions and effective buffer zone management (Tiernan and Lyons, 2000; Nisbet *et al*., 2002).

The effect of harvesting on sediment concentrations in receiving water is a function of the felling area size (Giller and O'Halloran, 2004; Broadmeadow and Nisbet, 2002, 2004). Carling *et al.* (2001) recommend that plots of 10–20 ha each should be harvested at a time. A move to harvest smaller coupes of 10–20 ha is supported by findings from two Welsh catchments, where 10- to 15-ha plots were harvested in accordance with the UK *Forest and Water Guidelines* (Forestry Commission Great Britain, 1993, 2003). The monitored increases in SS yield at Nant Tanllwyth of 240–440 kg/ha per year and at Hafren of 160–230 kg/ha per year were not regarded to be significantly harmful to aquatic life. The average suspended soil concentration below the clearfelled sites did not exceed 7 mg/l (Environment Agency, 1998). In the UK, there is now a partial move towards Continuous Cover Forestry (CCF), where the forest canopy is maintained without clearfelling (Farmer and Nisbet, 2004) to keep a continuous tree cover; however, CCF requires a greater road network. This has some economic and environmental advantages, as the crop may have the ability to regenerate itself and the visual impact of large clearfelled areas is reduced.

Using wide drainage channels at skid tracks could also reduce the sediment release from forestry activities. Wallbrink and Croke (2002) investigated the effectiveness of 5–6 m wide and 0.5 m deep drainage channels, in settling sediment from highly compacted 75-m^2 skid tracks. Overland flow drained from the skid tracks, entered the drainage channel, and then flowed over a metered V-notch weir into a 200-m^2 harvested area. In total, 12 sites were monitored. The gradients on the sites ranged from 8 to 25° and the time elapsed since logging varied from 0.5 to 5 years. Rainfall simulators were positioned over the sites and the sediment run-off was monitored at two locations: the outlets from the drainage channels and from the general harvested area. The experiments were conducted during three 30-min duration rainfall intensities of 45, 75 and 110 mm/h. The highest sediment production rates occurred during rainfall events immediately after logging, but decreased over time. The drainage channels reduced the sediment load by, on average, 60%. The general harvested area acted as a vegetative filter strip and retained most of the finer sediment over a flow length of approximately 5 m.

2.3.4 Buffer zones

Buffer zones are among the most important BMPs with potential to eliminate the impact of forest activities on the receiving waterbodies. Buffer zones with minimum widths of 10–25 m – as recommended in the Forest Service publication *Forestry and Water Quality Guidelines* – are a key element in controlling sediment delivery to aquatic zones. Giller and O'Halloran (2004) found that in a study of two felled catchments, with and without a 10-m wide buffer zone, afforestation operations produced no significant long-term hydro-chemical or physical habitat changes in either catchment. Broadmeadow and Nisbet (2004) reviewed the range of riparian buffer widths reported in the literature and found that they depended greatly on the type of control required.

Vegetated riparian buffer zones provide attenuation for sediment and nutrient releases and increase soil stability (Carling *et al.*, 2001). They also act to protect stream banks from erosion. Castelle *et al.* (1994) (referenced in Broadmeadow and Nisbet, 2002) state that these zones should comprise native riparian woodland and their widths should be at least 15–30 m, depending on the sensitivity of the receiving waters. The effectiveness of riparian buffer zones depends on their dimensions, species composition, structure, slope, aspect, altitude and management (Broadmeadow and Nisbet, 2002). It is suggested that 50% of the river bank ground surface should be under dappled shade, as excess shade may affect productivity of salmonid fisheries and restrict growth. Submerged sections within the buffer zone also increase biodiversity, as well as providing sites for sediment retention. Where planting is required in the buffer zones, mounding is recommended (Broadmeadow and Nisbet, 2002), as the buffer zone soil may be vulnerable to disturbance by machinery.

The *Forestry and Water Quality Guidelines*, the *Code of Best Forest Practice* (Table 2.1) and the *Forest Schemes Manual* regulate the establishment of buffer zones along all aquatic zones within which ground preparation and other forest operations are restricted or prohibited. Buffer zones should be in place throughout the rotation, and have particular relevance to establishment, harvesting and road construction. The *Code of Best Forest Practice* specifies buffer zone width by slope and soil erodibility (Table 2.1) and the Irish *Forestry and Water Quality Guidelines* give general recommendations in relation to buffer zones.

2.3.5 Summary

Soil erosion by water results in a depletion of soil *in situ* and the export of sediment to downslope and downstream areas. It is caused by the processes of rainfall detachment, entrainment of soil by overland

Table 2.1. Recommended buffer zone widths (*Code of Best Forest Practice*).

Average slope leading to aquatic zone	Buffer zone width on each side of the aquatic zone	Buffer zone width for highly erodible soils
Moderate (even to 1 in 7/0–15%)	10 m	15 m
Steep (I in 7 to I in 3/15–30%)	15 m	20 m
Very steep (I in 3/>30%)	20 m	25 m

flow and transport in sheet and rill flow. Forestry activities, such as cultivation, drainage, clearfelling, reforestation, forest road building and maintenance, can radically alter the soil characteristics and increase soil erosion, resulting in negative impacts on receiving waters.

To avoid cultivation and drainage erosion, BMPs for ground preparation, buffer zones, silt traps and drainage must be well planned, correctly designed, properly executed and managed, e.g. mounding, moling, ripping and subsoiling cause less soil disturbance than ploughing and can lead to more stable forests (Mulqueen *et al.*, 1999).

BMPs to minimise the magnitude of erosion and nutrient enrichment during harvesting operations include:

- strategic location of landings and turntables
- short and suitable extraction routes
- suitable extraction equipment
- good weather conditions, and
- the proper use of effective brash mats (Hutchings *et al.*, 2002), sediment traps and buffer zones.

Heavy equipment or skidding activities should not be allowed in or across drainage ditches.

Buffer zones, with minimum widths of 10–25 m, are among the most important BMPs used for controlling sediment delivery to receiving waterbodies.

2.4 Impacts of Forest Activities on Run-Off

Forest clearfelling and reforestation activities can release nutrients and SS to receiving waters (Cummins and Farrell, 2003a, b). These releases can trigger eutrophication. Over a 5-year period, Cummins and Farrell (2003a) measured alkalinity, pH, nutrients and dissolved organic carbon (DOC) releases in a number of streams draining a series of forested catchments in western Ireland. Following lodgepole pine and Sitka spruce harvesting operations, the P concentrations – measured as molybdate reactive phosphorus (MRP) – in streams draining three catchments, with areas of 115, 1 and 1 ha, increased from respective pre-felling (baseline) concentrations of 9, 13 and 93 µg/l to values of 265, 4,164 and 3,530 µg/l, respectively. Similar trends were noted by Renou and Farrell (2002) in a stream draining a 100-ha catchment. The time of the year at which felling was conducted appeared to affect the P release rates, as the stream P concentration gradually reduced over a 20-week period following felling in mid–late summer, whereas when felling was conducted in November the stream P concentration continued to increase until the following summer. Harvesting may also lead to a reduction in soil carbon (C), due to reduced photosynthesis, removal of above-ground biomass and increased respiration (Carter *et al.*, 2002). It may also trigger nitrogen (N) mineralisation, which could lead to nitrate (NO_3) loss, reducing productivity and contaminating surface and ground waters (Carter *et al.*, 2002). In two catchments in North America – St. Helena (SH) and Tyler (T) – Carter *et al.* (2002) examined the effects on the C and N concentrations in the top layer of well-drained soils and on their net N mineralisation. In the first year following harvesting, soil C reduced by between 7.6 (T) and 8.2 (SH) Mg/ha and soil N reduced by between 361 (SH) and 381 (T) kg/ha. In the second year after harvesting, the soil C and N increased to their pre-harvest levels in both catchments. The net N mineralisation was also higher in the first growing season after harvesting. Although harvesting caused some changes in the soil processes, the long-term effects were not pronounced. In a 3-year study of 51 clearfelled sites and 16 forested sites in Wales, each with a catchment area of 2–5 ha, Neal *et al*. (1998) found that there was a high degree of diversity in run-off from all sites. The catchments comprised the following soil types: peat soils, brown earths, podzols and gleys. This study strongly indicated that there were local effects on some chemical components of run-off for the first 4 years after felling in a small number of sites where NO_3 production and aluminium leaching were high.

Forest fertilisation activities also increase the nutrient concentrations in the run-off. In forest fertilisation, N is mainly applied as urea. Urea hydrolysis is rapid and can lead to rapid formation of ammonium (NH_4) in streams. Ammonium oxidation may lead to the leaching of NO_3 from the forest floor. Cummins and Farrell (2003a) found that when a single fertiliser dose of 70 kg P/ha was applied to four forested catchments following clearfelling, an initial P concentration increase resulted, followed by a gradual decline in P concentration. Nitrate, NH_4, and potassium (K) concentrations were also elevated by the fertilisation operations. Similar trends have been noted by other researchers (Reynolds and Edwards, 1995). Since the potential for blanket peat to adsorb P is low (Renou and Farrell, 2002) the Forest Service recommends a standard P application rate of 42 kg P/ha on peat soils at establishment (Cummins and Farrell, 2003a). Renou and Farrell (2002) examined a recently planted cutaway peatland forest that had been fertilised with rock phosphate applied at a rate of 25 kg P/ha. Immediately following fertilisation, the surface run-off water P concentration in drains increased from a pre-fertilisation concentration of less than 50 µg MRP/l to a maximum value of approximately 1,200 µg MRP/l, before declining to a median value of approximately 500 µg MRP/l in the second year.

Buffer zones are among the most important BMPs that have the potential to reduce the impact of the forest activities on the receiving waterbodies. In a review of a number of studies, Binkley *et al*. (1999) analysed the use of unfertilised buffer strips and found that they were effective in reducing the concentrations of urea and NH_4, but had little effect on NO_3. In the UK, Swift and Norton (1998) estimated that 60- to 70-m wide riparian buffers reduced 50% of the SS load when the vegetation was dense, but their effectiveness reduced on slopes in excess of 4°, due to the vegetation becoming flattened by surface run-off.

2.5 Conclusions

One of the main objectives of sustainable forest management is to ensure that forestry activities are conducted without causing significant diffuse pollution in streams. Forestry activities have the potential to increase soil and nutrient losses and alter stream channel conditions. Impacts from these activities are mostly site specific. However, in general, if BMPs are properly designed and implemented, the adverse effects of forestry activities on receiving waters can be minimised. Key measures include:

- careful planning and supervision of all operations
- good on-site discipline and attention to detail
- the use of machinery appropriate to site conditions
- varying the timing and scale of operations according to site sensitivity and weather conditions, and
- the use of a wide range of protective measures, particularly the use of riparian buffer areas.

Given the proposed expansion of plantation forestry throughout Ireland over the next 30 years and the increasing amount of harvestable crops, it is important that current guidelines and methods of BMPs are kept under review and enforced. The Irish Forest Service guidelines and the *Code of Best Forest Practice* provide good templates to achieve the overall objective (Forest Service, 2007).

Measures include:

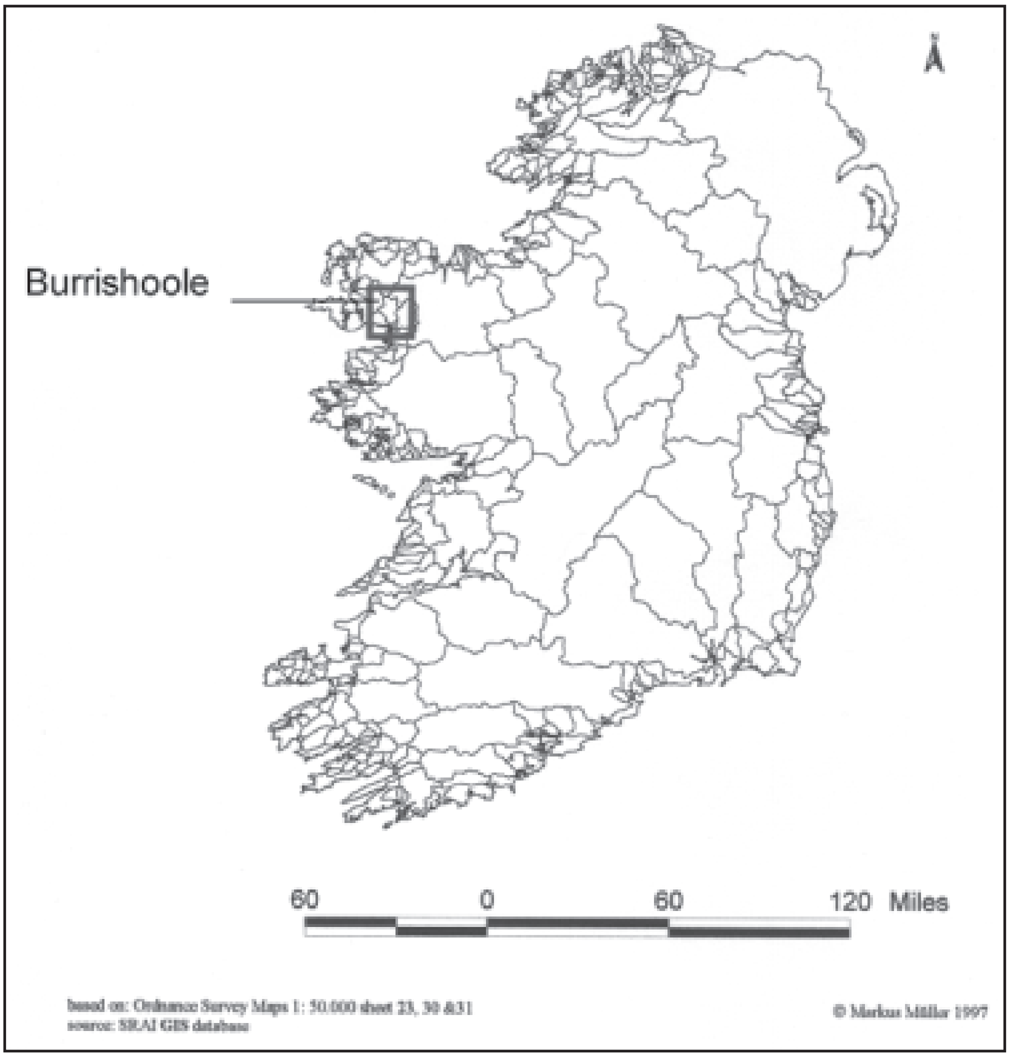
- no harvesting, fertilisation or ground work in the wet season
- no fertilisation within the buffer zone
- careful control of P application methods and rates
- careful treatment of the harvesting residues
- growth of the catchment vegetation, and
- proper sizing of the clearfelling area.

However, compared with soil loss control, more development work is required for nutrient release control, particularly soluble nutrients. For example, the use of buffer zones is one of the more important BMPs in minimising SS, but more research is required to study the effectiveness of buffer zones in reducing soluble P and N. Proper sizing of the clearfelling area relative to the upstream catchment area can reduce the negative effects of particulate and nutrient releases on receiving waters.

3 Burrishoole Catchment Description

3.1 Study Site Description

This study site was located in a 17.7-ha catchment in Burrishoole (9°55' W, 35°55' N), Co. Mayo, Ireland, that is drained by a small first-order stream (Figs 3.1–3.3). The stream is equipped with two monitoring stations, one upstream and the other downstream of the study area. The upstream station monitors flows from forest Coupe A with an area of 7.2 ha and the downstream station monitors flows from forest Coupes A, B and C with a total combined area of 13.2 ha pre-clearfelling, and Coupes A, B, C and D with an area of 17.7 ha post-clearfelling; the addition of Coupe D was due to the blockage of drains during harvesting. Coupe D is part of the whole harvested catchment and has similar soils. Considerable attention was paid to walking the boundary to identify any cases where the felling and harvesting activities had damaged the drains and altered the drainage network transporting water to the downstream gauge. The depths of the furrows and the collector drains were always less than the depth of peat. The invert of the study stream was deeper than the peat layer and rocks were exposed at its base.



based on: Ordnance Survey Maps 1: 50.000 sheet 23, 30 &31
source: SRAI GIS database

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Figure 3.1. Location of the study catchment.

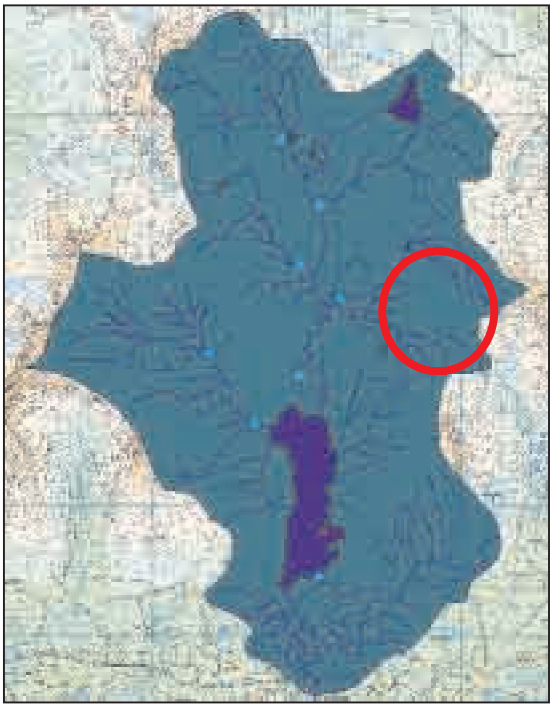

Figure 3.2. Location of the study stream.

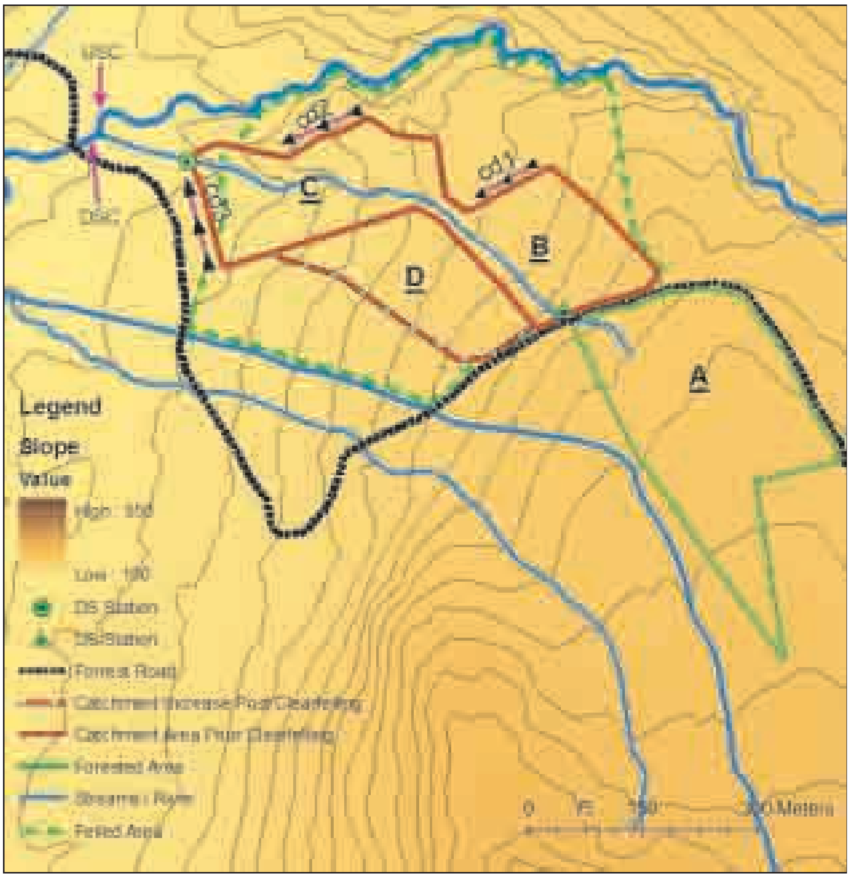

Figure 3.3. Contour plan of the catchment.

Table 3.1 details the morphometric data of the study catchment. Coupe A, which was not harvested, was used as a control site in this study as it has the same species (lodgepole pine), similar soil and hydrologic characteristics, and is of similar size to the combined harvested coupes of B, C and D. In the study catchment, the furrows and windrows – formed using the harvest residues – are parallel to the study stream, which flows approximately at right angles to the contours. The surface water flows along the furrows, is collected in collector drains (cd1, cd2 and cd3 in Fig. 3.3) before eventually joining the study stream.

3.2 Sampling and Measurement

A H-flume (installed in March 2005), a water level recorder, a multichannel data logger and an automatic water sampler were installed at both the upstream and downstream monitoring stations, along with a tipping bucket rain gauge at the downstream station. The water levels in the H-flumes at both stations were recorded every 5 min, facilitating the quantification of water flowing into and leaving the study area. During flood events, water samples were taken hourly at the upstream and downstream stations. In base-flow conditions, water samples were taken hourly over a 24-h period, once per week. Samples were transported to the Marine Institute Laboratory in Newport, Co. Mayo, and to the Environmental Engineering Laboratory in the Civil Engineering Department, NUI Galway, for physico–chemical parameter analysis.

3.3 Details of the Forestry Practices on Site

The lodgepole pine trees were planted on the study site between January and April 1971. The land was double mouldboard (DMB) ploughed creating furrows and ribbons at 2 m spacing. A collector drainage system was installed on the site using a single mouldboard (SMB) plough. The trees were planted at 1.5-m intervals along the ribbons, giving an area of 3 m^2 per tree. There were about 20,000 trees planted on the 6-ha study catchment but only approximately 10,000 survived according to a survey conducted in 1994. It is estimated that 28.5 g (1 oz.) ground mineral phosphate (GMP) per tree was spot-applied manually immediately after planting, giving a fertilisation rate of 12 kg P/ha.

The access road was upgraded in 2003. Harvesting operations commenced on 25 July 2005 for a period of 8 weeks. Clearfelling and harvesting were conducted using a shortwood system, whereby tree branches and tops were removed and left on the soil surface for windrowing. Two types of harvesting machines were used on site during the clearfelling period – a Valmet 941 harvester and a Valmet 840 forwarder (details are listed in Table 3.2). The Valmet 941 harvester (Fig. 3.4), having a 10 m reach, was capable of felling 12–13 rows of trees in one pass, minimising soil degradation. The brash from the felled trees was placed ahead of the Valmet 941 machine to act as a protective mat (Fig. 3.5), which extended downhill from the upper road where harvesting commenced. The de-limbed trees were laid adjacent to the brash mat

Table 3.1. Morphometric data of lodgepole pine study catchment.

	Forested catchment (Nephin Beg East – Srahrevagh River)
Area	13.2 ha pre-felling (Coupe A: 7.2 ha; Coupes B and C: 6 ha) 17.7 ha post-felling (Coupe A: 7.2 ha; Coupes B, C and D: 10.5 ha)
Highest/Lowest point	240 m/150 m OD (Malin Head)
Slope range	0–16°
Geology (bedrock)	Quartzite, schist, volcanics
Quaternary sediments	Blanket peat (95%), sand and gravels (5%) (metamorphic)
Drainage	First-order stream draining felling coupes
Morphology	Well-defined catchment within coupe, concave, bowl shape
Precipitation and hydrology	High rainfall area (over 2,000 mm/year), Nephin Beg East (Srahrevagh River) catchment 'open' to westerly fronts. Spatiest sub-catchment within Burrishoole catchment.

Table 3.2. Details of the machines used in harvesting and windrowing.

Name of the machine	Weight	Type of wheels	Ground pressure
Valmet 941 Harvester with Valmet 370.2 harvesting head	23,500 kg	6-wheel drive, 750-mm wide front wheels on flotation tracks and 1,000-mm wide rear wheels	Approx. 42 kPa
Valmet 840 forwarder	15,300 kg (unloaded)	1.2-m flotation tracks	Approx. 26 kPa
Fiat-Hitachi FH130-3	13,300 kg	800-mm triple grouser tracks	Approx. 26 kPa

Figure 3.4. The Valmet 941 harvester.

Figure 3.5. Brash mat formation.

Figure 3.6. Positioning of logs.

Figure 3.7. The Valmet 840 forwarder used in the harvesting.

(Fig. 3.6) for collection by the Valmet 840 forwarder (Fig. 3.7), which also travelled over the mats. The Valmet 840 forwarder delivered the shortwood to timber haulage collection points beside the road. Trees inaccessible to the harvester were felled and de-limbed using a chainsaw and were also delivered to collection points alongside the access road. The wood at these collection points was transported off-site by timber truck. Figure 3.8 illustrates the loading operation.

Windrowing of branches and tops, using a Fiat-Hitachi FH130-3 excavator (Fig. 3.9, with details in Table 3.2), commenced in November 2005 for a duration of 3 weeks. The windrows were fashioned at right angles to the contours (Fig. 3.10). There was no further drainage installed on the site. Due to drain blockage caused during the harvesting operation, the catchment area between the upstream and downstream stations was increased after clearfelling and harvesting from 6.0 ha to 10.5 ha. Reforestation, using lodgepole pine, commenced in December 2005, at a density of 2,800 trees per ha, and was completed by January 2006. A buffer zone of 15–20 m was left along either side of the study stream and was planted with birch, rowan, alder and willow. No fertiliser was applied in the replanting operation. Weevil control, using alphacypermethrin at a rate of 1 l/ha, was carried out in both March 2006 and August 2006.

Figure 3.8. Loading in operation.

Figure 3.9. The Fiat-Hitachi FH130-3 excavator used. in collecting forest residuals into windrows.

Figure 3.10 Formation of windrows across the contours.

4 Hydrological Analyses of the Burrishoole Study Site

4.1 Introduction

The Burrishoole study catchment (9°55’ W, 53°55’ N) in Co. Mayo is drained by a first-order tributary of the Srahrevagh River, with waters that eventually flow into Lough Feeagh. It receives an average precipitation of over 2,000 mm per year and is covered by a layer of blanket peat up to 2 m thick that overlies bedrock of mainly quartzite and schists. Continuous measurements of streamflow upstream and downstream of the selected felling coupe commenced in spring 2004. In 2005, the trees were about 20 m in height and the lower part of the catchment was felled and harvested during August and September of that year. The upper catchment, comprising forest and peatland, was not felled and acted as a baseline ‘control’.

The main aim of the hydrological analyses was to try to establish if the forest clearfelling and harvesting in the study area had an impact on flood risk downstream.

4.2 Hydrological Instrumentation

Streamflow was measured at two stations – upstream and downstream of the felled area. Continuous water level records began in April 2004 at stable channel sections, and a programme of check gaugings at a range of water levels using mainly a current meter, augmented by dilution gauging at higher flows, was carried out. These gaugings confirmed a strong and stable relationship between the water level (stage) and stream discharge, and enabled a tight stage-discharge rating to be derived to generate a series of flows. In March 2005, two H-flume flow gauges, each equipped with an Ott bubble gauge, were installed at the rated sections to further improve the data collection. Each flume had a capacity of approximately 168 l/s, which was adequate to contain all except the highest peak flows. Rainfall was measured by a tipping bucket gauge (0.2 mm/tip) and storage gauge situated in an open site close to the downstream flow gauge.

The research design, with both experimental and control catchments, meant that the hydrology and water quality changes due to harvesting could be studied by looking for changes between the pre- and post-felling flows. The tree harvesting enabled easy access across the experimental area for the first time, and the post-clearfelling flow-contributing area was defined accurately. Any differences due to the forest drains between the flow-contributing area and the topographic area, were recorded. Considerable attention was paid to walking the boundary to identify any cases where the felling and harvesting activities had damaged the drains and altered the drainage network flowing to the downstream gauge.

4.3 Hydrological Data

Two features immediately stand out in the flow data. Firstly, the streamflow is very spatey or flashy, with rainfall causing a rapid rise and subsequent steep decline to very low base flows (Fig. 4.1). The response of both gauges to rainfall was very direct, with flows rising within an hour or two of significant rainfall, and peak flows often almost coincident with peak rainfall. Secondly, there is generally a close linear relationship between the behaviour of the two flow gauges (Fig. 4.2), with correlation coefficients between monthly blocks of paired hourly flows of 90% or higher. Flows rose and fell in unison, both gauges showing a peaky response with rapid rises to sharply defined peaks, and falling back quickly to low base-flow rates.

The rapid responses and low base-flow levels indicate that the catchments have very limited storage capacity, which is consistent with the site’s soil and geology. This lack of storage is also manifested in the close dependence of flows on the prevailing weather conditions. For example, the period late March–July 2005 had dry weather (~600 mm) and there was only one occasion when the downstream flow was over 100 l/s, whilst in comparison the 5 months, mid-October 2005–mid-March 2006, had ~1,000 mm of rainfall and the flow rate of 100 l/s was exceeded on ten occasions. Such natural variability in flows needs to be taken into account in any analysis of harvesting impacts.

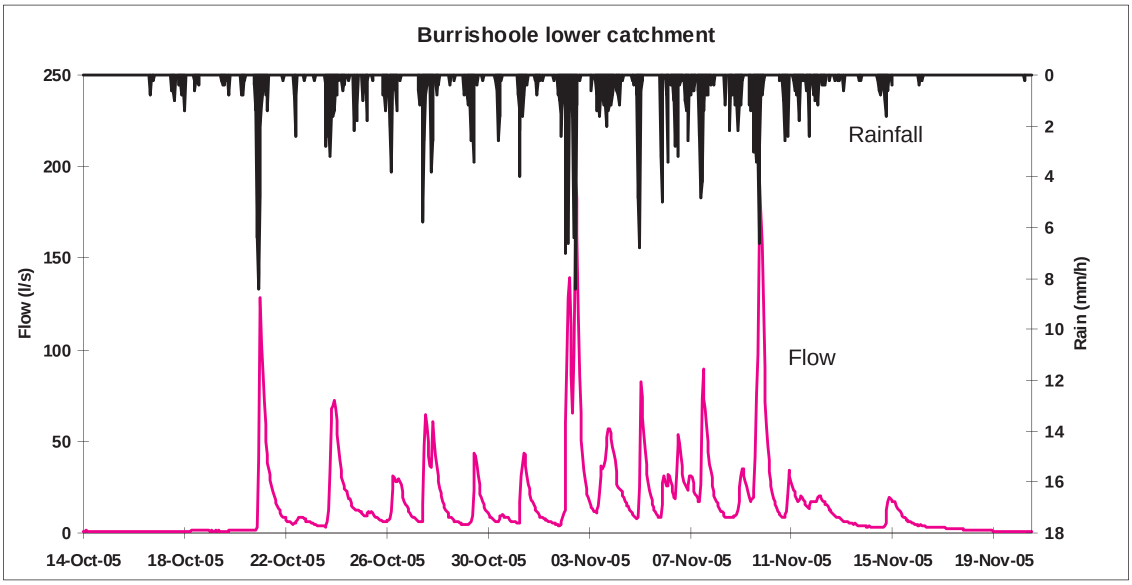

Figure 4.1. The catchments have a very rapid and direct response to rainfall.

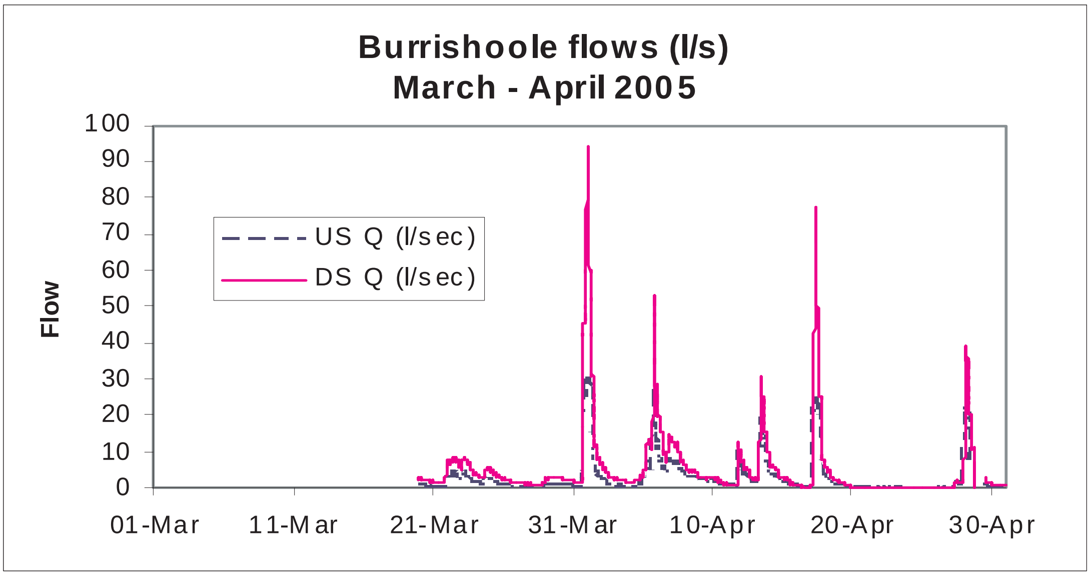

Figure 4.2. The close relationship between the hydrological responses of the upstream (US) and downstream (DS) catchments.

4.4 Storm Response

A simple rainfall run-off model, IHACRES, was fitted to the data to derive the characteristic 1-h storm response unit hydrograph for the downstream catchment hydrographs for separate periods before and after felling. The IHACRES model was used since this is a well-tested package that can derive unit hydrographs from continuous rainfall and flow data. The resulting 1-h unit hydrographs are shown in Fig. 4.3 for the rated section flows, together with the H-flume data before and after felling. Given the inherent uncertainties of the rating curve extrapolation for high flows, it is noteworthy how well the two pre-felling hydrographs agree. This agreement gives credence to the stage-discharge calibration, which is important, since most of the pre-felling period used the rated section flows.

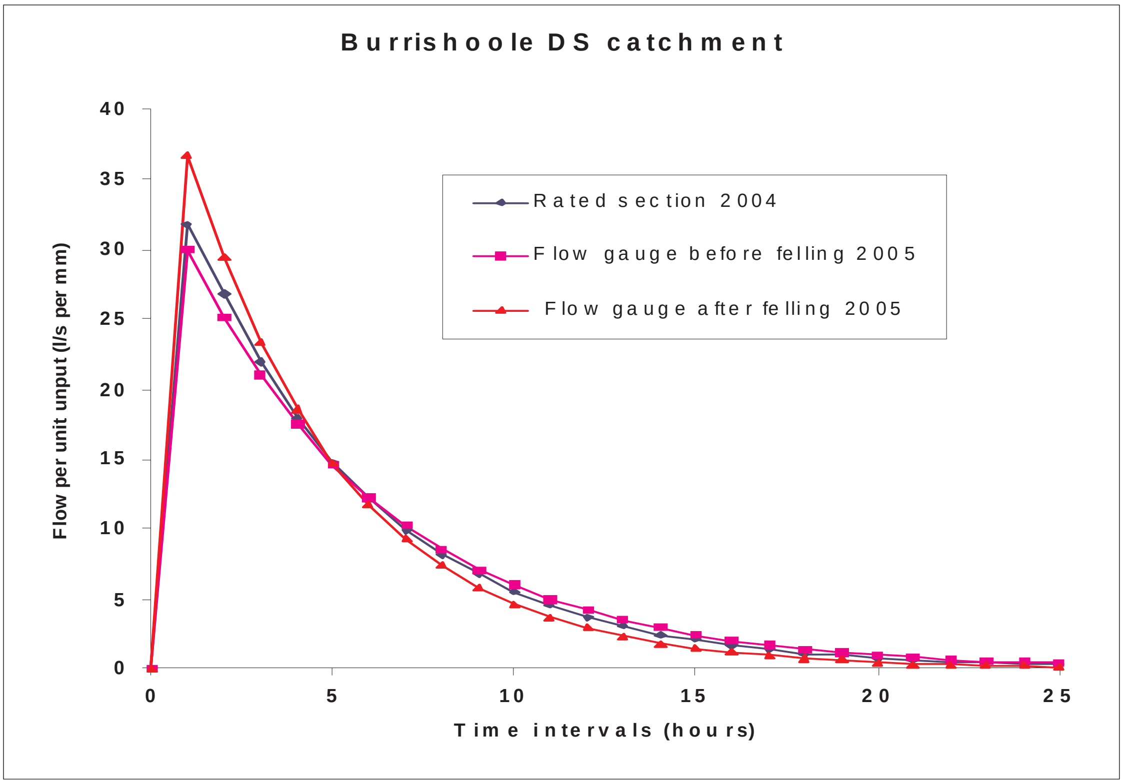

Figure 4.3. Storm unit hydrographs (1-h) for the downstream (DS) gauge for the periods before felling (rated section and subsequent flow gauge) and after felling.

The post-harvesting 1-h unit hydrograph peak was about 10–15% higher than both of the pre-felling unit hydrographs, but it must be remembered that this represents a theoretical maximum rather than a typical increase. The unit hydrographs, which represent the flow in response to a single hour's rainfall, are very narrow with the bulk of their flow occurring in the first 5 h. In any storm lasting several hours the flow response to each successive hour's rain will be lagged and added to produce a total hydrograph that has a much wider peak and is of longer overall duration.

The result of this smoothing and attenuation is to reduce the magnitude of the difference between pre- and post-felling hydrographs. The difference would be reduced by half for 5 h of rainfall and by three-quarters for 11 h of rainfall. Such storm durations are typical of this area, leading to the conclusion that there would only be a slight increase in flood flows under normal circumstances, perhaps 5%, which may be similar to or better than the accuracy at which high flows are measured in such steep flashy catchments. It therefore appears from this preliminary analysis that there is likely to be no major difference in flood regime for this particular area as a result of felling.

4.5 Conclusions

From the present analyses the forest clearfelling and harvesting had a very limited impact on flood risk downstream. This finding may at first appear surprising given the widely held belief that forest cover will prevent floods downstream. There is an extensive international literature reporting increases in peak run-off associated with clearfelling (e.g. Anderson *et al.*, 1976; Cheng, 1989; Jones and Grant, 1996). However, recent research suggests that this is not necessarily the case. Recent reviews of this literature (Beschta *et al.*, 2000; DeWalle, 2003) have concluded that the studies where significantly increased peak flows had been reported generally only examined small events (the impact on large events was much smaller) or else the sites had been subject to severe soil disturbance by the logging or road construction. Attempts to find a link between forests and large-scale or severe flooding have consistently drawn a blank (Kaimowitz, 2004).

It may be questioned to what extent these mainly North American studies may be relevant to Irish conditions, given the differences in climate, soils, tree species and felling methods. Fortunately, a similar study of felling has recently been reported from Wales where the site was physically similar to Burrishoole, with a high annual rainfall (>2,000 mm) and peat soils with open drainage. The impacts on streamflow were closely monitored in nested catchments from 1 to 10 km^2 in size. Commercial felling followed the GB Forestry Commission's harvesting guidelines (Forestry Commission Great Britain, 2003). It was found that there was a significant increase in base flows but a change in peak flows (Robinson and Dupeyrat, 2005) was not detected. The similar peak flow result at Burrishoole may be due to the care taken by the forest workers to comply with the Forest Service guidelines (Forest Service, 2000a,b). Taken together, the results of the Welsh and Burrishoole studies and that of the more recent published literature indicate that properly conducted felling can have a very limited impact on flood risk downstream.

5 Quantification of Sediment Entering and Exiting the Burrishoole Study Catchment

5.1 Introduction

The SS concentrations and flows entering and leaving the blanket peat forest study catchment in Burrishoole, Co. Mayo, were monitored before, during, and after clearfelling and harvesting at the two monitoring stations on the site's drainage stream – one just upstream and the other just downstream of the harvested study area. The clearfelling operations commenced on 25 July 2005 and lasted 8 weeks.

The main aim of this part of the study was to quantify the amount of SS arising from harvesting and reforesting operations on a representative Irish peat catchment, where current forestry practices are employed, and to evaluate and to make recommendations on – where appropriate – current BMPs in controlling sediment losses. The evaluation of the SS data is presented in this chapter and the recommendations are presented in Chapter 9.

5.2 Suspended Sediment Measurement

Suspended sediment concentrations of the water samples were measured in accordance with the Standard Methods (APHA, 1995) using Whatman GF/C (pore size 1.2 µm) filter papers. Monthly SS loads entering and leaving the harvested catchment in the study stream were calculated using the product of discharge-weighted mean concentration and the mean flows (Fergusson, 1987).

5.3 Results

5.3.1 Suspended sediment concentrations

During base-flow conditions, SS concentrations at the downstream station were generally low before, during, and after clearfelling and harvesting and ranged from 0 to 5 mg/l. Figure 5.1 shows peak SS concentrations on the sampling days at the upstream and downstream stations during the study period. Before and during the clearfelling and harvesting, the peak SS concentrations at the downstream station were similar to the peak SS concentrations at the upstream station

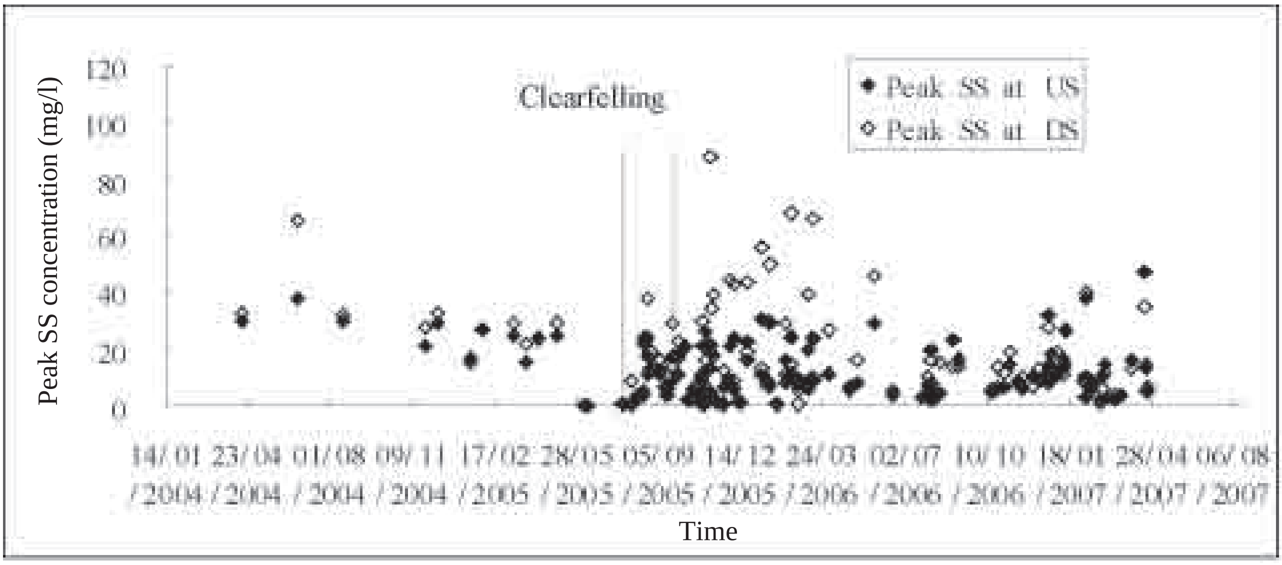

Figure 5.1. Daily peak SS concentrations at the upstream (US) and downstream (DS) stations during the study period.

(Fig. 5.1). After the clearfelling and harvesting period, from November 2005 to April 2006, the peak SS concentrations were less than about 30 mg/l at the upstream station but up to 97.5 mg/l at the downstream station (Fig. 5.1). The peak SS concentrations at the downstream station were similar to those at the upstream station after May 2006. Before clearfelling and harvesting, the mean SS concentrations in flood events were always between 12.3 mg/l and 13.2 mg/l upstream and between 13.7 mg/l and 16.9 mg/l downstream. One month after the clearfelling and harvesting were completed, the mean SS concentrations in a flood event on 2 November 2005 were 11 mg/l and 42.2 mg/l, respectively, at the upstream and downstream stations.

Figure 5.2 shows the SS concentrations at the upstream and downstream stations and flow rates at the downstream station in the flood event at the start of November 2005, just over 1 month after the clearfelling and harvesting operations were completed. At the upstream station, SS concentrations increased from 0 mg/l to 25.8 mg/l at the beginning of the flood event and then dropped back to 0 mg/l. At the downstream station, SS concentrations increased from 0.3 mg/l to a peak of 97.5 mg/l towards the beginning of the flood event as the flow rate increased from about 4.5 l/s to 12.5 l/s. After the flood event, the SS concentrations at the downstream station were at a relatively steady value of 5 mg/l. Similar data for 15 storm events were collected. Figure 5.3 shows the SS concentrations at the upstream and downstream stations in a flood event before clearfelling and harvesting. No significant SS concentration difference was found between the upstream and downstream stations. The SS concentrations were both 0.9 mg/l at upstream and downstream stations at the start of the flood event and increased to the peak values of about 25.1 mg/l and 28.7 mg/l, respectively.

5.3.2 Suspended sediment loads

Monthly SS loads at the upstream and downstream stations were calculated from the SS mean concentrations and the flows. The net SS loads released from the harvested area (Coupes B, C and D, Fig. 3.3) were computed by subtracting the SS loads at the upstream station from those at the downstream station. Figure 5.4 shows the net monthly SS loads at the upstream and downstream stations; the monthly SS loads at the upstream station ranged from 0.5 kg/ha to 30.3 kg/ha and at the downstream station from 1.1 kg/ha to 53 kg/ha.

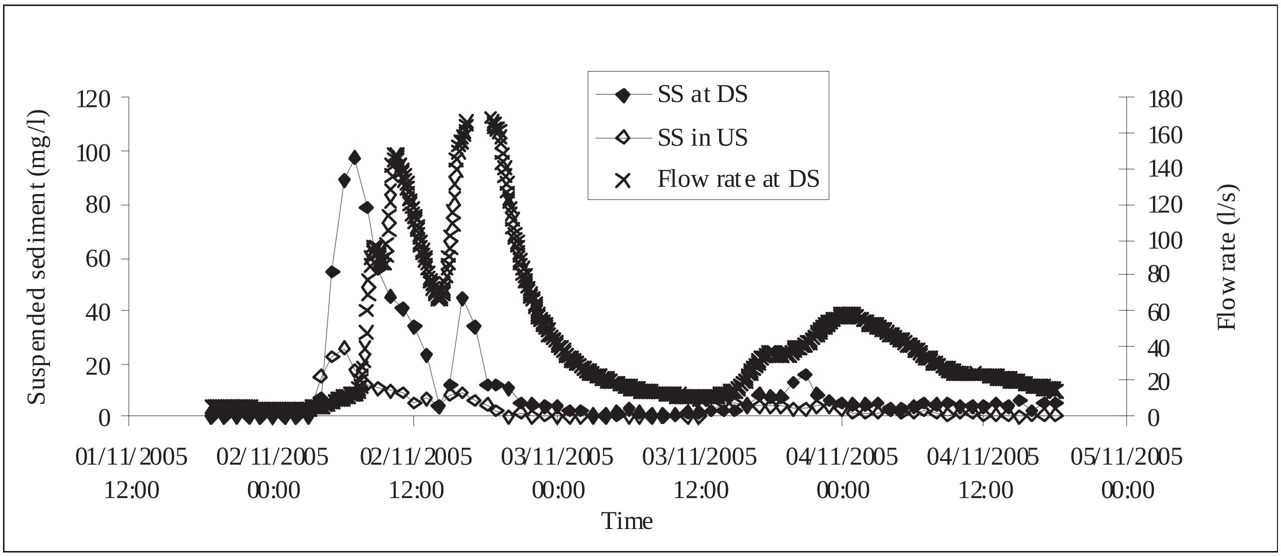

Figure 5.2. Suspended sediment (SS) concentrations at the upstream (US) and downstream (DS) stations and flow rates at the DS station in a flood event 1 month after the clearfelling and harvesting operations were completed (the truncated top of the flow-rate curve is due to the overflow in the flume).

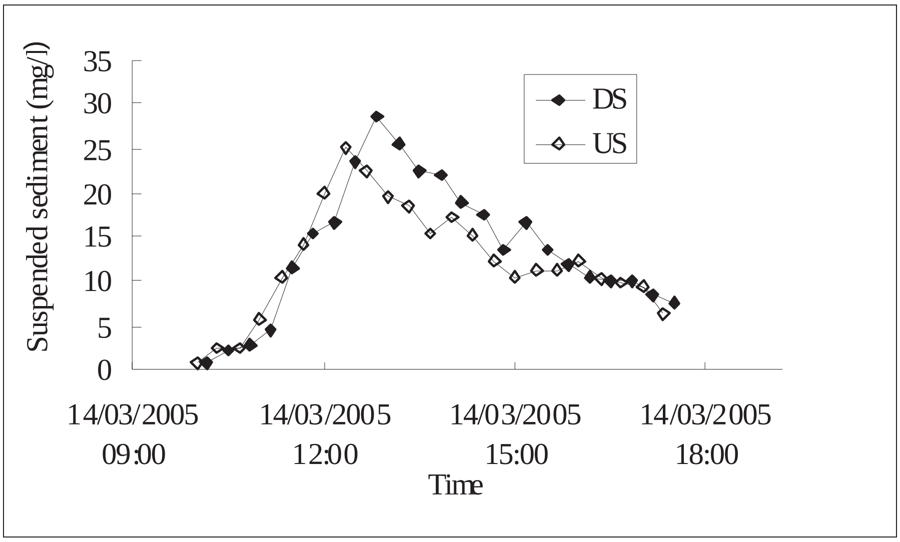

Figure 5.3. Suspended sediment (SS) concentrations at the upstream (US) and downstream (DS) stations in a flood event before clearfelling.

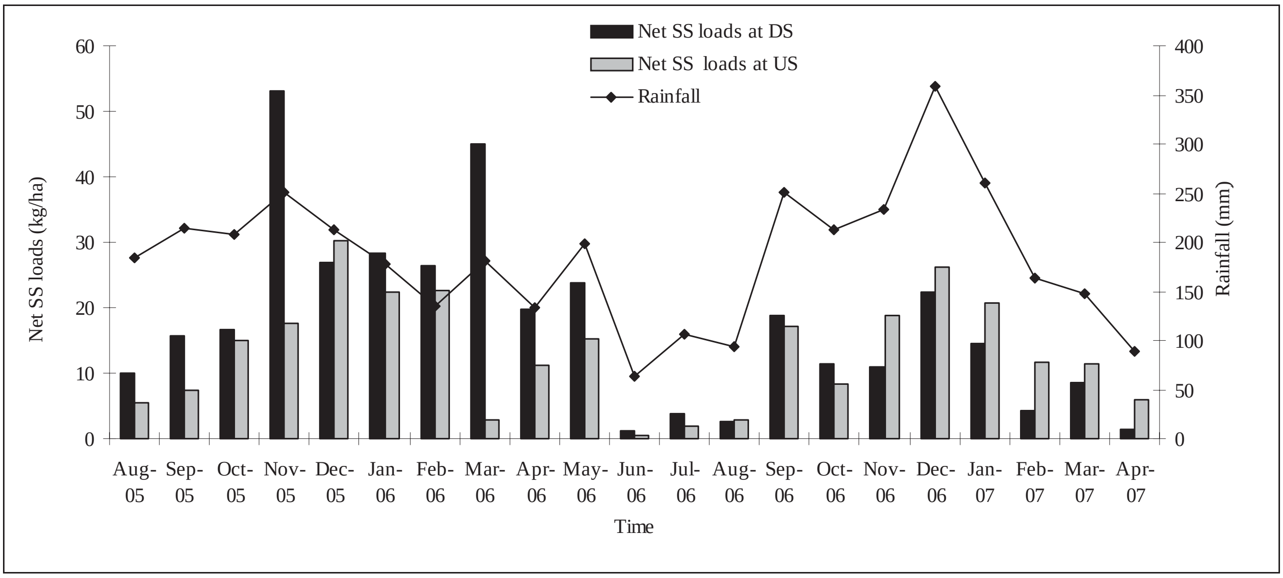

Figure 5.4. Net monthly suspended sediment (SS) loads upstream (US) and downstream (DS).

The highest monthly SS loads of 53 kg/ha at the downstream station occurred in November 2005. During the period of clearfelling and harvesting (August and September 2005), the 2-month total net SS loads of 13 kg/ha and 25.8 kg/ha were calculated for the upstream and downstream stations, respectively. From October 2005 to September 2006, the annual SS loads at the upstream and downstream stations were calculated at 1,078.6 kg and 3,940.7 kg, respectively, giving a net SS release rate of 272.6 kg SS/ha per year from the 10.5-ha harvested site (Coupes B, C and D, Figure 5.4). The SS yield from the undisturbed 7.2-ha catchment (Coupe A) during the same period was calculated at about 149.8 kg/ha per year.

From 19:00 h on 1 November 2005 to 18:00 h on 4 November 2005, total SS loads of 27.8 kg and more than 219.1 kg were calculated for the upstream and downstream stations (Fig. 5.5), respectively, giving

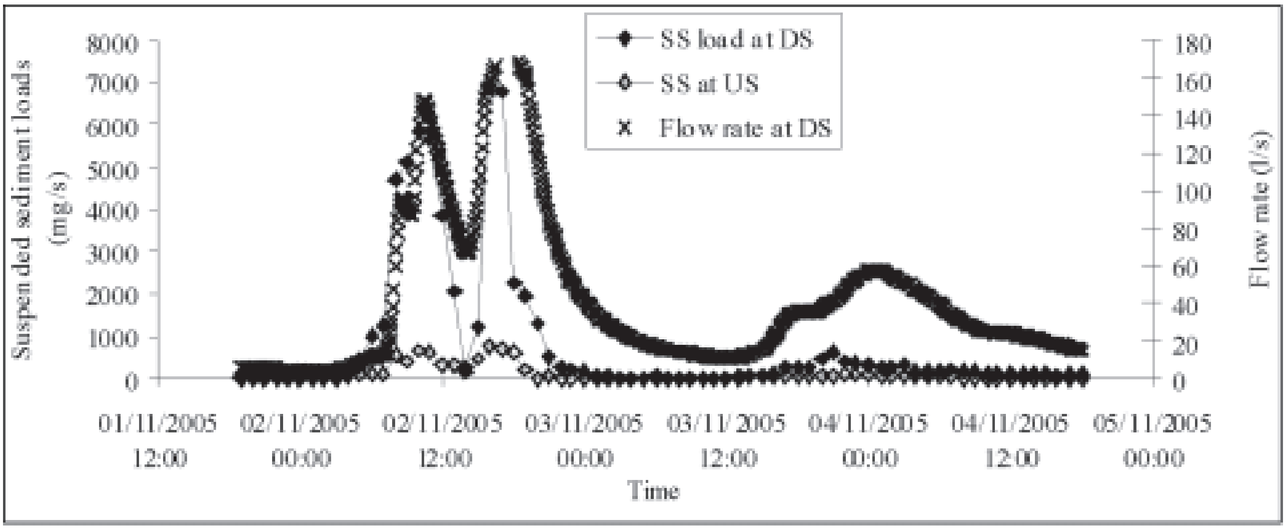

Figure 5.5. Suspended sediment (SS) loads upstream (US) and downstream (DS) in a flood event (the truncated top of the flow-rate curve is due to the overflow in the flume).

average daily mass rates of 9.3 kg/day and 73 kg/day at the respective stations. The net SS released load rate from the harvested area (Coupes B, C and D) was more than 6.1 kg/ha per day during this flood event period.

5.4 Discussion

With the tree species, similar soil, hydrological characteristics and size in the undisturbed upstream catchment (Coupe A), no significant SS concentrations difference was found between upstream and downstream station (Figs 5.1 and 5.3) before clearfelling and harvesting. The upstream station was used to provide control data in this study to investigate the effect of clearfelling and harvesting on SS release in the harvested area (Coupes B, C and D). The SS concentrations at the upstream station were similar to the pre-clearfelling and harvesting SS values calculated in other catchment studies in the Burrishoole area (Table 5.1) – Altahoney, Glendahurk and Sheskin catchments. The SS yield from the undisturbed upstream Coupe A was 149.8 kg/ha per year, which is comparable to the value of 135 kg/ha per year presented by Swank *et al*. (2001) and similar to the mean values for small forested catchments in the eastern USA summarised by Patric *et al*. (1984).

The SS loads released from the harvested area (Coupes B, C and D) were 25.8 kg/ha during the clearfelling and harvesting period, and 272.6 kg/ha per year during the first year after clearfelling and harvesting (2,012 mm rainfall: October 2005–September 2006); these loads were higher than the calculated respective loads of 13 kg/ha and 149.8 kg/ha per year released from the unharvested catchment (Coupe A). Martin *et al*. (2000) found that sediment yield increased from 64 kg/ha per year during

Table 5.1. Suspended sediment (SS) results from other catchment studies in the Burrishoole area.*

Catchment name	Catchment size (m^2)	Before clearfelling and harvesting		After clearfelling and harvesting	
		SS in base flow (mg/l)	SS in flood event (mg/l)	SS in base flow (mg/l)	SS in flood event (mg/l)
Altahoney	1,764,730	1.5–2.5	1–32	1–6	1.5–125.5
Glendahurk	807,545	1–3	1.5–43	1.5–4	1.5–52
Sheskin	1,053,559	4–8	2–32	2.5–3.5	–

*Marine Institute data, Newport, Co. Mayo, Ireland.

the clearfelling period to 112 kg/ha per year in the first year after whole-tree clearfelling. Grant and Wolff (1991) observed that the SS loads increased from 110 kg SS/ha per year pre-clearfelling to 1,700 kg SS/ha per year after clearfelling in a sandy soil catchment in the Western Cascade Range in Oregon, USA. Results showing increases after clearfelling were also reported in other studies (Roberts and Church, 1986; Cornish and Binns, 1988; Olive and Rieger, 1988). In flood events, significant increases in SS concentrations were observed at the downstream station (Figs 5.2 and 5.3) during the first year after the clearfelling and harvesting operations compared with the SS concentrations at the upstream station. The highest SS concentration of 97.5 mg/l at the downstream station after clearfelling and harvesting was less than the peak value of 125.5 mg/l measured in the Altahoney catchment but higher than the measured peak value of 52 mg/l from the Glendahurk catchment (Table 5.1).

The differences in SS concentrations and loads between the upstream and downstream stations decreased after May 2006 (Figs 5.1 and 5.4), indicating that the impact of clearfelling and harvesting on the SS release rates from the catchment was reducing. This will be investigated further from June 2007 to May 2008.

Statistical analysis was carried out with a paired samples *t*-test at the 95% significance level (P = 0.05) using SPSS – a statistical tool (http://www.spss.com). Results indicated that there was no significant difference in daily peat SS concentrations between upstream and downstream before clearfelling and harvesting (July 2005) and later than 8 months after the clearfelling and harvesting operation – post-May 2006. There were however, significant differences between the peak SS concentrations at the upstream and downstream stations in the period from August 2005 to April 2006

5.5 Conclusions

In base-flow conditions, the SS concentrations at the upstream and downstream stations were always low before, during, and after clearfelling and harvesting. Before clearfelling and harvesting, the mean SS concentrations in flood events were between 12.3 mg/l and 13.2 mg/l upstream and between 13.7 mg/l and 16.9 mg/l downstream. One month after the clearfelling and harvesting was completed, the mean SS concentrations in a flood event on 2 November 2005 were 11 mg/l and 42.2 mg/l, respectively, at the upstream and downstream stations. From August 2005 to April 2006 there were significant differences between the peak upstream and downstream concentrations. From May 2006 to May 2007, the SS concentrations at the upstream and downstream stations were similar, indicating that the effect of the clearfelling and harvesting operations on the SS concentrations in the study stream had ceased.

High SS can have an adverse impact on the aquatic flora and fauna. It reduces the penetration of sunlight, affecting fish productivity, feeding and respiration. Where the sediment settles it can damage spawning areas by physically covering the gravel redds, trapping fry and reducing the oxygen supply to fish. In the study catchment, the clearfelling and harvesting operation did not trigger high SS releases because: (i) the dry season was chosen for the operation, (ii) brash mats were used to protect the soil from damage by the harvesting machines, and (iii) manual harvesting was conducted along the lower steep slopes of the study stream which the harvesting machines could not access.

The following conclusions can be drawn from the analysis of the data:

- Before clearfelling, there was little difference in the SS concentrations in the study stream water at the upstream and downstream stations.

- The SS concentrations from the upstream 7.2-ha intact forested catchment (Coupe A) entering the harvested study area at the upstream station remained low before, during and after clearfelling and harvesting. They ranged from 0 to 5 mg/l during base-flow conditions and from 5 to 30.6 mg/l during flood events.

- At the downstream station, the SS concentrations in base-flow conditions before, during and after clearfelling and harvesting were always low and ranged from 0 to 5 mg/l.

- During the clearfelling and harvesting period (August and September 2005), about 25.8 kg/ha SS were released from the harvested catchment (Coupes B, C and D), compared with the release from the undisturbed forest catchment (Coupe A) of 13 kg/ha of SS.

- Statistical analysis showed that from November 2005 to April 2006 (post-felling), there were significantly greater peak SS concentrations at the downstream station than at the upstream station.

- In the first year after clearfelling and harvesting (when there was 2,012 mm rainfall), the net SS release rate from the harvested catchment was 272.6 kg/ha per year, which was greater than the 172.0 kg/ha per year released from the undisturbed forest catchment.

- In flood events, the highest measured peak SS concentration at the downstream station was 97.5 mg/l, which occurred on 2 November 2005, 1 month after the clearfelling and harvesting operations were completed.

- From May 2006 to May 2007, the peak SS concentrations at the upstream and downstream stations were similar.

6 Quantification of Phosphorus Entering and Exiting the Burrishoole Study Catchment

6.1 Introduction

Phosphorus has been identified as the primary factor for algal growth in the freshwater eutrophication process (Carpenter *et al*., 1998; Boesch *et al*., 2001). Controlling accelerated eutrophication of fresh waters mainly requires decreasing P inputs to surface waters (Shigaki *et al*., 2006a).

With the reduction in point-source discharges of P to surface waters by the commissioning of new wastewater treatment facilities, more and more attention is being directed towards diffuse sources of P. According to the US Environmental Protection Agency (2004), agriculture is the primary source of non-point-source pollution degrading the quality of streams and lakes. In Ireland, it was reported that in the Shannon River, about 50% of the MRP export load came from agricultural diffuse sources (Kirk McClure Morton, 1999).

Forests and forest management practices have been identified as potentially important diffuse sources of water pollution in upland areas of the UK (Nisbet, 2001). Phosphorus concentrations in run-off after planting, fertilisation, clearfelling, harvesting and reforestation operations can affect the P concentration in the receiving waterbody (Paavilainen and Päivänen, 1995; Ahtiainen and Huttunen, 1999; Nisbet, 2001; Cummins and Farrell, 2003b). Ensign and Mallin (2001) found that compared with a control site, the post-clearcut Goshen Swamp displayed significantly higher total phosphorus (TP) concentrations over a 15-month period. Lebo and Herrmann (1994) found slight increases in TP concentrations after the harvesting of timber in North Carolina, and Blackburn and Wood (1990) found significantly increased P in storm flows after clearfelling in eastern Texas in the USA. In Ireland, Cummins and Farrell (2003b) found that during clearfelling activities, concentrations up to 4,164 µg/l total reactive phosphorus (TRP) were found in the discharge waters.

In this study, the P concentrations and loads entering and leaving the 10.5-ha blanket peat forest catchment in Burrishoole, Co. Mayo, were monitored for TP and TRP just before, during, and after clearfelling and harvesting, from July 2005 to May 2007. The main objective of this section of the study was to quantify the amount of P arising from harvesting and reforesting operations in a representative Irish blanket peat catchment.

6.2 Sampling and Measurement

Rainfall was sampled using a plastic container at the downstream station. Water samples were taken hourly during flood events at the upstream and downstream stations. Also, in base-flow conditions, on 1 day per week, water samples were taken hourly for 24 h. Grab samples were also taken above the confluence of the study stream and the main river (USC, Fig. 3.3) and below the confluence of the study stream and the main river (DSC, Fig. 3.3) about once every 2 weeks. The water samples were frozen at –20°C in accordance with standard methods (APHA, 1995) as soon as possible after collection and were transported to the Environmental Engineering Laboratory in the Civil Engineering Department at NUI Galway for P analysis. Total reactive phosphorus and TP after digestion with acid persulphate (APHA, 1995) were measured using a Konelab 20 Analyser (Konelab Ltd.).

Monthly TRP and TP loads entering and leaving the harvested catchment in the stream water were calculated using the product of the discharge-weighted mean concentrations and the mean flows (Fergusson, 1987). Monthly TRP and TP loads entering the catchment in rainfall were calculated using the mean concentration and the volume of the rainfall.

6.3 Results

6.3.1 Phosphorus concentrations

Figure 6.1 shows the daily average TP and TRP concentrations at the upstream and downstream

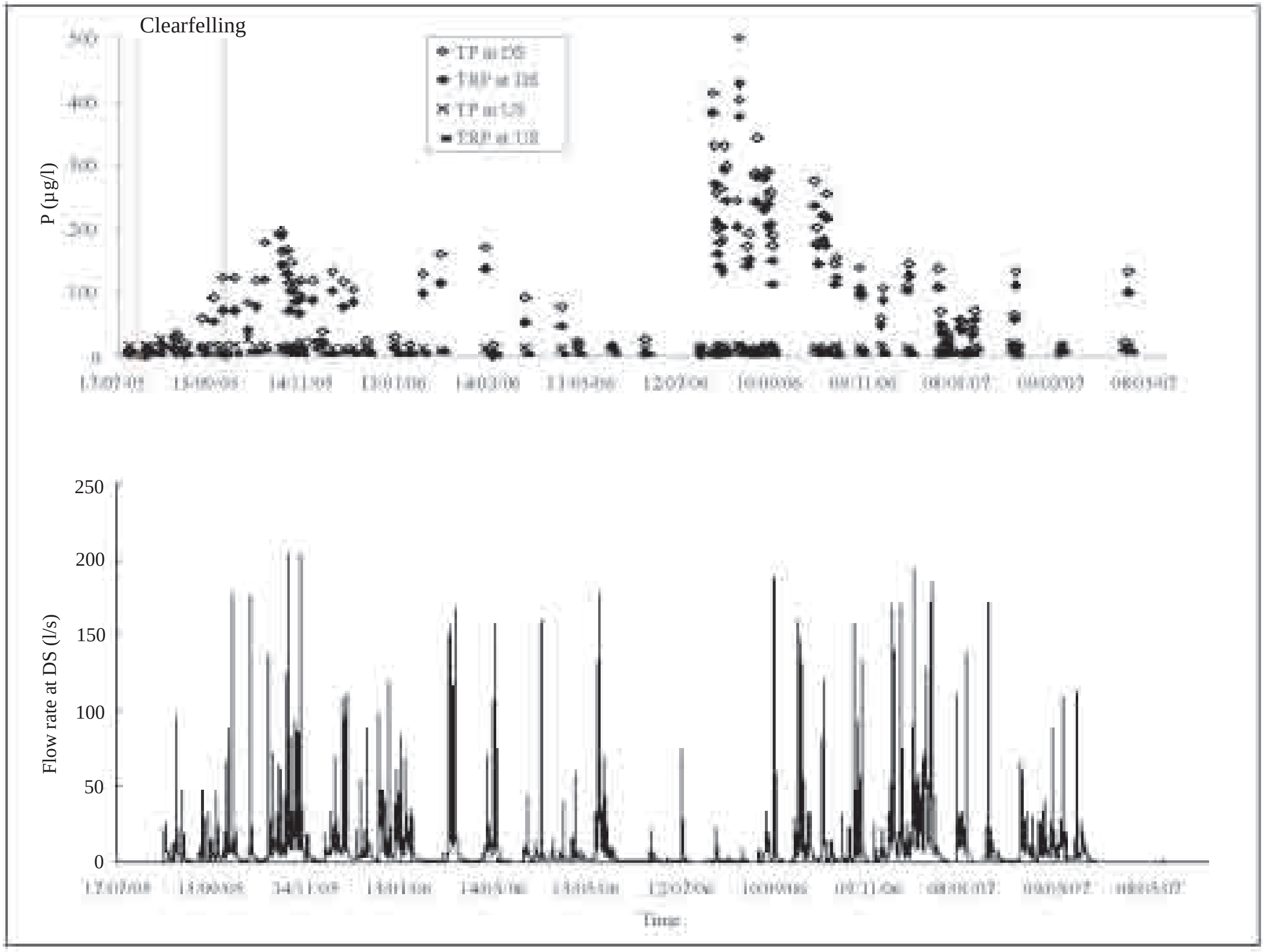

Figure 6.1. Average daily phosphorus concentrations at the upstream (US) and downstream (DS) stations and the DS flow rate during the study period.

stations during the study period. Measured P concentrations entering the harvested part of the study catchment through the upstream station were low, with average values of 14 µg TP/l and 6 µg TRP/l. The average P concentrations in the rainfall were 13 µg TP/l and 4 µg TRP/l.

Phosphorus concentrations at the downstream station were low just prior to and at the beginning of the clearfelling and harvesting activity, which took place between 25 July and 22 September 2005. Four weeks after the harvesting operations began, daily average P concentrations increased gradually from about 8 µg TRP/l to about 73 µg TRP/l at the end of the clearfelling and harvesting period, to the first peak daily average concentration of about 187 µg TRP/l on 28 October 2005. It decreased from the 187 µg TRP/l to about 10 µg TRP/l at the end of December 2005, when flows were very low. From December 2005 to July 2006, measured average daily P concentrations ranged between 3 µg TRP/l and 140 µg TRP/l. The P concentrations were low in the particularly dry month of June 2006 (Fig. 6.1). From the end of July to the middle of August 2006, average daily P concentrations increased significantly. On 15 August 2006, average daily concentrations up to 429 µg TRP/l were measured in the samples leaving the study coupe; these were the highest concentrations recorded during the study. Daily average P concentrations in August and September 2006 ranged from 429 to 140 µg /l. An average daily P concentration of about 100 µg TRP/l was recorded at the end of April 2007, 19 months after the clearfelling and harvesting operations were completed.

Figure 6.2 shows the P concentrations at the upstream and downstream stations during a flood event about 2 November 2005. At the upstream station, P concentrations slightly increased from 8 µg TRP/l to 15 µg TRP/l at the beginning of the flood event and then quickly dropped back to 8 µg TRP/l. At the downstream station at the beginning of the flood event, P concentrations increased significantly from 131 µg TRP/l to the peak of about 200 µg TRP/l as the flow rate increased from about 4.5 l/s to 12.5 l/s. After the flood event, the P concentration was relatively steady at about 100 µg TRP/l.

Because of the dilution, P in the study stream did not have a major impact on the P in the receiving river. During the study period, the P average concentrations above and below the confluence of the study stream with the main river were 17 µg TP/l and 5 µg TRP/l and 21 µg TP/l and 9 µg TRP/l, respectively.

6.3.2 *Phosphorus loads*

During the study period, P entered the clearfelling and harvesting study area through rainfall and the upstream flow. The P loads entering the study catchment from the rainfall were calculated as the product of the average P concentration and the total rainfall. The average TRP concentration in the rainfall was about 4 µg/l. Monthly TRP loads from the rainfall ranged from 2.5 g TRP/ha to 10 g TRP/ha. Monthly P loads at the upstream and downstream stations were calculated from the product of the P discharge mean concentrations and the flows. The net P loads released from the harvesting area were computed by subtracting the P loads at the upstream station and in the rainfall from those at the downstream station. Figure 6.3 shows that the monthly TRP loads/ha at the upstream and downstream stations ranged from 0.76 g to 18.68 g TRP/ha and 0.9 g to 573 g TRP/ha, respectively. The highest monthly P loads occurred in September 2006. During the period of clearfelling and harvesting (August and September 2005), the P loads entering the harvested catchment through upstream, leaving through downstream, and in the catchment rainfall were 75.7 g TRP, 1,437.9 g TRP and 95.6 g TRP, respectively, giving the net release of 120.6 g TRP/ha from the 10.5-ha harvested site. In the first year after clearfelling and harvesting, from October 2005 to September 2006, the P loads upstream, downstream and from the rainfall were 784.9 g TRP, 25,190.9 g TRP and 844.9 g TRP, respectively, giving a net P release rate from the 10.5-ha harvested site (Coupes B, C and D) of 2,243.9 g TRP/ha per year. The P loads in the rainfall and at the upstream station were of similar magnitude.

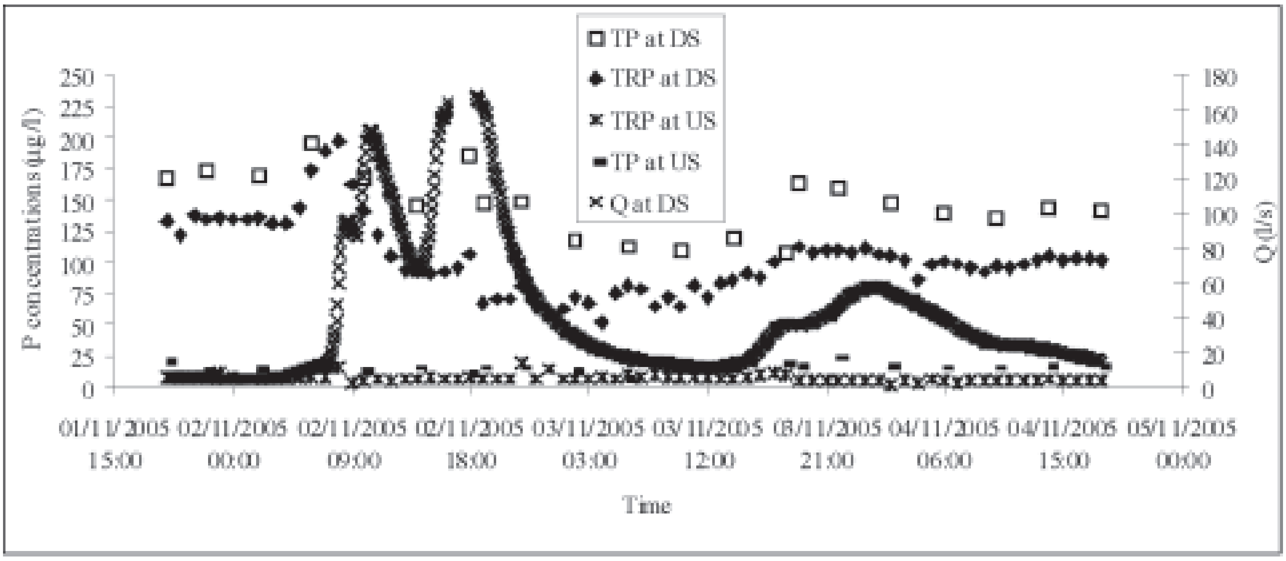

Figure 6.2. Phosphorus concentrations at the upstream (US) and downstream (DS) stations during a heavy storm event 3 months after clearfelling and harvesting (the truncated top of the flow-rate curve is due to the overflow in the flume).

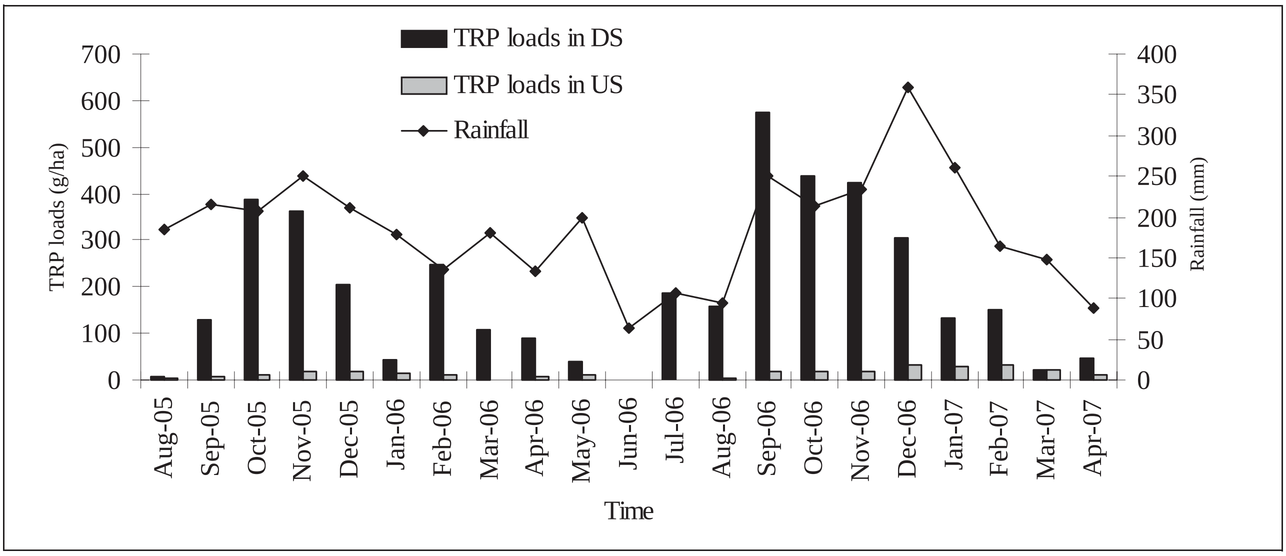

Figure 6.3. Monthly total reactive phosphorus (TRP) loads in upstream (US) and downstream (DS) sites.

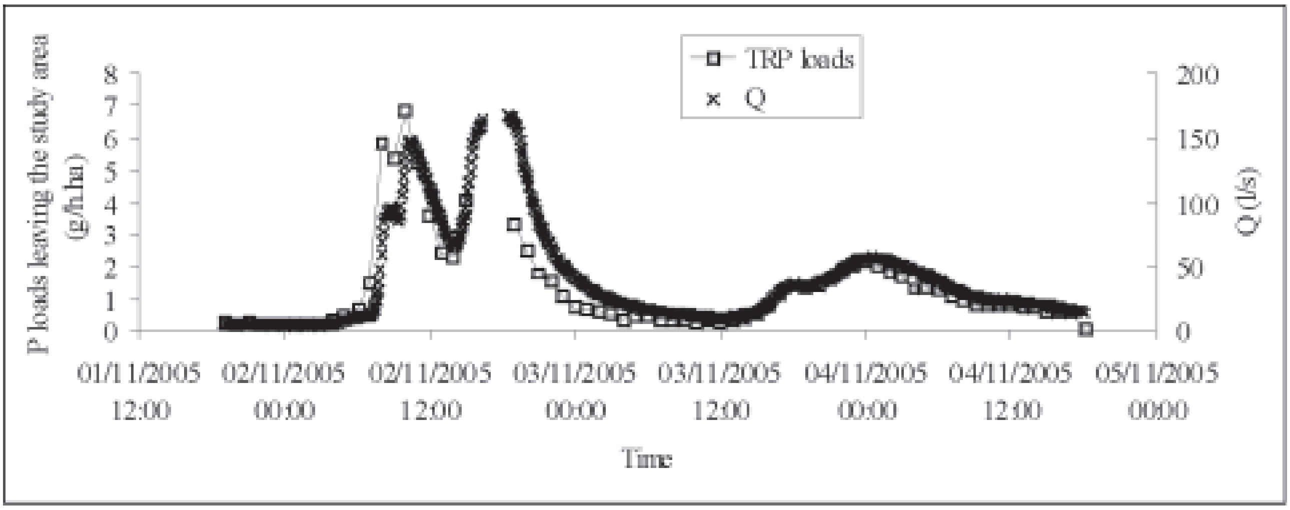

Figure 6.4. Phosphorus loads leaving the study area in a flood event (the truncated top of the flow-rate curve is due to the overflow in the flume).

In a flood event, the P loads leaving the study area were calculated by multiplying the flows at the downstream station by the corresponding P concentrations. Figure 6.4 shows the TRP loads at the downstream station in a flood event. More than 1.2 kg TRP were released from the study coupe from 1 November to 3 November 2005, giving the average daily release rate of more than 38.1 g TRP/ha per day for this period. The TRP load curve closely led the flow-rate curve. In the same flood event, only about 2.8 g TRP/ha per day were found passing the upstream station.

6.4 Discussion

As the P study commenced just a month prior to the beginning of the clearfelling and harvesting operation, pre-clearfelling P data are limited. However, with the same tree species, similar soil, hydrological characteristics and size in the undisturbed upstream catchment (Coupe A, Fig. 3.3), the upstream station was used to provide the control data in this study to investigate the effect of clearfelling and harvesting on P release in the harvested area (Coupes B, C and D; Fig. 3.3).

Significant increases in P concentrations and loads were observed at the downstream station (Figs 6.1–6.3) after clearfelling and harvesting compared with the P concentrations and loads at the upstream station. Phosphorus load release rates were 2,243.9 g TRP/ha per year in the harvested catchment and 20 g TRP/ha per year in the undisturbed forest catchment (Coupe A).

Transport and source are the two major factors influencing P concentrations in release (Gburek *et al.*, 2000; Sharpley *et al.*, 2001b; McDowell *et al.*, 2004; Shigaki *et al.*, 2006b). Transport factors include those mechanisms causing P movement within the landscape, such as erosion and run-off (Shigaki *et al.*, 2006b). During harvesting activities, the machines disturb the forest floor and as a result increase the probability of erosion of particulate matter during rain events, consequently increasing P levels in receiving waters (Ensign and Mallin, 2001). The export of P from the soil to the stream water is also linked to the P adsorption ability of the soil (Tamm *et al.*, 1974). Yanai (1998) found that in clearfelling and harvesting a catchment covered by Typic and Lithic Haplorthods, only 0.07 kg P/ha per year were released in stream water and sediment, though the leaching of P from the forest floor to the soil was 0.7 kg P/ha per year. Since peats have low levels of iron and aluminium resulting in low P sorption capacity (Tamm *et al.*, 1974; Ahti, 1984; Miller *et al.*, 1996), the estimated P release in Burrishoole of 2.2 kg TRP/ha per year is reasonable.

Clearfelling disrupts P cycling through multiple pathways and significantly reduces the uptake of P load by plants, resulting in increased P release (Pierce *et al.*, 1972; Bormann and Likens, 1979; Walbridge and Lockaby, 1994; Herz, 1996). In this study comprising shortwood extraction, the residues (i.e. needles, twigs and branches) were placed on the area in windrows – a practice that can lead to the decay and release of P (Yanai, 1998). Yanai (1998) also found that whole-tree harvesting removed 50 kg P/ha but stem only removed 6 kg P/ha. After clearfelling, an increase in soil temperature due to increased light penetration to the forest floor can increase decomposition rates (Messina *et al.*, 1997; Perison *et al.*, 1997) and increase P release from the soils (Walbridger and Lockaby, 1994). Yanai (1998) hypothesised that the elevated P concentration in the study stream caused by the clearfelling and harvesting could last years because of the slow decay process rates. In this study, about 19 months after the clearfelling and harvesting operations were complete, 100 µg TRP/l were found in the water at the downstream station.

The position of the water table and hydrologic flushing processes play important roles in the P movement from soil to stream water (Devito *et al.*, 2000; Macrae *et al.*, 2005). In this study, very low P concentrations at the downstream station were observed during dry days (Fig. 6.2) following clearfelling and harvesting, and Fig. 6.5 shows the downstream P concentrations during drought conditions.

McDowell and Wilcock (2004) and Monaghan *et al.* (2007) found that the major part of the P load after harvesting activities was derived from movement from the topsoil to the stream by overland flow. Macrae *et al.* (2005) found that low levels of run-off may reduce hydrologic flushing of inorganic P. In the Burrishoole study, high concentrations of P were recorded shortly after a prolonged dry period; this requires further investigation in controlled experiments.

Statistical analysis was carried out with a paired samples *t*-test at the 95% significance level (P = 0.05) using SPSS – a statistical tool (http://www.spss.com). Results indicated that there was no significant difference in P concentrations between upstream and downstream sites in the first half of the clearfelling and harvesting period (July and August 2005). There was a statistically significant difference in the P concentrations between upstream and downstream sites after the clearfelling and harvesting operation was completed.

6.5 Conclusions

In general, the P concentrations rose at the downstream station after the clearfelling and harvesting operation, which took place from 25 July to

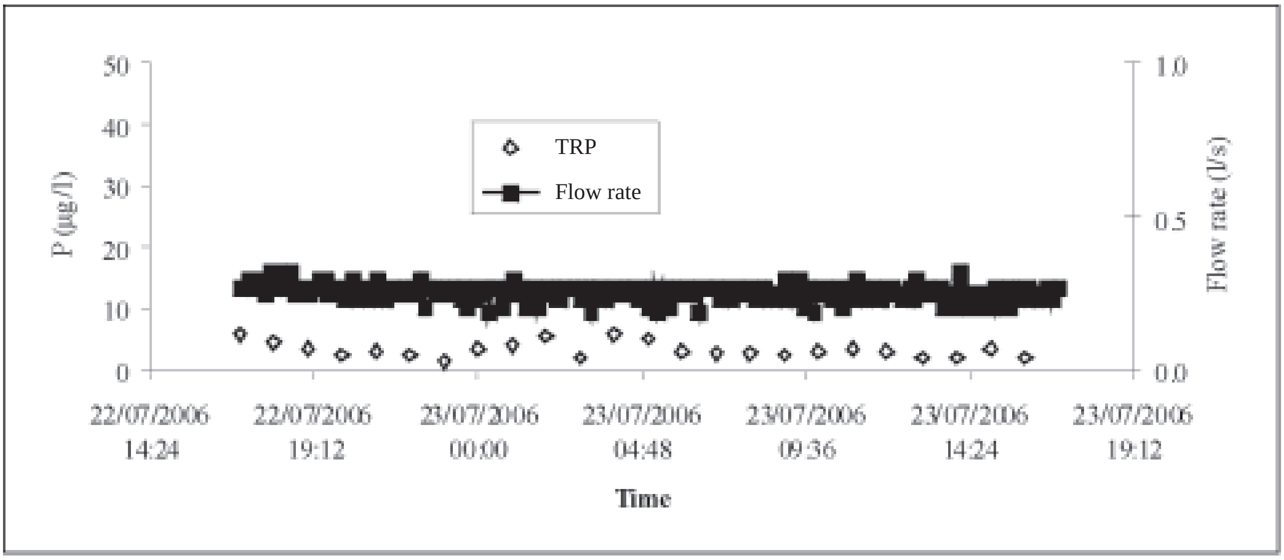

Figure 6.5. Phosphorus concentrations leaving the study area during drought conditions.

22 September 2005, to a first peak daily average concentration of 187 µg TRP/l at the end of October 2005, and then reduced, with temporal variations, to summer 2006. After a particularly dry spell in June and July 2006, the daily average P concentrations rose to their highest level of 428 µg TRP/l in the middle of August 2006. The daily average P concentration of about 100 µg TRP/l was recorded at the end of April 2007, 19 months after the clearfelling and harvesting was completed.

The following detailed conclusions can be drawn from the analysis of the study data.

- The average recorded concentrations in the rainfall at the study site were 13 µg TP/l and 4 µg TRP/l.
- Monthly TRP loads from the rainfall ranged between 2.5 g TRP/ha and 10 g TRP/ha with a total of 80.4 g/ha per year for the period October 2005 to September 2006.
- TRP concentrations entering the study area from a 7.2-ha upstream forested catchment were low and reasonably uniform, reaching peaks of 24 µg TRP/l. The average P concentrations from the upstream catchment were 14 µg TP/l and 6 µg TRP/l.
- There was a statistically significant increase in TRP concentrations leaving the study area from around 8 µg TRP/l immediately prior to and during the start of clearfelling and harvesting operations to 73 µg TRP/l by the end of the clearfelling and harvesting period.
- After clearfelling and harvesting, the recorded average daily P concentrations leaving the study site increased to a peak concentration of 187 µg TRP/l on 28 October 2005. From November 2005 to May 2006 the exiting concentrations reduced to about 90 µg TRP/l.
- Following an exceptionally dry June and July in 2006, the downstream P increased significantly to its highest daily average concentration of 429 µg TRP/l on 15 August 2006, almost a year after clearfelling and harvesting commenced.
- The daily average concentration of about 100 µg TRP/l was recorded at the end of April 2007, about 19 months after clearfelling and harvesting, indicating that the site was still releasing P in excess of the releases that applied before clearfelling.
- Statistical analysis indicates that there were significant differences in the P concentrations at the upstream and downstream stations after the clearfelling and harvesting operations.
- In the first year after clearfelling and harvesting – October 2005 to September 2006 – net P load

release rates were estimated at 2,243.9 g TRP/ha per year from the 10.5-ha harvested site and 20 g TRP/ha per year from the 7.2-ha forested upstream site.

- Because of the dilution available in the river receiving the flow from the study site, P exiting the clearfelled area only slightly increased the P concentration in the river. The catchment area for the main river above the confluence of the study stream and the river is about 240 ha, which is about 24 times the harvested area in the study catchment. Due to this dilution, the average TRP concentration during the study period in the receiving river was 9 µg TRP/l below the confluence of the study stream and the river.

7 Chemical, Physical and Biological Parametric Analyses of the Study Stream

7.1 Introduction

Interactions between forestry practices and the physical and biological processes occurring in small streams are numerous and potentially complex (Mellina *et al.*, 2004). Forest operations can alter the temperature, pH, chemistry and invertebrate populations of streams (Binkley and Brown, 1993; Murray *et al.*, 2000). Water temperature is one of the most important factors regulating biological processes in small streams (Mellina *et al.*, 2004). Removal of streamside vegetation increases the amount of solar radiation reaching the stream and elevates the temperature, particularly in summer, which may negatively affect temperature-sensitive species, particularly salmon (McCullough, 1999). However, Mellina *et al.* (2004) found that compared with the increases of about 5–7°C that have been reported in the literature, only modest temperature changes, averaging 0.05–1.1°C were found in their study in British Columbia.

Acid deposition from air pollution has resulted in ecological damage and poor surface water quality in some of the most natural and least disturbed sites in the UK (Battarbee and Charles, 1994). Increased acidity of soils and surface waters in forested catchments has been associated with enhanced levels of dry and occult deposition captured by forest stands, alterations in soil hydrology and direct physical disturbance of the soil structure during ploughing and harvesting (Miller, 1985). It is well documented that young trees have a high demand on the soil base cation pool and this process can also enhance surface water acidification (Miller, 1985; Reynolds *et al.*, 1994). Compared with the moorland catchment of the River Luce in Scotland, which has a mean annual surface water pH of 6.03, the afforested catchments of the Rivers Cree and Bladnoch are more acidic with pHs of 5.39 and 5.72, respectively (Helliwell *et al.*, 2001).

The use of macroinvertebrates in assessing river quality is well established and forms the basis for the EPA’s Q index, which is used for monitoring Irish rivers (McGarrigle *et al.*, 2002). Macroinvertebrates have been shown to be sensitive to surface water acidification resulting from forestry activities, as such streams tend to have low taxa richness and diversity, be dominated by plecopterans and have low (if any) numbers of ephemeropterans and molluscs (Wade *et al.*, 1989; Smith *et al.*, 1990; Ventura and Harper, 1996; Kelly-Quinn *et al.*, 1997; Bradley and Ormerod, 2002). Macroinvertebrates can also be used to assess the recovery of such surface waters following clearfelling (Cruikshanks *et al.*, 2006). Studies examining the effects of tree felling on invertebrate assemblages in streams show mixed results (Nislow and Lowe, 2006), with some reporting decreased abundance and diversity as a result of increased sedimentation. Other studies, however, have reported higher standing stocks of invertebrates following clearfelling, attributable to increased light penetration and light availability.

The aim of the biological, chemical and physical parametric studies was to try and establish what effects the clearfelling and harvesting operations had on the stream temperature, pH and invertebrates at the study site in the Burrishoole catchment.

7.2 Sampling and Measurement

A multichannel data logger with an OTT temperature and pH probe was placed at both the upstream and downstream monitoring stations. These probes were set up and calibrated about once a month, in accordance with the manufacturer’s instructions. The water temperature and pH at the two stations were automatically recorded every 5 min from April 2005 to May 2007.

A Surber sampler net with a 0.093 m^2 (1 ft^2) area was used to sample the benthic fauna. The substrate in the study stream was disturbed and rocks and cobbles overturned, and all animals were washed into the net. Three to five replicate samples were taken from riffle areas directly downstream of the two monitoring stations. All macroinvertebrates were sorted and identified using standard keys, and identifications were checked using the Ashe, O'Connor and Murray method (Ashe *et al.*, 1998). Species lists were also compiled at the most detailed taxonomic level possible and the Shannon Diversity Index ($H' = -\sum(P_i \ln P_i)$, where P_i is the proportional abundance of the ith species) was calculated for each sample. ANOVA was used to test for differences in univariate variables pre- and post-clearfelling, and ANOSIM (analysis of similarity) was used to test for differences in assemblages collected pre- and post-clearfelling.

7.3 Results and Discussion

7.3.1 Temperature

Figure 7.1 shows the monthly average water temperatures at the upstream and downstream stations before, during and after the clearfelling and harvesting operation. The water temperatures were similar at the upstream and downstream stations before and during clearfelling (April–August 2005). Slight temperature differences were found between upstream and downstream sites after clearfelling during periods when there were flows at each station, with the downstream temperature being, in general, about 1.0°C higher than the temperature at the upstream site, which is located in a felled area. The peak difference occurred when the water temperature downstream was about 5.6°C in February 2006, which was about 1.3°C higher than the temperature of 4.3°C upstream. After clearfelling and harvesting, a greater water surface was exposed to direct sunlight, which could result in the increase in water temperature (Corbett *et al.*, 1978). Binkley and Brown (1993) found that tree canopy removal can raise stream temperatures 3–7°C. In summer 2006, there was a drought with no flows upstream, and it was found that the temperature at the upstream station was about 14.7°C in July 2006, which was about 1.7°C higher than the temperature of 13°C downstream, where there was always a flow due to the presence of a small localised aquifer in the clearfelled site just upstream of the downstream site.

Similar phenomena were reported by Murray *et al.* (2000). Moore *et al.* (2003) found that temperature response was substantial in the clearcut treatments with no buffers, with maximum temperatures increasing by up to 8°C. The magnitude of temperature response for the no-buffer treatments varied with

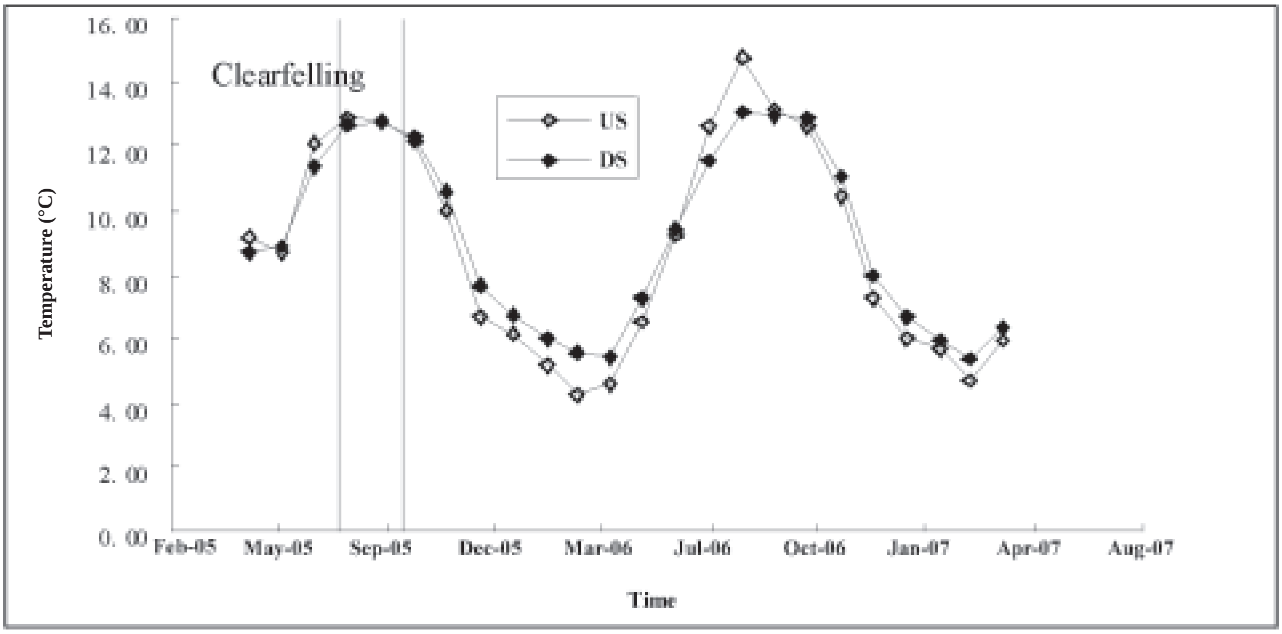

Figure 7.1. Monthly average water temperatures upstream (US) and downstream (DS) before, during and after clearfelling and harvesting.

channel morphology, particularly in relation to bank shading and stream depth. The clearfelling and harvesting effect on daily maximum water temperature increased with decreasing flow and increasing maximum air temperature (Moore *et al.*, 2003).

7.3.2 pH analysis

The pH in the rainfall at the downstream station was 5.8 ± 0.2 during the study period. Figure 7.2 shows the monthly average pH at the upstream and downstream stations before, during and after the clearfelling and harvesting operations. Monthly pH at the upstream station was relatively stable with an average value of 3.5 ± 0.1. At the downstream station, the monthly average pH fluctuated between 3.6 and 5.4; it reached the peak values of 5.2 in July 2005 before clearfelling and 5.4 in April 2007 after clearfelling. The lowest monthly average downstream pH of 3.6 was recorded in December 2006 during a period of heavy rainfall and high flows. Figure 7.3 shows the 5-min pH at the upstream and downstream stations before and after clearfelling and harvesting. It is worth noting that the pH responses appear to be dependent on the flow rates, e.g. at downstream the pH increased – both pre- and post-clearfelling – during periods when rainfall and flows were low (Fig. 7.3). At high flow rates, the downstream pH dropped to the same level as the upstream pH, which rose during the high flow rates. At low flow rates, the downstream pH increased to about 5.5, indicating that the pH of the water was possibly modified by increased residence time in the study area, including in the aquifer just upstream of the downstream station. The pH just downstream of the confluence of the study stream and the Srahrevagh River was 6.1 ± 0.8. The clearfelling and harvesting did not change the downstream pH responses significantly. Similarly, Ensign and Mallin (2001) did not observe a statistically significant change in pH at the Goshen Swamp after clearfelling. Blackburn and Wood (1990) also found that clearfelling of a forest had no significant effect on storm-flow pH.

7.3.3 Biological variables

In general, the numbers of animals collected were small, which is probably a reflection of the size of the waterbody, and the frequency with which it dries out. The macroinvertebrate assemblage in the stream comprised members of the orders Coleoptera (beetles), Diptera (true flies), Plecoptera (stoneflies), Trichoptera (caddis flies) and Oligochaeta (worms). Replicates from both sites in all years contained an average of 11 individuals (minimum = 0, maximum =

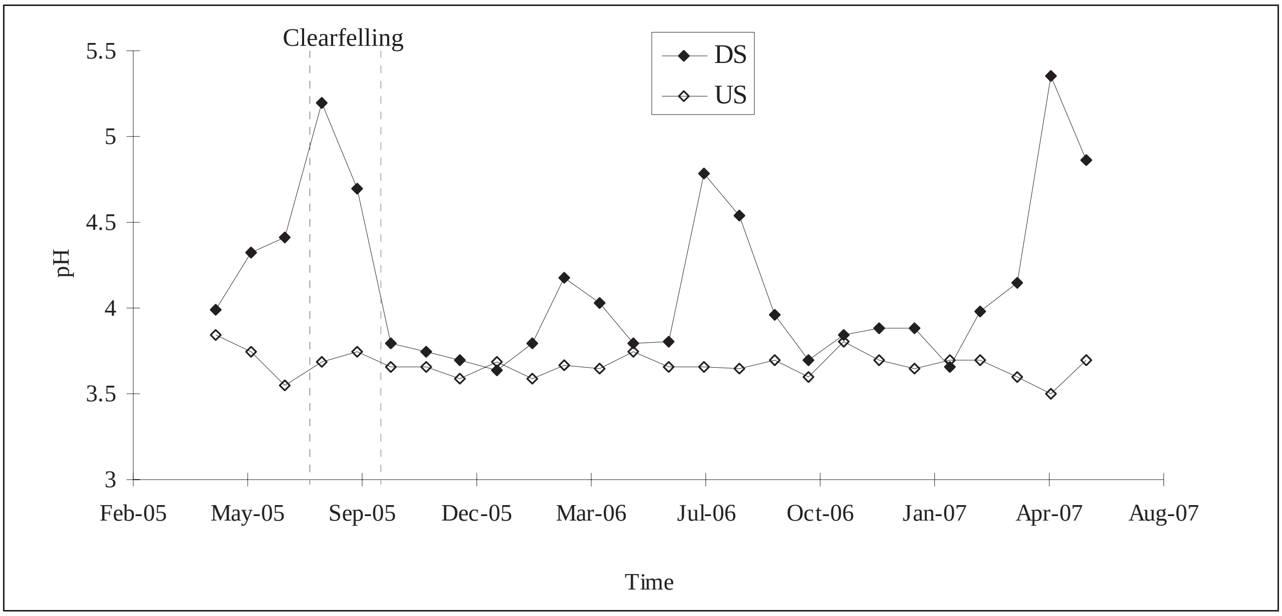

Figure 7.2. Monthly average water pH upstream (US) and downstream (DS) before and after clearfelling and harvesting.

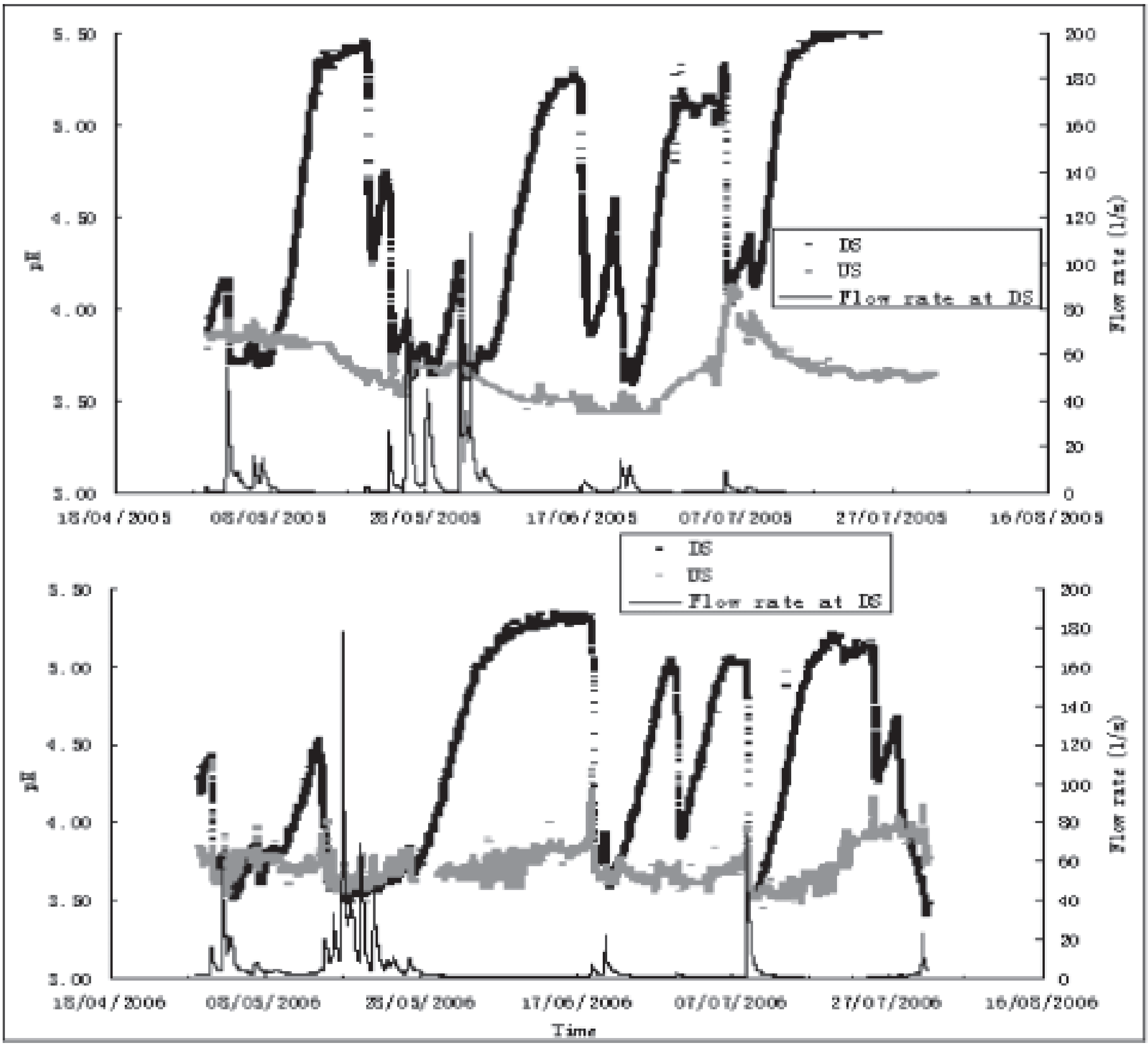

Figure 7.3. pH upstream (US) and downstream (DS) before (May, June and July 2005) and after (May, June and July 2006) clearfelling and harvesting with the DS flow rate.

51), with representatives from 12 taxa (Tables 7.1 and 7.2).

There were no significant differences in abundance (ln(x+1) transformed data), taxa richness or diversity according to site or year (ANOVA, $P > 0.05$), although the interaction term site × year was a significant source of variation ($P < 0.05$) for all three variables. Least significant difference (LSD) *post hoc* tests revealed that this significance was owing to the higher abundances, richness and diversity at the top site (upstream) in 2005.

Plecoptera were the most numerous group on all sampling occasions, comprising 60% of each sample on average (Fig. 7.4). The vast majority of stoneflies were *Nemoura cinerea* individuals. This is consistent with the acidic nature of the stream. In general, the macroinvertebrate assemblages are characteristic of those found in small acidic upland streams, being dominated by species of acid-tolerant Plecoptera, Coleoptera and Trichoptera (Henrikson and Medin, 1986). No acid-sensitive species were found in any of the samples (e.g. species of Hirudinea, Elmididae, Gastropoda, Bivalvia).

Table 7.1. Average abundance, taxa richness and Shannon diversity of macroinvertebrate assemblages in two sites on the experimental stream in the Srahrevagh (Rough) River sub-catchment.

	Abundance	Taxa richness	Shannon diversity
2004 Upstream	3.4	2	0.61
2004 Downstream	9.8	3	0.85
2005 Upstream	21.2	5	1.16
2005 Downstream	7.4	2	0.46
2006 Upstream	17.7	3	0.45
2006 Downstream	12.7	3	0.69

Table 7.2. Average abundance of macroinvertebrate taxa in two sites of the experimental stream in the Srahrevagh (Rough) River sub catchment.

Order	Taxa	2004 Upstream	2004 Downstream	2005 Upstream	2005 Downstream	2006 Upstream	2006 Downstream
Coleoptera	*Agabus* sp.			1		1	1
Plecoptera	*Amphinemura sulcicollis*		2				
	Leuctra hippopus			6			
	Nemoura cinerea	2	6	14	8	15	10
Diptera	Chironominae			5			
	Diptera	2					
	Tanypodinae	1		1	1		
	Orthocladiinae	2	3	2	2	3	2
	Simulidae		2				
Trichoptera	Limnephilidae		2	2			
	Plectrocnemia conspersa	1	1	1	3	1	1
Oligochaeta	Oligochaete	2	1	3	2		

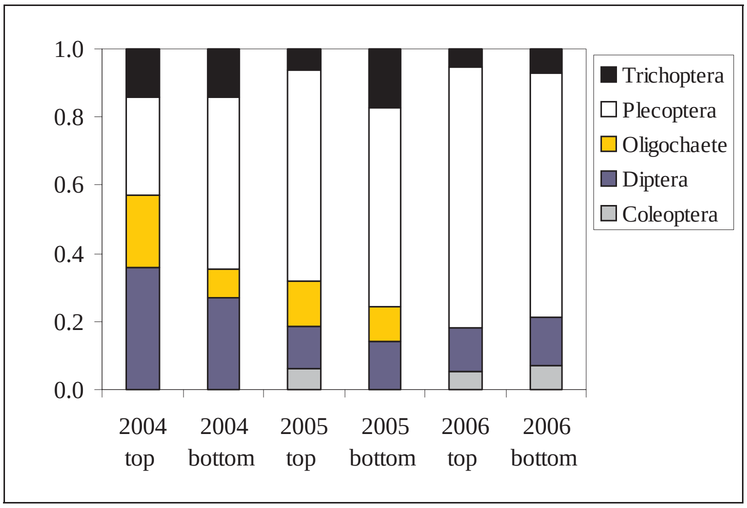

Figure 7.4. Percentage composition of macroinvertebrate samples taken from two sites of the experimental stream in the Srahrevagh (Rough) River sub-catchment.

ANOSIM results comparing pre- and post-felling assemblages showed no significant differences at either the upstream site (P = 0.64) or the downstream site (P = 0.38), despite the obvious changes in tree coverage adjacent to the stream.

7.4 Conclusions

In general, clearfelling and harvesting may have slightly increased the stream water temperature by about 1.0°C between the upstream and downstream stations when there was flow at both stations, e.g. the monthly average downstream water temperature was about 5.6°C in February 2006, 1.3°C higher than the temperature of 4.3°C upstream. The higher stream temperature and greater fluctuations upstream in summer compared with downstream could be due to the drought at the upstream station and the clearfelling.

Clearfelling and harvesting did not change the downstream pH significantly. The monthly pH average upstream was relatively stable with a value of about 3.5. Downstream, the monthly pH averages fluctuated between 3.6 at high flows and 5.4 at low flows, indicating the possible mitigation effect of the aquifer just upstream of the downstream station. The monthly average pH reached the pre-clearfelling peak value of 5.2 in July 2005 and the post-clearfelling peak value of 5.4 in April 2007 – both during very low flows. The lowest monthly average downstream pH of 3.6 was recorded in December 2006 during high flows.

The macroinvertebrate survey of the study stream indicates that there have been no significant changes in the assemblages following clearfelling. However, in coming to this conclusion, it must be acknowledged that the baseline assemblages (2004 and 2005) were fairly depauperate, comprising only small abundances of acid-tolerant species. The plecopteran species, which are very sensitive to eutrophication, appeared to be unaffected by the clearfelling operations. The depauperate assemblages may be due to two factors – the acidification effects of the forestry over the last three decades, or the temporal nature of water flow given the size of the stream. Long-term monitoring of this site will be useful in assessing whether the stream is capable of supporting a more diverse and abundant macroinvertebrate fauna without the influence of closed canopy forestry.

8 Conclusions

8.1 Introduction

The clearfelling and harvesting operations on the Burrishoole catchment site were carried out carefully and employed BMPs, which included not carrying out any harvesting during wet periods. The harvesting operations commenced on 25 July 2005, and lasted for 8 weeks. Two monitoring stations were established, one above and the other below the selected clearfell area, to study the effects of clearfelling and harvesting on the hydrology, sediment losses, water P, water physico–chemical and biological parameters in the first-order stream flowing through the catchment site. Measurements were taken before clearfelling for about 1 year, during clearfelling and harvesting, and post-clearfelling for about 19 months.

8.2 Conclusions

The main conclusions from the study are as follows:

- **Hydrological analysis**

  From the present analyses the forest clearfelling and harvesting had a very limited impact on flood risk downstream in this study. A similar study of felling has recently been reported from Wales, where the site was physically similar to Burrishoole, with a high annual rainfall (>2,000 mm) and peat soils with open drainage. The impacts on streamflow in the Welsh sites were closely monitored in nested catchments from 1 to 10 km^2 in size. Commercial felling followed the Forestry Commission's harvesting guidelines (Forestry Commission Great Britain, 2003). It was found that there was a significant increase in base flows but a change in peak flows (Robinson and Dupeyrat, 2005) was not detected. The similar peak flow result at Burrishoole may be due to the care taken by the forest workers to comply with the Forest Service guidelines (2000a,b). Taken together, the results of the Welsh and Burrishoole studies and that of the more recently published literature indicate that properly conducted felling can have a very limited impact on flood risk downstream.

- **Sediment release**

  In base-flow conditions, the SS concentrations at the upstream and downstream stations were always low before, during and after clearfelling and harvesting. From November 2005 to April 2006 there were significant differences between the daily peak upstream and downstream concentrations. From May 2006 to May 2007, the SS concentrations at the upstream and downstream stations were similar, indicating that the effect of clearfelling and harvesting on SS concentrations in the study stream appears to have ceased. During the clearfelling and harvesting period (August and September 2005), about 13 kg SS/ha were released from the undisturbed forest catchment (Coupe A) and 25.8 kg SS/ha from the harvested catchment (Coupes B and C). In the first year after clearfelling and harvesting (2,012 mm rainfall), the net SS release rate from the harvested catchment was 272.6 kg SS/ha per year, which was greater than the 172 kg SS/ha per year released from the undisturbed forest catchment.

- **Phosphorus release**

  Measured P concentrations entering the harvested part of the study catchment through the upstream station were low, with average values of 14 µg TP/l and 6 µg TRP/l. The average P concentrations in the rainfall were 13 µg TP/l and 4 µg TRP/l. The P concentrations rose after clearfelling and harvesting to a first peak daily average concentration of 187 µg TRP/l in November 2005, and then reduced, with temporal variations, to summer 2006. After a particularly dry spell in June and July 2006, the highest peak daily average concentration of 429 µg TRP/l was measured in August 2006, a year after clearfelling commenced. The daily average P concentration of about 100 µg TRP/l was recorded at the end of April 2007, 19 months after the clearfelling and harvesting operations were completed. During the clearfelling and harvesting period, an estimated net 120.6 g TRP/ha were released from the harvested area. In the first year after clearfelling and harvesting – October 2005 to September 2006 – net P load release rates were estimated at 2,243.9 g TRP/ha per year from the 10.5-ha harvested site and 20 g TRP/ha per year from the 7.2-ha forested upstream site. Because of the available dilution in the receiving river downstream of the study site – based on the comparison of the river catchment and study catchment – P exiting the clearfelled area only slightly increased the P concentration in the receiving river. Average concentrations in the receiving river were 5 µg TRP/l above and 9 µg TRP/l below the confluence of the study stream and the river.

- **Biota**

  The macroinvertebrate survey of the study stream indicates that there has been no significant change in the assemblages following clearfelling. However, in coming to this conclusion, it must be acknowledged that the baseline assemblages (2004 and 2005) were fairly depauperate, comprising only small abundances of acid-tolerant species. The plecopteran species, which are very sensitive to eutrophication, appeared to be unaffected by the clearfelling operations. The depauperate assemblages may be due to two factors – the acidification effects of the forestry over the last three decades, or the temporal nature of water flow given the size of the stream. Long-term monitoring of this site will be useful in assessing whether the stream is capable of supporting a more diverse and abundant macroinvertebrate fauna without the influence of closed-canopy forestry.

- **Temperature**

  In general, clearfelling and harvesting may have slightly increased the stream water temperature by about 1.0°C between the upstream and downstream stations when there was flow at both stations, e.g. the monthly average water temperature downstream was about 5.6°C in February 2006, which was about 1.3°C higher than the temperature of 4.3°C upstream. The higher stream temperature and greater fluctuations upstream in summer 2006 compared with downstream could be due to no flows at the upstream station and to the clearfelling.

- **pH**

  Clearfelling and harvesting did not change the pH response downstream significantly. The pH upstream was relatively stable with a value of about 3.5. Downstream, the monthly average pH fluctuated between 3.6 at high flows and 5.4 at low flows, indicating the possible mitigation effect of an aquifer just upstream of the downstream station. The monthly average pH reached the pre-clearfelling peak value of 5.2 in July 2005 and the post-clearfelling peak value of 5.4 in April 2007 – both during very low flows. The lowest pH of 3.6 was recorded in December 2006 during high flows.

9 Forestry Guidelines and Recommendations

9.1 Forest Guidelines and Recommendations having Regard to Soil Erosion

Forestry activities, in common with other soil-based activities, have the potential to release nutrients and SS into receiving waters (Cummins and Farrell, 2003a,b). Since forests have been extensively planted in upland blanket peat areas, many Irish watercourses rise in, or receive drainage from, forest areas. This has led to concerns about the possible impacts that clearfelling, harvesting and replanting activities in these forests may have on aquatic systems. These nutrients and SS releases can lead to eutrophication and affect biodiversity, including fish spawning success (Heaney *et al.*, 2001). Many of the soil-loss problems associated with forestry activities can be reduced if not eliminated by proper planning, consultation, and careful preparation and execution of all works. The trees on the Burrishoole study site were clearfelled and harvested by Coillte Teoranta and its contractors in accordance with the Forest Service guidelines. No operations took place during wet weather. As a result, there was little soil loss from the clearfelled blanket peat area, and the SS concentrations returned to their pre-clearfelling values within a year of the completion of the harvesting activities. This soil loss could probably have been further reduced by developing buffer zones. In summary, it appears from the study, that if blanket peat forest areas are clearfelled in accordance with the Forest Service guidelines there will be little loss of soil from the felled catchment.

9.2 Forest Guidelines and Recommendations having Regard to Phosphorus Loss

As a result of the commissioning of new waste-water treatment facilities in Ireland and the consequent reduction in point-source discharges of P to receiving waters, more and more attention is being directed towards diffuse sources of P (Forest Service, 2000b; US Environmental Protection Agency, 2004). Forests and forestry activities, amongst other soil-based activities, have been identified as potentially important diffuse sources of P (Nisbet, 2001). Fertilisation and harvesting are the two most important forest operations that could significantly elevate the P concentration in the receiving water if proper management is not exercised (Cummins and Farrell, 2003b). In this section of the report, the Forest Service guidelines are assessed with regard to P movement into the receiving water.

Strategies that can reduce the release of P from clearfelling and harvesting operations to receiving waters include minimisation of the P sources available for release, and prevention of the P from reaching the waterbodies. The *Forestry and Water Quality Guidelines* require all harvesting and extraction operations to be carried out in accordance with the *Forest Harvesting and the Environment Guidelines*, which, in turn, require that the size of the felling coupe should be carefully selected. Smaller-sized felling coupes tend to promote better water quality. In the blanket peat forest catchment in Burrishoole, Co. Mayo, a study area of about 10.5 ha was clearfelled. The clearfelling and harvesting operations raised the average daily P concentrations in the first-order study catchment stream from the pre-clearfelling concentrations of 15 µg TRP/l in July 2005 to 429 µg TRP/l in August 2006; these P concentrations reduced to 100 µg TRP/l by April 2007. Because of the dilution available in the main river into which the study stream discharged, the measured P concentrations were always lower than 15 µg TRP/l downstream of the confluence of the study stream and the main river. This indicates that selection of the coupe size for felling should be based on the dilution available in the catchment to reduce P concentrations exiting from the felled area to acceptable values in the receiving waters. Dilution could be based on estimates of the areas of the proposed felling coupe and of the catchment into which discharge from the felling coupe area takes place. Simple staff gauges could be installed at regular stable stream and river cross-sections, and at culverts to provide, after flow rating, estimates of the flows to facilitate dilution calculations. Regular water sampling and analyses should be carried out in the catchment prior to felling, along with searching and using data from previous studies on similar sites, to ensure that the dilution is sufficient to reduce the nutrient concentrations in the receiving waters to acceptable levels. Water samples should also be tested after felling to confirm that the concentrations are acceptable and to build a database for future felling strategies. Based on the data collected in the measures above, it should be possible to decide – on a rational and factual basis – the size of the coupe that could be felled without affecting receiving waters adversely.

The *Forestry and Water Quality Guidelines* advise several measures to control the disturbance of the forest floor and soil erosion such as (i) using brash mats to avoid soil damage, erosion and sediment release, and (ii) developing sediment traps and buffer strips prior to harvesting, and maintaining them during and after harvesting. These measures not only reduce sediment release, but also particulate nutrient release. Based on the *Forestry and Water Quality Guidelines*, branches, logs or debris should not be allowed to build up in aquatic zones and all such material should be removed when harvesting operations have been completed. These measures could also limit nutrient releases. It should be noted that in the Burrishoole study, where the felling and harvesting operations were carefully executed only during dry periods and employing BMPs, most of the P released from the site was in solution and it is not clear how effective buffer strips would be in reducing these soluble P concentrations. Until this is established, it would be prudent to base the felling coupe size on the dilution available in the catchment, along with nutrient concentrations (i) existing near the time of felling, and (ii) measured during and after clearfelling on similar sites.

The recommendations for P control on forested sites are:

1. Before forestry activities take place, good baseline information should be obtained on nutrient concentrations, rainfall and flows at strategic points within the catchment area to enable management to make rational decisions on felling coupe size based on factual information.

2. Along with the use of BMPs, a strategy based on dilution for the selection of felling coupe size should be employed to offset the potential adverse effects of released nutrients.

3. Buffer zones should be employed for the removal of particulate organic matter.

4. Field and laboratory experiments should be carried out to examine the effectiveness of buffer zones and the use of local stone and rock materials in removing soluble nutrients from discharge waters.

5. The effectiveness of silt traps in removing nutrients should be investigated, as it is well established that P can be released into solution from particulate biomass during anaerobic phases. These releases are more likely to occur during warm weather when the receiving waters are most vulnerable.

6. The efficacy of windrowing the brash in terms of nutrient release distribution to the soil and ease of replanting should be examined.

7. Mathematical models of nutrient releases should be developed, calibrated and tested to provide additional tools for management in decision making.

8. Further detailed field studies, complemented by controlled laboratory flume and agitator tests, should be carried out to provide data and insight into mechanisms of nutrient release, which can be incorporated into the developed mathematical models.

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NDP
National Development Plan 2007 - 2013

Science, Technology, Research and Innovation for the Environment (STRIVE) 2007-2013

The Science, Technology, Research and Innovation for the Environment (STRIVE) programme covers the period 2007 to 2013.

The programme comprises three key measures: Sustainable Development, Cleaner Production and Environmental Technologies, and A Healthy Environment; together with two supporting measures: EPA Environmental Research Centre (ERC) and Capacity & Capability Building. The seven principal thematic areas for the programme are Climate Change; Waste, Resource Management and Chemicals; Water Quality and the Aquatic Environment; Air Quality, Atmospheric Deposition and Noise; Impacts on Biodiversity; Soils and Land-use; and Socio-economic Considerations. In addition, other emerging issues will be addressed as the need arises.

The funding for the programme (approximately €100 million) comes from the Environmental Research Sub-Programme of the National Development Plan (NDP), the Inter-Departmental Committee for the Strategy for Science, Technology and Innovation (IDC-SSTI); and EPA core funding and co-funding by economic sectors.

The EPA has a statutory role to co-ordinate environmental research in Ireland and is organising and administering the STRIVE programme on behalf of the Department of the Environment, Heritage and Local Government.

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